Experimental evaluation of a novel robotic hospital bed mover with omni-directional mobility

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ABSTRACT

Bed pushing during patient transfer is one of the most physically demanding and yet common tasks in the hospital setting. Powered bed movers have been increasingly introduced to hospitals to reduce physiological strains on the users. This study introduces and quantifies the manpower efficiency and health benefits of a novel robotic-assisted omni-directional hospital bed transporter (SESTO Bed Mover) in comparison with a conventional manual transport stretcher (Stryker Trauma Stretcher 1037) and a powered transport stretcher (HOSPIMEK HMPT 740), which has a fifth powered wheel providing power assistance only in the forward direction. A total of 14 subjects were recruited (7 porters and 7 students) and were tasked to complete a course within a controlled lab environment. It is concluded that the robotic bed mover is able to halve the required manpower to push hospital beds as compared to conventional bed pushing without any additional physiological strain, potentially improving efficiency by two-fold. Electromyography (EMG) patterns showed that users relied on the shoulder and back muscles in a fashion similar to conventional pushing, further confirming the intuitive drive of the robotic bed mover. Overall, the robotic bed mover shows reduced physical demands, less manpower required for patient transport and reduced back muscle activities, which strongly suggest health benefits for workers in the hospital.

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1. Introduction

1.1. Background

With a growing trend of ageing population and workforce, there is an increasing challenge for the quality and sufficiency of health care services (Ilmarinen, 2006). Bed pushing is one of the most common and essential tasks in patient transfer within the hospital (Ando et al., 2000). Hospitals face many problems such as the lack of manpower and high incidence of work-related injuries, which eventually affect the efficiency of patient transfer in hospitals (Daynard et al., 2001; Hendrich and Lee, 2005; Dutta et al., 2012).

Currently, in Singapore, bed pushing in hospitals requires two persons - one porter pushing behind and a nurse steering in front. Heavy labor and low incentives have caused manpower scarcity in the porter profession. This leads to a very tight work schedule in patient transfers, where delays cascade down daily work schedules, affecting many patients. Ideally, using only one person per patient transfer increases manpower for other activities two-fold, and thus optimizes efficiency.

Work-related musculoskeletal disorders (WMSDs) are prevalent among nurses (Schibye et al., 2001; De Castro, 2004; Weiner et al., 2017). Recent statistics showed that nursing assistants were one of the 7 occupations with the highest occurrences of nonfatal injuries and illnesses in U.S. (Bureau of Labor Statistics, 2013) and was listed as a high-risk occupation for overexertion injuries (Putz-Anderson et al., 1997). Specifically in 2013, WMSDs related cases in both nursing assistants and registered nurses combined had the highest incidence rate out of all occupations at 142 cases per 10,000 full time workers, compared to a national average of 38 per 10,000 in U.S. (Bureau of Labor Statistics, 2013). In the long run, WMSDs grow to be a larger concern as injuries such as lower back pain develops into a chronic disease that affects quality of work life, mental and physical health (Marras and Karwowski, 2006), with subsequent economic costs borne by healthcare organizations (Katz, 2006).

Specifically, moving hospital beds has been listed as one of the
most risky physical tasks that may lead to injuries that require absence from work (Ando et al., 2000; Hill-Rom, 2009; Wiggermann, 2017; Zhou and Wiggermann, 2017). This is because porters are required to move repeatedly in forward-backward, left-right, and rotational directions by pushing and pulling beds with patients, with combined weights between 250 and 400 kg, over an 8-h or 12-h shift with little to no rest, where muscle strain is further elevated in confined areas (e.g. hospital rooms, narrow hallways, etc.) (Jager et al., 2003). Therefore, in addition to overexertion, porters are at risk of Repetitive Strain Injury (RSI) where injuries stem from insufficient recovery time. Statistically, RSI and over-exertion were the two leading causes of injuries for nursing assistants in 2013 (Bureau of Labor Statistics, 2013). Back pain has been identified as one of the highest injury risks healthcare workers are exposed to (Jang et al., 2007). Statistics from the Bureau of Labor Statistics further showed that of all WMSDs reported by registered nurses, back problems alone were responsible for more than 50% of reported cases, while other cases consisted of injuries in the shoulder, neck and arms (Bureau of Labor Statistics, 2013; Jang et al., 2007).

