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Original Article

Biomechanical investigation of optimal bed height for egressing and ingressing hospital beds

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A R T I C L E I N F O

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Ergonomics
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Ground reaction forces
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A B S T R A C T

Aims and objectives: To determine what bed heights are optimal for egress and ingress to the bed, based on quantitative measures and subjective perception.
Background: Many patient falls are related to the patient's interaction with the hospital bed. Beds with lower heights were introduced to reduce the impact of injury due to patient falls. However, low-height beds imposed different kinds of issues during ingress/egress without assistance, such as greater forces and increased inertia required to overcome the center of mass being below the knees.
Design: A cross-sectional controlled laboratory study with 24 healthy adults was conducted to assess the biomechanical parameters at different bed heights.
Methodology: The bed height ranged from 43 cm to 86 cm, in 2.54 cm increments (completed in random order). Two force plates measured ground reaction force and center of pressure. Perception of stability and difficulty were collected from the subject after each trial. Documentation of hand-support of subject was also recorded for each trial. A two-factor Analysis of Variance was conducted to determine the significance between ingress/egress and bed height with post hoc Tukey test to determine source for significance.
Results: Bed Height emerged as a significant factor in determining the ability to ingress/egress from a hospital bed. The results indicated that for medium bed heights (51–66 cm), ingress/egress were less difficult (1–2, on a scale of 10), more stable (approximately 9/10), and had less vertical ground reaction forces (<1000 N).
Conclusion: The ingress/egress was found to be best executed at medium heights (51–66 cm) as participants performed better biomechanically and were more stable than lower or higher heights.
Relevance to clinical practice: The results conclude that hospitals should endorse policies to keep the bed heights between 51 and 66 cm for ingress and egress.
Patient or public contribution: No Patient or Public Contribution.

Introduction

Patient falls during egress from bed in long-term facilities and hospitals remain one of the most prevalent adverse events for a patient (Fragala & Fragala, 2014; Oliver, 2002). It has been found that more than 60% of patient falls are partially related to the patient's interaction with the hospital bed (Fonda et al., 2006; Cáceres Santana et al., 2022). Fall prevalence ranges from 2.3 to 7 falls per 1000 patient days, with 30% of falls leading to injury (Ash et al., 1998; de Souza et al., May, 2019; Halfon et al., Dec., 2001; Lane, 1999; Roberts, 1993; Venema et al., 2019). More than half of the fall cases occur during bed ingress and egress activities, with some of these falls resulting in a serious physical injury (Oliver, 2002; Oliver et al., 2010). Various studies have reported that bed egress and ingress accounts for 12–77% of total falls (Grasso et al., 2001; Hignett & Masud, 2006; Kerzman et al., 2004; Vassallo et al., 2004). Out of 200 fall cases in different hospital wards, 20 falls (about 10%) were recorded while patients were trying to egress the bed (Hitcho et al., 2004). Patient falls increased the risk of mortality, the

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length of hospital stays, and ultimately the hospital care costs (de Souza et al., May, 2019; Heng et al., Sep., 2019; Morris & O'Riordan, Aug., 2017). The length of stay for patients who fall in the hospital gets increased by around 8 days, leading to an extra hospital cost of $6669 as compared to the non-fallers (Morello et al., 2015).

Few studies were found to investigate the impact of height of the hospital bed on the person when egressing the bed (Hitcho et al., 2004). One study investigated the bed heights of occupied hospital beds and concluded that the bed heights were significantly higher for patients who were on fall precaution as compared to those who weren't on fall precaution (Tzeng & Yin, 2008). To combat the serious injuries due to patient falls, beds with lower heights were introduced into the market (a bed deck height as low as 13 cm). This was recommended and promoted as an injury prevention approach by various fall prevention guidelines and reports (Ganz et al., 2013; Alert, 2015; Workgroup, 2003; Tzeng & Chang-Yi, 2006). One study found no impact of low bed height as an intervention to protect patients from falls (Haines et al., 2010). This encouraged the manufacturers in the hospital bed industry to make bed heights lower and lower. However, recommendations for low bed heights have been based mainly on perceptions of nurses that falls happen as patients roll out of bed and not when they are egressing and ingressing the bed (Alderby et al., 2017; Innab, Mar., 2022; Tzeng & Yin, 2013).

