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Research Article

Development of an Electric Tugger for Patient Bed Transportation

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ABSTRACT

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Transporting a patient in a bed within Songklanagarind Hospital, Faculty of Medicine, Prince of Songkla University, typically requires at least two workers. During peak hours, insufficient personnel often overburdens the patient transportation team. To address this challenge, this research aims to develop an electric tugger, or e-tugger, to facilitate patient bed transport. The e-tugger is designed to enable a single staff member to haul a patient bed on flat surfaces and up to a 5% incline to the destination. The e-tugger's design includes an electric tugger and a forklift. The tugger's structure provides space to install the necessary components. A 3-kW brushless DC motor, powered by 72V, 15Ah Li-ion batteries, drives the system, allowing it to move a patient bed weighing up to 400 kg on a 5% incline. The staff can control the e-tugger's motion using either a control box or a joystick. The forklift, when viewed from the side, has an L-shape and is equipped with an integrated electric scissor jack that lifts the forklift up and down, operated via the control box. The e-tugger's performance study focuses on two main aspects: (1) the user experience of coupling the e-tugger to the patient bed, and (2) the e-tugger's operation on a 30-meter flat surface and in a passageway. Onsite testing demonstrates that one staff member can effectively transport a patient in a bed using the e-tugger. Coupling the e-tugger to a patient's bed takes only 10 seconds. The e-tugger can propel a 255-kg patient bed at approximately 1.66 m/s. The electric motor consumes 2.46 A on a flat surface and 4.46 A on a 5% incline. Additionally, after transporting a 380-kg patient bed for 2.36 km, the battery's state of charge decreases by 2 %, with the e-tugger's average energy consumption rate being approximately 91.5 Wh/ 10 km.

1. Introduction

Patient transportation is an essential task in healthcare facility management because it affects staff productivity, the quality of treatment that patients receive, and the hospital's efficient operation (Naesens and Gelders, 2006). Moving patients between areas with their beds has typically required healthcare workers to use their strength, which can be physically demanding and put them at risk of musculoskeletal injuries (Dadashi -Tonkaboni *et al.*, 2023). In addition, the manual process can be quite time-consuming, often requiring the coordination of several staff members. Unorganized patient transport, in addition to delays in patient care, causes higher operational expenses and even leads to patient-life-threatening situations

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(Hendrich and Lee, 2005). Several transportation systems have emerged in recent years to handle this challenge. A bed transfer system can incorporate a bed mover (Guo *et al.*, 2018; Faria *et al.*, 2021), a patient transfer apparatus (Dhelika *et al.*, 2021), and optimization tools to attain high-quality services for patients (Fathollahi-Fard *et al.*, 2020; Schäfer *et al.*, 2023). These technologies make it much easier to move beds or patients between rooms, effectively reducing transportation risks in hospital environments. However, the development of a hospital bed design is still ongoing to achieve more effective patient transportation.

Recently, Songklanagarind Hospital, Faculty of Medicine, Prince of Songkla University, Thailand, has noticed a significant rise in the number of overweight or obese patients seeking healthcare services. According to the collected data from 2021 to 2023, the overall count of obese patients in 2021 was approximately 5,183. The number then increased to around 8,226 in 2022, indicating a significant escalation in obesity instances. In 2023, there were an additional 221 patients added, representing a 2.69% increase in comparison to the previous year. The rise in obese patients emphasizes the need for supplementary medical facilities to accommodate the growing number of people suffering from obesity.

Given the increasing prevalence of obesity as a health concern, it is critical to ensure that suitable resources and services are available to properly assist these patients. Understanding the importance of this matter, Songklanagarind Hospital has taken various measures to cater to the requirements of obese patients. One such measure is to acquire more patient beds specifically designed to accommodate and support obesity treatment. The hospital's objective is to improve the comfort and treatment outcomes of obese patients by providing specialized beds. These specialized beds are a component of the hospital's dedication to providing high-quality healthcare services to all patients, regardless of their weight or size.