A previous study of muscle activity on static pushing and pulling a pallet jack in two loads (250 and 500 kg) using different pushing approach recorded EMG data on 9 muscles across the body (Bennett et al., 2011). Results showed that the muscles of the shoulders and upper limbs were affected to a greater degree than those of the lower limbs. Average Maximal Voluntary Contraction % (MVC) values were compared against recommended ‘acceptable’ levels to determine if tasks are likely to result in fatigue and injuries: tasks extending over a period of 60 min were deemed to cause fatigue for muscle activity over the most conservative limit of 5% MVC (Jonsson, 1978; Sjøgaard et al., 1986). However, these limits were only applicable to static tasks, and on the other hand varied between different studies (Jonsson, 1978; Sjøgaard et al., 1986; Bennett et al., 2011), largely limiting its usefulness in this study. Furthermore, despite extending these limits to dynamic tasks in Jonsson’s study, its underlying assumptions of a continual task with minimal rest is not met in bed pushing (where porters stop when necessary) and thus no such limits could be applied in this study.

Studies on bed pushing remain limited, while other fields of assistive technology such as automated wheelchairs prioritize the performance of the system (Zhuang et al., 1999; Arthanat et al., 2009; Sharma et al., 2010; Wang et al., 2015). Marras et al. (2009) also investigated the spine loads and low back pain risk associated with patient lift transfer devices. The results indicated that ceiling-mounted patient lift systems imposed spine forces upon the lumbar spine that would be considered safe. The most relevant study has been taken by Davis on a power-drive bed or stretcher for nurses, providing the evidence that the power-drive mechanism could potentially be effective in reducing the risk of low back injuries (Davis et al., 2011; Davis and Orta Anes, 2014; Davis and Kotowski, 2015). Another relevant investigation of physiological strain and muscle activation for the Stamin Lift Bed Mover also concluded with reduced muscle activation levels in the lower back muscles for a majority of the 7 muscles assessed (Daniell et al., 2011, 2014). The major limitation of this study is that the use of a joystick control in the Stamin Lift Bed Mover guarantees a reduction in muscle activation given that only the fingers are needed to move the bed. In addition, while such powered bed movers allow for one man drive, they face some common key design limitations: poor maneuverability and mobility in tight spaces due to the differential drive and less user-friendly and ergonomic interfaces using joystick and buttons.

1.2. Study aims

The Sesto bed mover is a novel robotic powered omnidirectional mobility unit (Fig. 1A). This device is added onto an existing hospital bed or stretcher, transforming a conventional manual bed or stretcher into a power-assisted system which can be easily operated by one person via its intelligent human interaction control (Fig. 2). It is hypothesized that the addition of the bed mover will reduce the amount of muscle activity necessary to maneuver the bed as compared to a traditional or powered bed or stretcher. The aim of the study was to investigate muscle activity of users of the bed mover to assess (i) if a reduction in manpower from a 2p (two persons) drive mode to a 1p (one person) drive mode in the Sesto robotic bed mover has additional physiological strain to a user, and (ii) the potential health benefits of using the robotic bed mover compared to other commercially used hospital stretchers\textsuperscript{1} - namely the 2p Stryker manual transport stretcher\textsuperscript{2} (Fig. 1B) and both 2p and 1p Hospimek powered transport stretcher\textsuperscript{3} respectively (Fig. 1C).

2. Material and methods

All protocols for the experiments were administered in compliance with the ethics approval from the Institutional Review Board (IRB) of National University of Singapore. All experiments were conducted in the Singapore Institute for Neurotechnology (SINAPSE) under a controlled laboratory setting.