The rationale is that the lower the bed, the lower the risk of injuries from falls due to the individual being closer to the ground. However, a decreased impact from a fall would only be true if the patient rolls out of bed and falls. Otherwise, having the knees in a biomechanical disadvantage would likely result in the individual being required to induce a large motion of the upper body and require greater strength to maintain an upright posture (Buckley et al., 2009; Dehail et al., 2007). Moreover, the low height bed may impose a new kind of risk on the individuals with orthopedic problems or muscle strength issues since a higher torque and muscle strength is required to balance the body during egress from a low height bed.

When the center of mass shifts rapidly during egress, the person needs sufficient balance that includes postural stability. Rising from a hospital bed for standing demands greater torque at the knee joints and the hip joints. It also requires an adequate joint range of motion (Buckley et al., 2009). The loss of strength in the quadriceps muscles also imposes a high risk of fall for elderly patients trying to rise from a seated position (Dehail et al., 2007). Thus, there is a need to determine the egress pattern at different bed heights to determine the critical height that increases the risk of a fall.

The ingress in hospital bed usually gets easier for average bed heights as compared to higher bed heights. When the bed height gets above the pelvis, a person needs to lift themselves up to get into the bed or may slide themselves up in the bed when they are weakened. A patient might require additional force to be generated by pushing off the mattress with the hands, or by jumping off the ground to reach the level of hospital bed surface. The lowered bed height imposes high torque requirements at the hip joint for ingressing the bed. Also, the Morse Fall Scale score (a measure of fall risk) is significantly affected by the knee torques of the patients ingressing bed with lower bed heights (Merryweather et al., 2015). The biomechanical stresses during ingress are expected to increase as the bed height is decreased to a considerably lower position. The lower bed height causes reduced hip angles, which in turn forces the patients to position their torso over their knees (Merryweather et al., 2015). Low bed height (when compared to medium and high bed heights) was found to significantly increase postural stability demands required to maintain balance for healthy and individuals with Parkinson's disease (Xu et al., 2021). Balance of a patient can be highly affected in such a posture since the increased knee and hip torque shifts the center of mass more posteriorly, which ultimately increases the risk of fall (Pavol et al., 2002).

The impact of hospital bed height on biomechanics during bed egress and ingress is still largely unexplored, especially on a more continuous basis. Previous works have investigated bed height with few heights. The study objective was to determine what bed heights are optimal for egress and ingress to the bed, based on quantitative measures (e.g., ground reaction forces and center of pressure) and qualitative measures (e.g., perceived stability and difficulty) . The study aimed to identify potentially dangerous bed heights where the bed is likely to be too low or too high for certain height patients, resulting in higher risk of falls. The biomechanical outcomes provide indication into risk of falls: (1) ground reaction forces—higher forces indicate more momentum of body into the ground (up-down force), producing more torque on body joints and horizontally (anterior-posterior and medial-lateral) that require a step, in order not to fall, and (2) center of pressure, which provides measures stability where larger values approach the limits of the base of support, increasing need to step or fall. It was hypothesized that the medium heights of the hospital bed will minimize these biomechanical outcomes.

Methodology

Study overview

In order to determine the ability of an individual to ingress and egress from the hospital bed on different heights, an IRB approved cross-sectional controlled laboratory study (#2022–0016) with 24 healthy adults was conducted to assess the ground reaction forces and perceived stability and difficultly during a series of ingress and egress trials on a medical-surgical hospital bed with a foam mattress.

Subjects

Twenty-four (12 male/12 female) healthy adults were recruited for this research. For biomechanical studies with repeated measures, this represents a large sample with adequate power ($\beta = 0.80$). To ensure a range of individuals were tested, subjects were recruited into three categories of height (short/average/tall), two categories of weight (normal/overweight) for both the genders (male/female). Thus, for each gender, there were six height-weight categories: (1) short-normal weight, (2) short-overweight, (3) average height-normal weight, (4) average height-overweight (5) tall-normal weight, and (6) tall-overweight. The categories of height were defined as short—heights less than 171 cm (for males), and less than 157 cm (for females), average— heights between 171 cm and 180 cm (for males), and between 157 cm and 166 cm (for females), and tall—heights more than 180 cm (for males), and more than 166 cm (for females). The categories on body mass index (BMI) were defined as normal—BMI less than 25 kg/cm^2 and overweight—BMI between 25 kg/cm^2 and 30 kg/cm^2. Anthropometric and demographic data collected included age (years), weight (kg), height (cm), shoulder height (cm), elbow height (cm), hip height (cm), knee height (cm), foot length (cm), and body mass index (BMI, kg/m^2). The summary of anthropometric data of subjects has been provided in Table 1.