Furthermore, in every hospital, the transfer of patients between wards after receiving medical treatments is a critical responsibility. At Songklanagarind Hospital, a minimum of two personnel is necessary to transfer patients who are in bed. To ensure efficient patient transportation, it is crucial to address the problem of delays that frequently occur during peak hours because of insufficient delivery personnel. According to the average number of patient transportation orders at Songklanagarind Hospital during the weekdays, the hospital experiences a high volume of transportation orders, with as many as 1,300 requests. However, on weekends, the number of orders decreases to around 650. It demonstrated the significant demand for patient transportation services at the hospital. There are two potential solutions to this issue: increasing the workforce or acquiring an electric tugger or cart. One potential solution to the issue of delays in patient transportation is to increase the number of personnel employed to deliver patients. Nevertheless, there are certain drawbacks associated with this approach. First and foremost, recruiting new staff would increase the hospital's reliance on labor. The growing reliance on human resources can have substantial long-term consequences, as it necessitates substantial expenditures on recruiting, training, and salaries. If the demand for patient transportation continues to rise, it may not be a long-term solution either.

An alternative and more favorable approach to addressing delays is to acquire an electric tugger or cart that can assist delivery workers in transporting patients. This alternate technique provides numerous benefits compared to the recruitment of additional staff. Electric tuggers can enhance patient transportation to achieve greater speed and efficiency. Patient transporters, which use bed movers, are safe from the physical strain associated with moving patient beds (Daniell *et al.*, 2014). Furthermore, the use of electric tuggers reduces the need to employ supplementary staff. Rather than relying more on labor, the hospital has the option to invest in this equipment, which can prove to be a more economically efficient alternative in the long term.

Ueno *et al.* (2014) developed a power-assist omni-directional mobile bed and tested how power assist and fuzzy reasoning affect its operation. This is an important step forward in the development of patient bed transportation in hospitals. The results of experiments demonstrated the power-assist system's effectiveness and highlighted the importance of fuzzy reasoning in reducing the operation burden. Power assist reduced the operating force, but without fuzzy reasoning, it caused vibrations. The fuzzy reasoning method helped reduce vibrations and improve operation times. The study contributes to the development of innovative power-assist omni-directional mobile beds and suggests potential applications in actual nursing-care tasks.

Guo *et al.* (2018) proposed an innovative way to overcome the drawbacks of conventional bed-pushing techniques, such as labor constraints, work-related injuries, and delays in patient transportation. Their study presented a motorized robotic bed mover that offers omnidirectional mobility. It consisted of an omnidirectional mobility unit, a force-sensing-based human-machine interface, and control hardware equipped with batteries and electronics. A single individual can easily attach this device, known as the OmniBed, to a manual hospital stretcher, transforming it into a convenient, powered omnidirectional bed. Their study findings revealed that the OmniBed effectively decreased the need for human resources in patient transportation while also reducing back muscle exertion. This is particularly advantageous for elderly staff members. The study concluded that the OmniBed outperformed conventional powered beds, which only provide forward assistance when using a fifth powered wheel, in terms of comfort, effectiveness, and safety.

In addition, Faria *et al.* (2021) discussed the critical issue of physical exertion experienced by healthcare staff while transferring patients to healthcare facilities. Their study highlighted the increasing strain on healthcare professionals due to the use of heavy equipment, which causes musculoskeletal injuries and necessitates extended medical leave. They conducted finite element method (FEM) evaluations in their study to confirm the structural reliability and operation of the automated device. Their design approach involved structural optimization to minimize expenses and decrease the weight of the equipment, thereby improving its efficiency and benefit in healthcare environments. They designed the automated moving device to adapt to various hospital bed models, enabling its application in diverse healthcare environments. Their results showed that their technology improves the efficiency of patient care in hospitals by making it easier to move patients and improving their maneuverability with motorized wheels and portable structures.

In addition, Dhelika *et al.* (2021) developed a motorized patient bed that is capable of holonomic mobility. They replaced all the bed's casters with motorized wheels equipped with a swerve mechanism. The motorized wheels with swerve mechanisms were lightweight and enabled a sudden change in the movement direction. However, further development of a sophisticated motor control system was necessary to ensure the synchronization of all wheels. Furthermore, it is necessary to modify all patient beds with motorized wheels and swerving mechanisms.