2.1. Bed moving methods

Three kinds of hospital patient transport devices (robotic bed mover, manual transport stretcher and powered transport stretcher) were included in the study (Fig. 1). The manual transport stretcher is with wheel-to-wheel measurements at W65 cm × L140 cm and handle height of 98 cm and the user interface where the subject holds on to handle bars (Fig. 1B, see the red circle). When using the stretcher, one person steers in the front of the stretcher while the other pushes the stretcher from behind. The powered transport stretcher is with wheel-to-wheel measurements at W85 cm × L140 cm and handle height of 97 cm and the user interface which the subject controls the system consists of a motorized wheel using the lever with the right hand (Fig. 1C, the red circle). In addition, the heights of the two stretchers can be adjusted according to the subject’s anatomical characteristics for comfortable bed pushing. While during bed pushing process, the height of handle bar of each stretcher is fixed. The robotic bed mover is a new omni-directional mobility unit developed for improving the maneuverability in either an assisted or independent fashion (Fig. 1A). As shown in Fig. 2A, this bed mover prototype consists of an omni-directional mobility platform, a custom designed user-friendly human-machine interface and control system with electronics and batteries. As shown in Fig. 2B, this robotic bed mover is added onto an existing standard hospital bed, transforming the conventional standard bed into a power-assisted bed system. In this design, we adopted the unique Active Split Offset Caster (ASOC) for the omni-directional mobility platform development (Yu et al., 2004). This ASOC module is composed of two independently driven coaxial wheels. The ASOC module can achieve an arbitrary velocity at the joint of the offset link (point c1) by independent control of its two wheels. If the velocities at these two

\textsuperscript{1} Currently used in National University Hospital (Singapore).

\textsuperscript{2} Stryker Trauma Stretcher 1037.

\textsuperscript{3} HOSPIMEK HMPPT 740.
points can be controlled arbitrarily, motions in three Degrees of Freedom (Fig. 2C, velocity $V_x$, $V_y$, and angular velocity $\Omega$) can be achieved, which also means Omni-directional mobility can be achieved. Therefore, with two sets of the ASOC unit, Omni-directional mobility can be achieved. For the mobility control, it uses a Force/Torque (F/T) sensor based control interface with a virtual dynamic model which defines exactly the dynamic behavior of the system to provide an intuitive haptic feel to the user as if he or she is pushing a normal bed with a much lighter weight and better control (Yu et al., 2004). This robotic bed mover was developed with wheel-to-wheel measurements at W80 cm × L217 cm, handle height of 108–118 cm (Fig. 1A) where subjects are free to operate the bed mover anywhere along the handle.

### 2.2. Subjects

For this study, a total of 14 subjects were recruited, consisting of 7 porters 3F/4M (average age, height and weight of 26.6 ± 6.2 years, 167.5 ± 9.5 cm and 69.7 ± 10.9 kg) and 7 students 1F/6M (average age, height and weight of 24.6 ± 3.8 years, 169.6 ± 6.5 cm and 60.5 ± 8.6 kg). The recruited students had no experience on each transport device. The porters who participated in this study were randomly selected. These porters had work experience ranging from 2 months to 4 years and did not have any prior experience in using the robotic bed mover.

### 2.3. Session protocol

An obstacle course was set up with the sequence as described in Table 1 and Fig. 3. The cones and duct tape act as imaginary walls where subjects were instructed not to cross. The width of the walls was decided in a pilot test conducted by having enough space to turn while ensuring a certain level of difficulty. Cones were more densely packed at the turns where the stretchers were more likely to cross the walls. Subjects were constantly reminded to travel at the same speed for all trials and at a speed appropriate for patient transfer. Subjects only reversed out from the parking section (interval 4) after an “OK” signal was given (by a member of the team). Subjects were told to adjust the heights of the manual and powered stretchers to their comfortable height. The handle height of the robotic bed mover was measured at two points, where subjects are free to operate the device at any point along the handle.