Table 1
Summary of the Anthropometric Data of the Subjects.

Anthropometry of subjects	Males (12) (Mean ± SD)	Females (12) (Mean ± SD)
Age (years)	23.1 ± 2.8	23.50 ± 7.3
Weight (kg)	78.1 ± 13.9	70.46 ± 13.2
Height (cm)	174.4 ± 8.6	163.13 ± 8.1
Shoulder Height (cm)	143.8 ± 8.9	136.53 ± 7.0
Elbow Height (cm)	112.4 ± 7.1	104.78 ± 6.6
Hip Height (cm)	99.5 ± 6.1	95.46 ± 7.6
Knee Height (cm)	48.5 ± 3.5	45.83 ± 2.5
Foot Length (cm)	26.9 ± 1.1	24.13 ± 1.2
BMI (kg/m^2)	25.7 ± 4.1	26.44 ± 4.1

The inclusion criterion for the subjects were: (1.) age between 18 and 75 years, (2.) no current musculoskeletal pain or injury, (3.) no prior musculoskeletal surgery, (4.) not pregnant (if female), and (5.) no balance issues. A self-report questionnaire was utilized to assess health status. All the participants completed the informed consent process that included reading and signing of the approved consent form.

Apparatus

The laboratory set-up included a hospital bed with adjustable height, two force plates positioned in the floor beside the bed, and a motion capture system.

Hospital bed

A Hill-Rom P3207D-01 VersaCare™ hospital bed was used for this study. The height of the hospital bed was adjustable within the range of 43 cm (17 inches) to 86 cm (34 inches) from the ground. The height of the bed was to the top of the uncompressed mattress with the mattress having a height of 10 cm (4 inches). A pointer was attached to the surface of the bed and a measuring scale was placed on the ground beside the pointer in such a manner that the pointer depicted the height of the surface of bed from the ground (Fig. 1a). The bed deck and mattress were kept flat for all the trials of this study. The only variable parameter of the bed was the height of bed surface from the ground.

Force plates

Two force plates (OR-6–7-1000, Advanced Mechanical Technology, Inc. (AMTI), Watertown, MA) having surface area of 51 cm x 46.5 cm each, were installed in the floor right beside the bed to measure the three-dimensional ground reaction forces and the position of the center of pressure (COP). AMTI Force Plates were linked to the Cortex Motion Analysis system.

Motion capture system

The Motion Capture System included 6 Eagle cameras (Motion Analysis Corporation, Santa Rosa, California). These cameras used the reflective markers on selected body landmarks, which included the forehead, right and left shoulders, elbows, hips, knees, ankles, and toes. This 6-Eagle camera scheme was connected to the Cortex software (8.1.0.2017) to collect and synchronize the kinematic and kinetic data of the subjects during each of the ingress and egress trials. The whole-body kinematic data were collected for subsequent analysis not included in this analysis.

Perception assessment

After each ingress and egress trial, the subjects were asked the following two questions based on their perception of stability and difficulty during the trials:

a) "How stable did you feel while getting in/out of the bed?"
The subjects provided an answer on a scale of 0–10, 0 being completely unstable and 10 being completely stable.
b) "How difficult was it to get in/out of the bed?"
The subjects provided an answer on a scale of 0–10, 0 being not difficult at all and 10 being extremely difficult.