Figure 1 Delivery staff and a patient bed at Songklanagarind Hospital

According to the studies mentioned earlier, there are several advantages to developing modernized patient bed transportation. Thus, this present study focuses on the creation of a small electric vehicle, called the e-tugger, designed specifically to aid hospital personnel in the transport of patients. The primary goal is to design a cart that can provide enough propulsive force to drive a bed carrying a patient weighing up to 400 kg on a slope with a 5-% grade (2.86°). Moreover, this research investigates the design and engineering considerations essential for the successful development of the compact electric cart. The design of the e-tugger ensures easy operation for the user, enabling them to effortlessly adjust and control the patient's bed. The creation of such a vehicle would significantly improve the efficiency and convenience of patient transportation within hospitals, thereby enhancing the overall quality of care provided by the hospital.

This paper's organization is as follows: The section titled "MATERIALS AND METHODS" provides an explanation of the requirements and limitations involved in the design and construction of the e-Tugger. Next, this work outlines the e-tugger's design features. This section ends with an instruction to connect the e-tugger to the patient's bed. "RESULTS AND DISCUSSION" reports and discusses the e-tugger's performance test data. The final section, "CONCLUSION," concludes this work and provides outlooks for future development of the e-tugger.

2. Materials and Methods

Before constructing the e-tugger, we reviewed documentation, conducted observations, and interviewed delivery personnel. We have since developed a prototype of the e-tugger and completed its performance evaluation. The following subsections will present the design requirements and limitations identified from the preliminary studies.

Requirements for Patient Transportation

In addition to the maximum payload and gradeability of the e-tugger, several additional design requirements need to be considered. The new patient beds used at Songklanagarind Hospital in Hat Yai are manufactured by Paramount and Berlin. This research based the e-tugger's design on the Paramount bed, as its structure closely resembles that of the Berlin beds. The empty Paramount bed weighs 154 kg and measures 2.19 m in length and 1.06 m in width. It has a safe payload capacity of 240 kg. Figure 1 shows a delivery staff member demonstrating how to transport the Paramount bed. As illustrated in Figure 1, the e-tugger is attached to the bed from the same side where the staff member is pushing it. The tugger must be positioned underneath the bed. The e-tugger's jaws, shown in Figure 2, connect to one of the transverse circular tubes (highlighted in the red rectangle in Figure 1) of the bed's lower frame. Thus, the tugger's height and width must not exceed 0.8 m and 0.6 m, respectively.

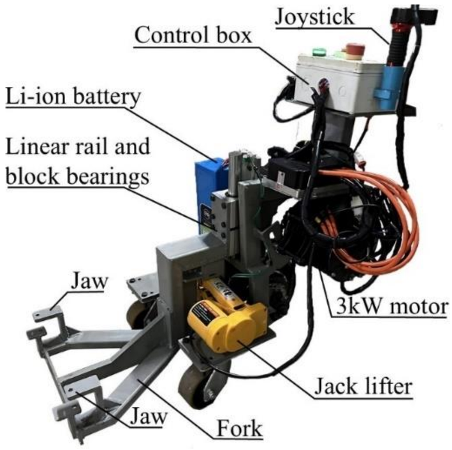


Figure 2 Electric tugger built in this research for patient bed transportation

Figure 3 The e-tugger's main structure for installing other components

Patient transporters frequently use elevators to move between floors. Therefore, the e-tugger must be compact enough to allow for patient bed transportation via elevators. However, the current design does not fully meet this requirement; it only addresses the initial requirements outlined in the introduction. Future development will focus on determining the size limitations of the elevators.

Another crucial aspect of the tugger's design is ensuring a user-friendly experience. Delivery personnel must be able to operate the e-tugger with ease. We conducted a study on bed-wheeling speeds, finding that male transport staff can push a patient bed with a payload ranging from 60 to 100 kg at a speed of approximately 1.2 m/s. When two staff members work together, the bed-wheeling speed increases to 1.4 m/s. Based on these findings, we set the e-tugger's speed limit at 2 m/s. Additionally, the e-tugger should be equipped with basic safety features and be simple to operate. It is also essential to design the e-tugger with sufficient energy storage to ensure it can cover the required distance per charge.