Subjects were instructed to complete the obstacle course using the 4 following modes: 2p Manual Stretcher (one person pushing stretcher and the other steering in front), 2p powered transport stretcher, 1p powered transport stretcher, 1p robotic bed mover, with 4 repeats respectively, giving a total of 16 trials totaling 2 h. Caution was taken to only change the direction at the front of the device with minimal to zero pulling force. A few minutes of break time was given between each trial. In the two person tasks, EMG readings were obtained from the person pushing stretcher, the other steering in front did not recorded because he did not pulling the stretcher in each trial. There was no patient weight simulated during the experiments so that the test conditions are the same.

### 2.4. EMG data recording

Four muscles were selected for the EMG data recording: the Anterior Deltoid (AD), Trapezius (TR), Latissimus dorsi (LD), and Erector Spinae (ES). EMG raw data were collected using a BioRadio 150 (Great Lakes Neurotechnologies) with the included algorithm implemented in LabVIEW 13.0 (National Instruments), at a sample frequency of 960 Hz. Muscle palpation for electrode attachment and MVC techniques were performed according to established guidelines (Fig. 4) (De Luca, 1997; Criswell, 2011; Francisco et al., 2010; Konrad, 2005). An electrode on the elbow was placed as a ground. For the TR muscle, static resistance was arranged by manually pushing the shoulder downwards while asking the subject to raise the shoulder upwards. For AD muscle, a static resistance was applied downwards on the arm while the subject was asked to keep 90° abduction at 45° to the anterior in the transverse plane. For LD muscle, the subject was asked to lie face down on a surface and with one arm at the back reaching towards the thighs to produce bending in the upper trunk in the coronal plane. Similarly a static force was applied to counter this motion. For ES muscle, while lying face down, a static force was applied downwards while subjects were instructed to raise their upper trunk upwards. All MVC procedures were repeated at least 3 times for a period of 5–8s, with 10s rest in between. In addition, An Inertia Measurement Unit (IMU) was placed on the front end of the device to detect the angular rate. The angular rate was used for offline syncing with EMG data and also used to identify data point of each interval along
the course. Then EMG data of each interval was separated for further analysis.

2.5. Data processing and statistical analysis

Raw EMG data were collected, and processed using MATLAB (MathWorks). All EMG data were filtered using a band pass filter 2-200 Hz with a band stop filter to remove motion artifact and high frequency noise. Then, root mean-squared rectification was performed with a 50 ms window. A low pass filter with a cut-off frequency of 3 Hz was applied to produce a linear envelope representation of signals. The averaged amplitude of EMG activity was performed for the total trial length as well as for individual intervals. Max values of filtered EMG data from the trial recorded from MVC calibration were extracted for each subject respectively. EMG data were then normalized with MVC. %MVC is represented as the EMG unit across all muscles and all conditions for each trial. Finally, EMG data were combined into 4 intervals: i) straight (section 1, 7), ii) turn right (section 2, 5), iii) turn left (section 3, 6), iv) parking (section 4), due to the large variability of EMG data between subjects and also due to repeated motions within each interval that recruits the same groups of muscle.

A one-way ANOVA with Bonferonni post-hoc analysis at a significant level of $\alpha = 0.05$ was performed to investigate whether there were significant differences between the different bed moving methods in muscle activity. The independent variable would be
the method of bed moving while the dependent variable would be the muscle activity of that particular muscle (TR, AD, LD and ES).

3. Results

3.1. Averaged amplitude of EMG

The required muscle activity was reduced with the robotic bed mover in comparison with the other two stretchers, according to the mean values of EMG data for all 4 muscles in all 4 movements (Fig. 5). More specifically, as compared to the other 2p manual transport stretcher and powered transport stretcher modes, 1p robotic bed mover shows EMG reduction for the TR, LD and ES muscle groups and also 3 out of 4 movements for AD. Therefore despite a drop in manpower, the subject generally still exerts less force in driving the robotic bed mover. Additionally, in comparison to current powered bed pushing technology, the 1p robotic bed mover shows a reduction in muscle activation levels in all movements of TR, LD and ES muscle groups and also 2 out of the 4 intervals in AD as compared to the 1p powered transport stretcher.