Procedures

Once the subject completed the consent process, he/she changed into tight fitting clothes if they were not wearing them, usually shorts (or leggings for females) along with a tight t-shirt with no socks/shoes on the feet to minimize movement of motion capture markers, which had to be placed on top of clothing or skin. Thirteen reflective markers were placed on the body landmarks for specific body parts with double sided adhesive tape. Markers were placed on the forehead, on each shoulder, elbow, hip, knee, ankle, and toe using standardized placement procedures (Fig. 1b and c). To minimize fall risk during the ingress/egress trials, a spotter was situated next to the bed to assist if necessary (no occurrence happened during the study). Subjects were asked to stand beside the bed facing away from the bed. For all subjects and heights, the participants egressed/ingressed from the same side of the bed. They were instructed to always have one foot on each of the force plates every

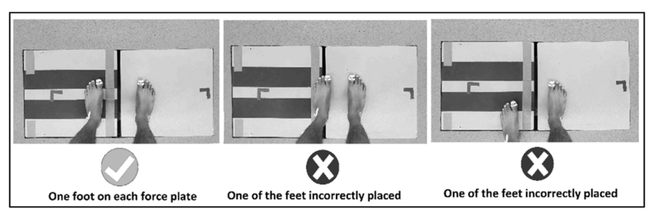

Fig. 2. Pictorial representation of the correct placement of feet on the force plates.

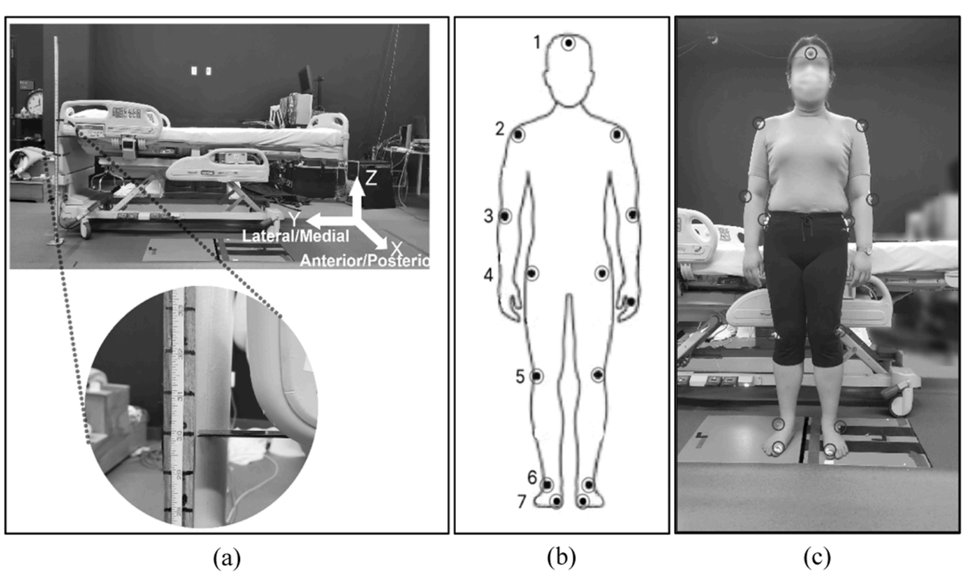

Fig. 1. Study set-up and marker placement: (a) Hill-Rom P3207D-01 VersaCare™ hospital bed; (b) Body landmarks for reflective markers; (c) Subject with reflective markers.

time they performed the ingress and egress manoeuvre (Fig. 2).

The trials started with an ingress task, during which subjects stood stationary facing away from the bed with one foot on each of the force plates. The subjects were then asked to naturally ingress the bed while still facing away from the bed. The ingress data collection stopped once the subject was in a completely flat supine position on the bed. Then, the egress task was conducted where the subjects were asked to naturally egress the bed so that they were facing away from the bed with one foot on each of the force plates. As soon as they were in a completely upright standing position the egress trial ended, and data collection was stopped. At each height, a set of ingress and egress conditions were repeated twice. The bed heights were completed in randomized order at 1-inch (approximately 2.5 cm) intervals, ranging from 17 inches (43 cm) to 34 inches (86 cm). Thus, there were a total of 72 trials per subject (2 egress/ingress X 18 heights X 2 repeats), and the data collection for each subject took around two hours. The sequence of the heights was uniquely randomized (by a research team member) for each subject, using excel random number generator. The randomization was done on bed height while blocking on egress/ingress (e.g., ingress was first followed by egress). For Enhancing the QUAlity and Transparency Of health Research, CONSORT checklist was chosen for this study. After each ingress and egress task, subjects provided a rating about how stable and difficult the trial seemed to them. The markers were removed upon completion of the data collection. A gift card ($30) was provided to the subjects for their time and effort.