E-Tugger Components

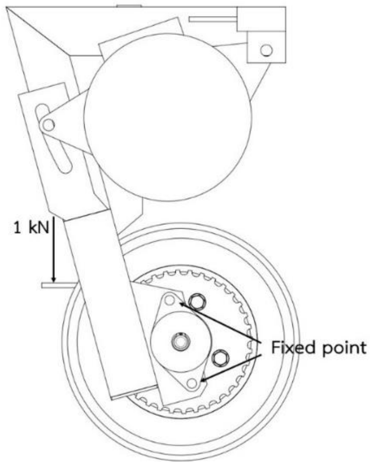
Figure 2 shows the e-tugger designed for this research, which consists of two components: the electric tugger and the forklift. This e-tugger measures 73 cm tall, 85 cm long, 42 cm wide, and weighs 65 kg.

The structure of the tugger is constructed from a rectangular metal pipe measuring 25 mm by 50 mm by 3 mm (Figure 3). One side of the metal frame is attached to a brushless DC motor (BLDCM). A metal chain transmits mechanical power from the BLDCM to the rear wheel. The driven sprocket, connected to the BLDCM’s spindle, has 14 teeth, while the wheel’s pinion has 32 teeth.

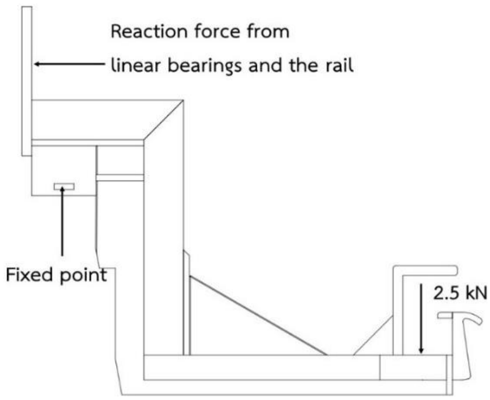
The driven wheel is the rear wheel, which is a pneumatic wheel with a diameter of 251 mm. A 24-mm shaft, measuring 230 mm in length, supports both the wheel and the 32-tooth sprocket. Additionally, we included two 2-hole flange ball bearings with a 15-mm bore to ensure smooth rotation of the rear wheel. Figure 4 illustrates how the driven wheel is attached to the fork of the main structure.

The strength of the tugger's structure and L-shaped forklift was analyzed using computer-aided design software. Figure 5 (a) and (b) illustrate the points where the estimated weight of the patient bed is transferred to the L-shaped fork and the e-tugger structure, respectively. Given that the patient’s bed at its maximum payload weighs 400 kg, the weight transferred to the transverse tube, where the L-shaped fork is connected, is 2.5 kN. Additionally, the weight transferred to the e-tugger frame is approximately 1 kN. Simulation results indicate that the fork deforms by 1.7 mm, with a factor of safety (FoS) of 1.571. Moreover, the e-tugger’s structure exhibits minimal deformation, with a FoS of 2.1 at the load of 1 kN.

Figure 4 A rear pneumatic wheel, installed on the fork of the e-tugger structure



(a)



(b)

Figure 5 The fixed points and the points, at which the designed load exerting on (a) the L-fork and (b) the structure of the tugger

When selecting the motor and battery size, it is necessary to estimate the maximum power required to push a 400-kg patient bed on a 5-% incline. First, we measured the applied forces that initiate the patient bed's movement at different payloads. Then, the required force, F_re [N], for propelling the patient bed on the flat floor was approximated as a quadratic function of the bed's total mass, m_B [kg], as follows:

$$F_{re} = -0.0003m_B^2 + 0.387m_B - 44.91 \quad 1$$

If the bed is on an incline, its weight generates an additional force; the perpendicular component of the weight equals the total weight times a sine function of the incline's angle. Setting the incline's angle at 2.87° and the bed's total mass at 400 kg results in a traction force of 258.3 N, which initiates the upward movement of the patient's bed

The rear wheel's diameter is 251 mm, and the reduction ratio of the transmission chain and sprockets is 2.57. Thus, the electric motor must generate at least 12.62 Nm. The minimum motor speed is around 41 rad/s or 391 rpm, so the e-tugger moves at a speed of 2 m/s. Thus, for the intended application, the output continuous power from the electric motor equals 517.4 W. Given the specifications in Table 1, the BLDCM appears overdesigned for the e-tugger. However, initially, the output torque can reach up to three times the continuous propulsive torque. Thus, the selected motor is a reasonable choice for the electric prime mover in the development of the e-tugger.