Fig. 5 also illustrates the one-way ANOVA with Bonferroni post-hoc analysis computed for average EMG amplitudes for individual movements. Upon specific analysis, the LD muscle showed significantly lower activation levels for 3 out of the 4 movements of the robotic bed mover compared to manual transport stretcher ($p = 0.011$–$0.049$). There were also reduced activation levels in the LD when comparing the 1p robotic bed mover to the 1p powered transport stretcher ($p = 0.013$) during the parking section, as well as in comparison to the 2p powered transport stretcher for left turn ($p = 0.003$). The ES muscle also showed a significant reduction in muscle activity when comparing the robotic bed mover to other 2p methods of pushing. There were significantly lower muscle activation levels for the robotic bed mover in both the left and right turns when compared to manual transport stretcher ($p = 0.036$–$0.039$) and the 2p powered transport stretcher ($p = 0.017$–$0.035$). In contrast, the TR does not show obvious
reduction in muscle activation levels for the robotic bed mover except the right turn between the manual transport stretcher and the robotic bed mover ($p = 0.042$), likewise for the AD, with an exception in the right turn when compared to manual transport stretcher ($p = 0.05$).

Fig. 6 illustrates the one-way ANOVA analysis computed for average EMG amplitudes for all 4 muscles across the entire trial length. Only the LD showed significant differences in 4 bed pushing modes. There were significantly lower muscle activation levels of the robotic bed mover when compared to manual transport stretcher ($p = 0.003$), the 2p powered transport stretcher ($p = 0.025$), and 1p powered transport stretcher ($p = 0.005$). Fig. 6 also shows the averaged EMG amplitudes for the entire trial for all 4 muscles. Muscle activity for the robotic bed mover is the lowest (highlighted in green) while that of manual transport stretcher is the highest (highlighted in red). Averaged EMG amplitudes for the 2p and 1p powered transport stretcher are inconsistent, with higher TR and AD activity in the 1p powered transport stretcher and higher LD and ES activity in the 2p powered transport stretcher.

3.2. Comparison between porters and students

Fig. 7 presents the average EMG amplitudes (%MVC) for all 4 muscles over the whole trial between porters and students. The one-way ANOVA analysis computed for average EMG amplitudes showed no significant differences between porters and students in 4 bed pushing modes. In addition, a two-sample $t$-test also has been computed for each of the differences of the mean EMG amplitudes. All results were equal to “0”, which means no differences of the mean muscle activity between porters and students when using the stretcher or the bed mover.

4. Discussion

4.1. Major findings

The 1p robotic bed mover showed either an equivalent or reduced muscle activity required as compared to all other 2p modes. This is an essential finding as hospitals can use half of the manpower for each bed transfer without the concern of additional physiological strain placed on the porter. This could potentially increase manpower efficiency in bed moving by two-fold, freeing up a large amount of resources and greatly improving hospital operation efficiency.

While the robotic bed mover generally reduces muscle activation levels for all muscles, statistical analysis presents significant differences in only the back (LD and ES), with less pronounced reductions in the shoulder and neck area (TR & AD) (Fig. 6). Parallels are also drawn in the mean muscle activation levels (Fig. 5) where the robotic bed mover has the lowest mean value for all muscles except for the AD with only 2 out of 4 movements being the lowest. This can be mostly attributed to the reliance of the robotic bed

Fig. 5. Averaged EMG amplitudes for all 4 muscles in 4 intervals.
mover on force inputs (and hence arm and shoulder muscle activity) on the handle bar to drive the machine, users are required to simulate motions similar to that of manual pushing. Therefore, the muscle activation patterns prove the intuitive drive of the robotic bed mover.