Data analysis

For each trial, the biomechanical parameters including the ground reaction forces (in x, y, and z directions) and the position of center of pressure (COP) (in x and y directions) were extracted from the motion capture system. The x-direction was the direction of the anterior/posterior (AP) of the subject, while the y-direction was the direction of medial/lateral (ML) of the subject, and the z-direction denoted the upward/downward (UP/DN) direction. The maximum values of the instantaneous ground reaction forces (in x, y, and z direction) and the center of pressure were determined for each trial. The maximum distance for center of pressure (in cm) was used to find the imbalance towards anterior/posterior (AP) and medial/lateral (ML) for each trial.

Statistical analysis

Statistical analysis of the collected data was performed using the Statistical Analysis System (SAS Institute, Cary NC). Statistical analysis included a comparison of means in the form of two factor Analysis of Variance (ANOVA) with post-hoc Tukey tests used to determine the significance of bed height with other variables.

Results

A summary of the analysis of variance (ANOVA) outcomes has been provided in Table 2, indicating the level of significance for the main effects and interactions.

As compared to the female subjects, males generated a higher ground reaction force in all three directions. The ground reaction forces in the AP and ML directions were higher for ingress trials than the egress trials (136.9 N vs 93.4 N for AP ground reaction forces; and 65.7 N vs. 58.8 N for ML ground reaction forces). The maximum AP center of pressure was greater for males as compared to females (334.8 mm vs. 306.9 mm), whereas the maximum ML COP was greater for females than males (358.6 mm vs. 347.3 mm). Egress trials had greater maximum AP COP as compared to the ingress trials (325.1 mm vs. 316.8 mm), whereas the maximum ML COP for ingress trials was greater than for egress trials (355.1 mm vs. 350.8 mm).

The ground reaction forces for each of the bed heights are shown in Fig. 3. In general, the UP/DN ground reaction forces increased with the bed height up to 61 cm, at which the values remained the same until 81 cm, at which the maximum UP/DN ground reaction forces increased again. An increasing trend was also found for AP ground reaction forces with a step trend where increases were seen between 43 and 56 cm, 58–66 cm, 69–79 cm, and above 81 cm. The ML ground reaction forces increased linearly with the bed height.

The maximum AP and ML COP for all bed heights are in Fig. 4. The maximum AP COP was considerably lower when the hospital bed was at the height of 61 cm above from the ground (Fig. 4a). There were small reductions in ML COP in heights below 76 cm (Fig. 4b)

Two-way interactions between the nature of the trial (egress/ingress) and bed height on the ground reaction forces are shown in Fig. 5. The UP/DN and ML ground reaction forces during the egress task were lower for medium heights (51–66 cm from the ground) as compared to other heights of the hospital bed. Nonetheless, for ingress, the ground reaction forces linearly increased with the height of hospital bed.

The effect of gender on the perception of stability and difficulty indicated that the female subjects perceived the ingress and egress trials to be more stable (8.8 vs. 7.7, on a scale of 10) and less difficult (1.5 vs. 2.9, on a scale of 10) as compared to the male subjects. For perception of difficulty, subjects perceived the ingress task to be more difficult than the egress task (2.5 vs. 2.0, on a scale of 10). The effect of hospital bed height on perception of stability and difficulty can be seen in Fig. 6. It can be seen from the figures that the subjects perceived the trials in the 51–66 cm heights to be considerably more stable and less difficult than those trials in higher or lower ranges.

The two-way interaction of ingress/egress and bed height with perceived difficulty can be seen in Fig. 7. The lowest level of perceived difficulty for both ingress and egress were observed at the medium heights from the ground.

Discussion

There are few studies that have determined the impact of the height of the bed on the biomechanics during ingress and egress. Tzeng and associates (Tzeng & Yin, 2008) investigated the heights of hospital bed in acute care facilities and concluded that the bed heights were significantly higher for patients on fall precaution. However, this approach may not be beneficial if the patients wanted to ingress or egress the hospital bed without assistance. Based on the results of our study, it can

Table 2
Summary of Analysis of Variance Tests (p-values).