$LiFePO_4$ batteries, packed to the size of 72 V and 15 Ah, serve as the primary energy source for the e-tugger in this work. The following equation provides an estimate of the continuous battery current, [A].

$$I_B = DoD \times \frac{C_B}{T} \quad 2$$

Table 1 Technical specification of the brushless DC motor used in this work

Rated power	3 kW
Rated voltage	72 V
Maximum Speed	3,800 rpm
Maximum torque	45-55 Nm
Continuous current	67 A

where DoD is the depth of discharge [-], C_B represents the battery capacity [Ah], and T is the operation time [hrs.]. Also, the battery current, I_B, might be approximated using a power balance between the battery power and the motor's mechanical power: $2\pi\tau N/60 = VI$, where τ is an electric torque from the motor [Nm], N is the motor speed [rpm], and V is the battery nominal voltage. Thus, a simple expression for estimating the operation time of a battery with a certain capacity is as follows:

$$\frac{2\pi\tau N}{60} = \frac{VC_BDoD}{T} \quad 3$$

According to Equation 3, the 72-V and 15-Ah batteries can provide continuous power for 1 hour and 40 minutes, or 100 minutes, as long as the BLDCM operates at 391 rpm, 12.62 Nm, and DoD=80%. Therefore, the selected battery has sufficient power to operate the e-tugger for up to 100 minutes. Consequently, with the chosen battery, the e-tugger can achieve a maximum range of 12 km. Equation 3 indicates that a battery capacity greater than 18 Ah is required to extend the operating period to 120 minutes (2 hours). These calculations will be re-evaluated based on the experimental results obtained at the hospital.

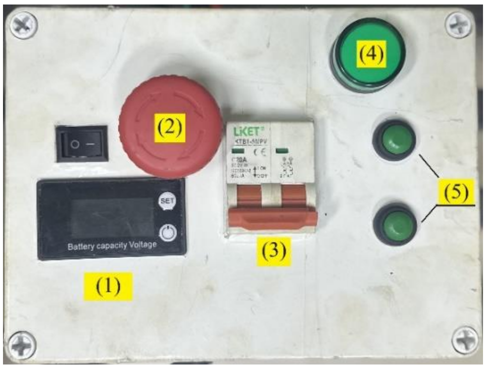
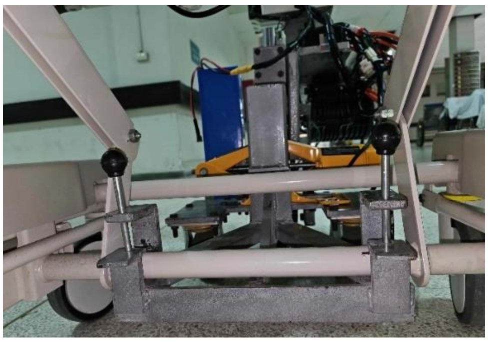


Figure 6 The control panel of the e-tugger's drive includes the following features: (1) a battery state of charge display, (2) an emergency button, (3) the main switch, (4) an LED status lamp, and (5) lifter control buttons.

(a)



(b)

Figure 7 (a) The e-tugger hitched to the patient bed; and (b) two ball lock pins used to safely secure the jaws of the fork to one transverse circular tube of the bed's structure

Figure 2 shows a forklift connected to the e-tugger. The forklift is used to secure the e-tugger to the patient's bed. As shown in Figure 3, attach this machine to the tugger with nuts and bolts. The forklift consists of an L-shaped fork, a 3-ton scissor jack lifter, a metal plate base, and two polyurethane casters. The jack lifter enables the user to connect the L-shaped fork to a bed's frame. Two linear block bearings and a linear rail guide the fork's movement. To hitch the patient bed to the e-tugger, use the two jaws at the end of the fork (Figure 2).

Users can control the e-tugger from the control panel on the circuit containment (Figure 6), which is installed on the back of the e-tugger. Figure 6 shows switches, a lamp, and a battery state of charge display on the control panel on the circuit box. Alternatively, users can operate the e-tugger using a joystick. However, the joystick only allows for regulating the motor and switching the motion directions.