When analyzing turning and parking motions, the robotic bed mover displays its superiority in the reduction of muscle activity for 3 out of the 4 muscles tested in at least one of the movements. This
can be supported by its ability to transfer input force on the driving handle to a multiplied output velocity in all directions, allowing for ease of maneuver especially in tight spaces and crowded areas. This effect is not as pronounced in the straight sections, given that the powered bed mover provides power in only the forward direction. In fact, the omni-directional drive is likely to widen the reduction in TR and AD muscle activity at higher loads, where the torque required in moving manual stretchers would be nonlinearly increased. This is a significant contribution especially for porters, as it was revealed that moving hospital beds in the Intensive Care Unit (ICU) was the most physically and mentally demanding because of the extreme weight from the numerous equipment and devices attached to the bed.

It is also apparent that the robotic bed mover significantly reduces activation levels in the back muscles as further supported by statistical analysis, which is very beneficial for hospital workers given that the highest occurrence of work related injuries occur in the back. In comparison to other powered bed movers, the StaminaLift (Daniell et al., 2014) had a much more obvious reduction in muscle activity, in 9 out of the 14 muscles tested. This, however, is not a fair comparison to the robotic bed mover given that the StaminaLift system uses a joystick user interface, which only requires the movement of the fingers and thumb, and a lever compared to the robotic bed mover, which is designed to have an intuitive force-based control where it is meant to amplify the input force while simulating manual pushing and thus, activating similar muscle groups to achieve the same motions. In fact, in this same study, the Gzunda Bed Mover, which uses a twist grip variable speed control, shows mean activation levels higher than manual pushing in 3 out of the 14 muscles. This would be a closer comparison to the robotic bed mover given the force input by the user is amplified by the motors, but yet the robotic bed mover stands superior given that none of the muscle activation levels are significantly higher.

In this study, it is noted that the 2p powered transport stretcher surprisingly shows no statistically significant reduction in the muscle activation levels when compared to the manual transport stretcher. This is surprising given that the powered stretcher only requires the user to press slightly on the lever to produce movement. The lack of significant reduction in muscle activity could be due to the subject using his/her body weight to counter the stretcher’s movement when there is a loss of control of the stretcher. Holtermann et al. (2013) also stated that such awkward postures can lead to even higher muscle activation of the health care workers and are highly associated with lower back disorder and pain. Furthermore, the addition of another person in the 2p powered transport stretcher did not result in a consistent decrease in muscle activity (Fig. 6). Therefore, in comparison, the omni-directional mobility unit of the robotic bed mover indicates novelty in the field of powered bed movers, and displays a possible health benefit for healthcare workers.

4.2. Limitations

It is noted that the large standard deviation values of the averaged EMG amplitudes shows certain limitations of this study. This can be attributed to the varying reasons such as a lack of data points, muscle crosstalk from neighboring muscles, muscle activity simultaneously on the contralateral side. Also, subjects were of a fairly young age, and EMG results may not be applicable to older healthcare workers, given the apparent concerns of an ageing workforce. Due to hardware limitations, other muscles in the legs and also in the forearms were not investigated. This can be essential in controlling and maneuvering the bed mover given the higher reliance on the upper torso. Most importantly, while a reduction of muscle activity may result in a lower incidence of lower back injury, it is not a definite claim and cannot be used to predict long-term effects. It should be mentioned that the lack of the weight of a patient in the bed is a limitation. Muscle response patterns and amplitudes are likely to change as more weight is added. In addition, we did not investigate the potential impact of body part kinematics and spinal loads on human subject in this study. Further investigation is needed in a realistic hospital setting given the presence of many external factors. We will put patients in the beds to simulate the real hospital condition and randomize the order of the conditions between subjects in our future studies.

5. Conclusion

This study has met its intended aims by showing that the robotic bed mover can reduce required manpower from the conventional manual transport stretcher. This study shows the robotic bed mover can reduce back muscle activities, revealing potential health benefits it can bring for porters. Moving forward, the robotic bed mover will be tested in a hospital setting to investigate its performance while exposed to various external factors.

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