Coupling Instruction

Figure 7 (a) illustrates the combination of the e-tugger and the patient bed. Here are the instructions for securely attaching the e-tugger to the patient bed:

- Raise the tugger's fork until the jaws are at the same height as the bed's frame.
- Push the tugger under the patient's bed until the jaws fit a transverse circular tube in the bed's frame.
- The scissor jack lifter raises the fork. Then, the ball lock pins are inserted at the jaws to secure the bed frame to the jaws, as shown in Figure 7 (b). The tugger is now ready to pull the bed for delivery.

E-tugger Performance Study

The e-tugger performance evaluation consists of two primary studies. The first study focuses on the usability of the e-tugger in a hospital setting. It aims to determine whether the coupling instructions are easy to follow, whether maneuvering the patient’s bed with the e-tugger presents any challenges, and to identify potential improvements to the current e-tugger design.

The second study assesses the e-tugger’s performance on both flat surfaces and a 5% incline. The objectives of this study are to evaluate the e-tugger's energy consumption, measure its average travel speed, and assess its ability to transport patient beds under varying payloads. We conducted tests on the e-tugger’s performance over a 30-meter flat surface and studied its gradeability in a 120-meter passageway, detailed in the following section. Additionally, we evaluated the e-tugger's energy consumption on a flat surface by transporting a bed with a 225-kg payload 10 times along a 236-meter rectangular track in the hospital hallway.

In this study, motor parameters such as voltage, current, and RPM were recorded using the FarDriver motor controller mobile application (Anonymous, 2024). The average travel speed was calculated by dividing the total distance traveled by the total time taken. We calibrated the FarDriver mobile application measurements using a Lutron CM-9940 clamp multimeter for voltage (up to 400 VDC ± 1%) and DC current (up to 400 A ± 1%), as well as a Digicon DT-235T tachometer for motor speeds below 19,999 RPM ± 0.05%.

3. Results and Discussion

At the hospital, researchers studied the e-tugger's performance. The initial study investigated a coupling between the tugger and the bed. The coupling steps described in the previous section took only 10 seconds to secure the e-tugger to the bed. The hospital staff was also able to finish coupling the machine to the bed with ease after a single demonstration. Thus, we can conclude that connecting the bed mover machine to the patient's bed is simple.

The e-tugger was designed to assist patient transport staff without causing any discomfort to the bedridden patient. The e-tugger slightly lifts the bed using its L-shaped fork, keeping all the bed's casters on the floor. This allows the e-tugger's driven wheel to effectively propel the bed while preventing any wobbling that could disturb the patient during transport. Based on our preliminary study, the carting speed ranges between 1.1 and 1.5 m/s. Setting the speed limit at

2 m/s is reasonable, as it allows the staff to maintain a comfortable pace while ensuring the patient does not experience anxiety. Additionally, the e-tugger cannot cause the bed to overturn because it propels the bed from a position lower than the bed’s center of gravity.

The results, reported in the following section, highlight the significance of payload and track grade in affecting the e-tugger's performance and energy consumption. During testing, the jaws shown in Figure 2 securely hold the bed and e-tugger together. The patient bed, propelled by the e-tugger, can cruise, turn, and smoothly climb a 5% incline without detachment. Furthermore, a single member of the transport team can easily detach the jaws from the patient's bed.

Table 2 shows the results from the bed mover’s tests on a flat surface with a total distance of 30 m. These tests aimed to evaluate the performance of the motor under different conditions, specifically in relation to the patient's mass. The motor’s continuous current, speed, and power vary according to the patient’s mass. The motor’s power and current at zero payload are 161 W and 2.24 A, respectively. The motor’s continuous current change in terms of a payload's size is subtle. Additionally, an increase in the payload causes a slight drop in motor speed. These findings indicate that the motor's performance is relatively stable and can handle varying loads without significant disruptions.

Using second-order polynomials, we were able to approximate motor currents and powers from specific cases described in Table 2. For example, for all payloads totaling 240 kg, we estimated approximately 3.87 A and 261 W for current and power, respectively. These approximations provide valuable insights into the motor's performance under heavier loads. We can conclude from this observation that the tugger's electric drive is robust enough to support a patient’s bed at its full payload on a flat floor. These results emphasize that e-tugger is reliable and capable of meeting patient transportation demands.

Table 2 Results from test runs of the e-tugger on a flat surface of a 30-m distance

Payload [kg]	Motor Current [A]	Power [W]	Motor Speed [rpm]	Travel Speed [m/s]
0	2.24	161	393	2.01
70	2.33	168	387	1.98
80	2.39	172	381	1.95
90	2.43	175	373	1.91
100	2.46	177	370	1.89

Table 3 Results from test runs of the e-tugger in the L-shaped passageway at the hospital, where the horizontal and vertical distances are 75 m and 1.9 m, respectively.

Payload [kg]	Motor Current [A]	Power [W]	Motor Speed [rpm]	Travel Speed [m/s]
0	2.54	183	222	1.13
70	3.54	255	294	1.50
80	4.00	288	308	1.57
90	4.19	302	316	1.62
100	4.46	321	333	1.70

We conducted more tests in Songklanagarind Hospital's L-shaped passageway to further evaluate the bed mover's performance. This passageway leads to an operating room. The area behind the passageway's entrance is flat. After the entrance area, there is an alternation between slopes and 3-meter-long landing areas. The slopes at the passageway have a maximum grade of 5%, which is not too steep for carting the patient's bed. The landing areas allow intermittent stops during carting. The passageway has a 75-meter horizontal distance and a 1.9-meter vertical distance. These measurements provide a complete understanding of the terrain that the tugger must cross to transport a patient. Performance testing in this specific environment sought valuable insights into the e-tugger's capabilities and suitability for hospital use. An overall evaluation of how well the tugger meets hospital patient transportation requirements will include this assessment.

When the tugger pushes the bed up on the passageway, Table 3 shows the motor parameters at different payloads. The motor current and power vary directly with respect to the payload. With no payload, the current in Table 2 is the same as that in Table 3. However, the payload's impact on the incline is more noticeable than that on the flat route. The perpendicular component of the total weight causes the electric drive to draw a greater current. When the payload reaches 240 kg, the motor's current and power are approximately 9.81 A and 840 W, respectively, according to the quadratic polynomials of the data in Table 3. This approximation indicates that the tugger's electric drive can transport the bed at full load on a 5-% incline.

The bed speeds in Table 3 differ from those in Table 2. As the patient's mass increases, the bed speed on an incline tends to be higher. The electric drive controller in this tugger is designed to limit the motor speed to 2 m/s. However, the speed controller performs well at high speeds. One solution to this control challenge is to increase the gear ratio of the transmission system by enlarging the pinion on the driven wheel. A larger pinion would cause the motor to operate faster, resulting in improved speed control for the e-tugger. Additionally, increasing the pinion size would reduce the required motor torque and current, enabling the e-tugger to better regulate speed differences due to varying patient masses and inclines, ensuring efficient and safe bed movements.

In the final test, the e-tugger hauled a patient’s bed with a 226 kg payload around a 236-meter rectangular track for ten laps, covering a total distance of 2.36 km. During the test, the battery voltage ranged from 80.1 to 80.7 V, the battery current was around 3.91 A, and the motor speed was 285 rpm. The average speed of the bed was 1.05 m/s. The total energy consumption was approximately 21.6 Wh, representing 2% of the battery's depth of discharge. Therefore, the e-tugger's average energy consumption was about 91.5 Wh per 10 km.

According to the battery selection discussed in the “MATERIALS AND METHODS” section, the e-tugger may require a larger battery pack to extend its usage time to 2 hours. However, the average energy consumption from the last test suggests that the battery size could be reduced. One reason is that the current design of the e-tugger does not include turning assistance, requiring bed transporters to manually propel the bed during cornering. Additionally, the battery calculation was based on the power required to initiate bed movement at maximum payload on a 5% slope. Therefore, further study on e-tugger usage is needed to determine the appropriate battery size.

Table 4 compares equipment created to solve patient transportation challenges in healthcare centers. Table 4 reveals that bed movers do not have a speed limit of 2 m/s. Dhelika *et al.* (2021) introduced an automated bed-moving device that converts existing beds into motorized ones. However, due to the large number of patient beds in large healthcare centers, converting all beds to motorized beds is not practical and can be time-consuming and costly. The motorized bed mover (Guo *et al.*, 2018), the automated bed moving device (Faria *et al.*, 2021), and the e-tugger proposed in this paper require professional operation rather than full automation for safety reasons. The operator needs to apply a slight force to steer the motorized bed mover and the automated bed-moving

Table 4 A general comparison between the inventions for patient transportation presented in this paper and those proposed by other scholars

References	Inventions	Size [cm×cm×cm]	Weight [kg]	Maximum speed and gradability	Payload [kg]
Guo *et al.* (2018)	Motorized bed mover	80×217×118	50	2 m/s and 14%	300
Faria *et al.* (2021)	Automated bed moving device	100 cm wide	40	1.11 m/s and 4%	351
Dhelika *et al.* (2021)	Swerve Drive module	Not reported	Not reported	Not reported	100
In this work	e-tugger	42×85×73	65	2 m/s and 5%	400

device. The e-tugger, nonetheless, lacks a steering assistance unit, so the operator must manually steer the bed. This weak point needs improvement to enhance the e-tugger's mobility. Thus, the redesign of the e-tugger's main structure appears to be necessary to provide enough room for the installation of a swerve mechanism. Also, the e-tugger's appearance is still like an industrial machine compared to the motorized bed mover (Guo *et al.*, 2018) and the automated bed moving device (Faria *et al.*, 2021). On the one hand, we will consider the e-tugger's appearance in our future work to ensure patient trust and comfort during transfers using our equipment. On the other hand, we will optimize the material and design complexity to reduce manufacturing costs, thereby making the e-tugger suitable for commercialization.

Based on all performance studies and literature reviews, several improvements to the current e-tugger design are still necessary. First, the patient's bed equipped with the e-tugger requires more space to turn corners. Second, the electric drive has a fixed maximum speed, which causes the carting speed to decrease as the payload increases. Adding a speed potentiometer would allow for speed adjustments. Additionally, while operating the e-tugger, users should be able to monitor the battery's current, temperature, and speed of the driven wheel. Furthermore, to prevent collisions, the e-tugger should incorporate an electric brake that locks immediately upon pressing the emergency button. Lastly, the e-tugger weighs 65 kg, which is relatively heavy. Reducing the factor of safety (FoS) of the L-shaped fork to 1.5 could help lower the e-tugger's weight. Additionally, utilizing a smaller electric drive could further reduce the equipment's overall weight, as the current motor's dimensions are excessively large

4. Conclusion

This research proposes the design of an electric tugger to assist hospital personnel in patient transport. The e-tugger consists of two main components: the tugger and the forklift. The e-tugger's design integrates an electric tugger with a forklift mechanism. The structure of the tugger provides space for installing various e-tugger components. The electric drive system includes a 3-kW brushless DC motor and a 72V, 15Ah Li-ion battery pack, which together provide the power needed to propel a patient bed weighing up to 400 kg on a 5% incline. Additionally, staff can control the e-tugger's movement using either a control box or a joystick. The forklift has an L-shaped design when viewed from the side and is equipped with an electric scissor lift to raise and lower the fork. The control box allows staff to operate the scissor lift with ease.

Onsite testing shows that a single staff member can efficiently transport a patient in a bed using the e-tugger. The coupling process between the e-tugger and the patient bed takes just 10 seconds. The e-tugger successfully propels a 270-kg patient bed, with the electric motor drawing a maximum current of 2.46 A on flat surfaces and 4.46 A on a 5% incline. After transporting the patient bed for 2.36 km on a flat surface, the battery's state of charge decreases by only

2%, with an average energy consumption of approximately 91.5 Wh per 10 km. As a result, the e-tugger's battery capacity is sufficient to handle all routine patient transport tasks without exceeding its limits.

Future efforts will focus on reducing the weight and size of the tugger to improve its maneuverability in medical settings. Additionally, we plan to incorporate more safety features into the e-tugger to ensure the well-being of both staff and patients. For example, we will integrate an emergency brake and speed potentiometer, allowing delivery staff to operate the device more effectively. We will also include meters to display the battery's charge level, temperature, and wheel speed, enabling staff to monitor the e-tugger's operation easily. These improvements aim to make the e-tugger more user-friendly and safer for use in healthcare environments.

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