	F(z)	F(AP)	F(ML)	Max COP(AP)	Max COP(ML)	Stability	Difficulty
GENDER	**0.02**	**0.03**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
HEIGHT	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
EGRESS/INGRESS	0.71	**<0.0001**	**<0.0001**	**<0.0001**	**0.01**	0.46	**<0.0001**
GENDER*HEIGHT	0.74	0.63	0.33	0.40	0.25	0.97	0.61
EGRESS/INGRESS*HEIGHT	**<0.0001**	**0.002**	**<0.0001**	0.76	0.24	0.98	**<0.0001**
GENDER*EGRESS/INGRESS	**<0.0001**	0.44	**<0.0001**	0.87	**<0.0001**	0.58	**0.01**

F(UP/DN): Ground Reaction Force (in z- direction); F(AP): Ground Reaction Force (in x- direction); F(ML): Ground Reaction Force (in y- direction); Max COP(AP): Maximum Center of Pressure (in x- direction); *Max COP(ML): Maximum Center of Pressure (in y- direction); Stability: Perception of Stability; Difficulty: Perception of Difficulty* ***Bold Values*** *indicated significant at p-value < 0.05.*

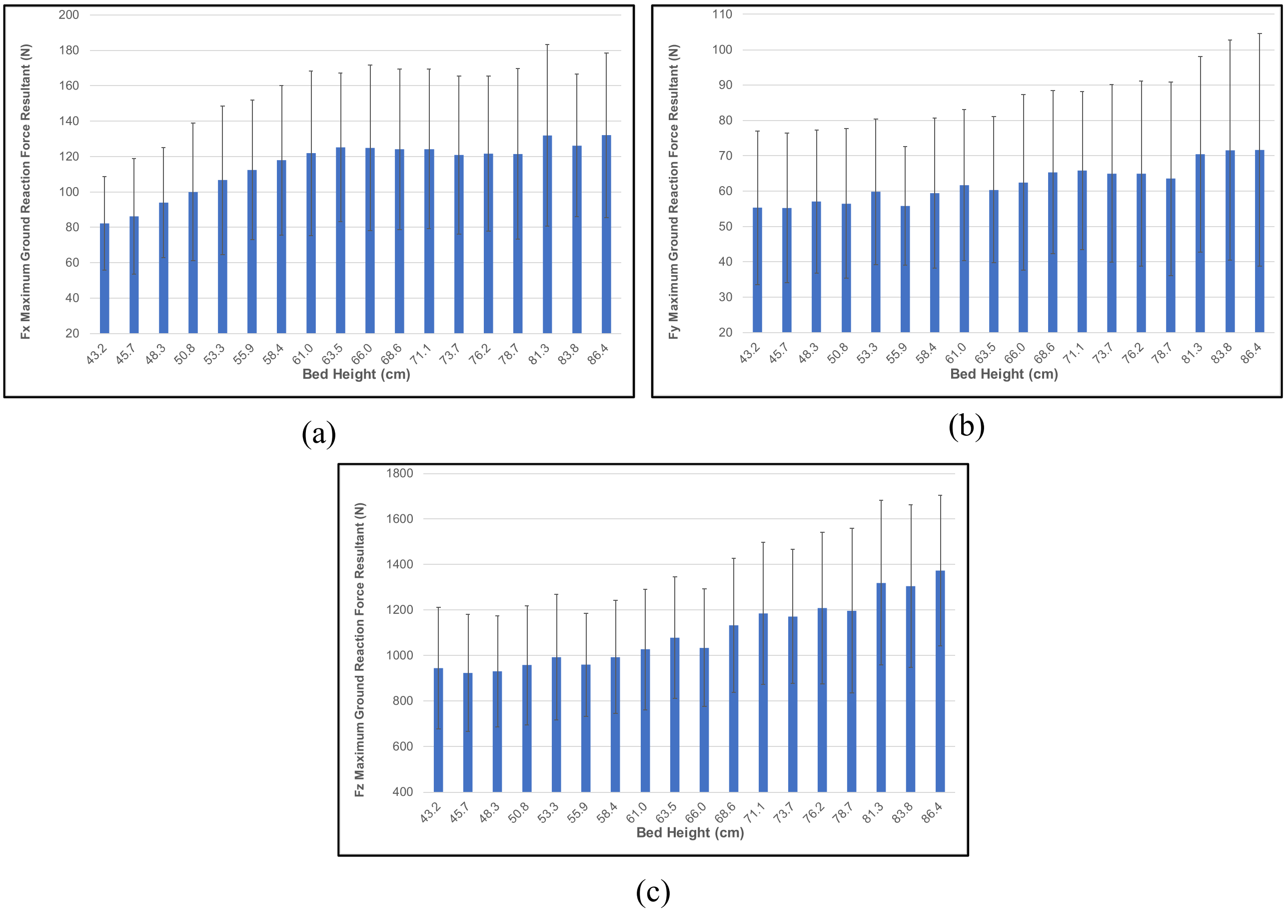

Fig. 3. Maximum ground reaction forces as a function of bed height for Fx (anterior/posterior), b) Fy (medial/lateral), c) Fz (upward/downward) for the average of ingress and egress.

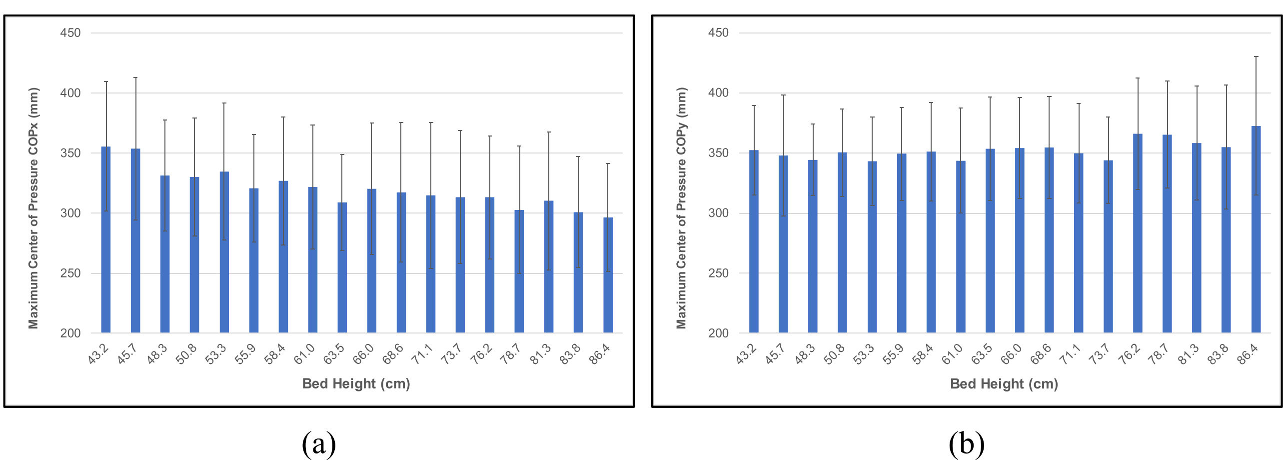

Fig. 4. Maximum Center of Pressure as a function of bed height for anterior/posterior (x) and medial/lateral (y) directions for the average of ingress and egress.

be said that the ingress and egress from higher bed heights can be considerably difficult and unstable for the subjects.

The current study investigated the three-dimensional ground reaction forces as individuals egressed and ingressed the bed at different heights. Results indicated medium bed heights (51–66 cm from the ground) produced the lowest ground reaction forces. This implied that the subjects required the minimal amount of force to perform the ingress-egress trials sufficient not to fall and were minimized at heights that were not too high or low. These findings question the approaches suggested by numerous fall prevention guidelines and reports (Ganz et al., 2013; Alert, 2015; Workgroup, 2003; Tzeng & Chang-Yi, 2006; Haines et al., 2010) focused on lowering the bed heights as an injury prevention measure. This laboratory study focused on finding the biomechanically optimal heights for a hospital bed when an individual attempt to ingress/egress the bed with no assistance. It must be noted that the lowest height might prove out to be safer if they roll out of bed (Tzeng & Chang-Yi, 2006; Alderby et al., 2017; Innab, Mar., 2022), but it will significantly put an individual at risk if they try to naturally ingress/egress the bed without assistance. The results of this study focused on examining the bed heights based on the actual biomechanics

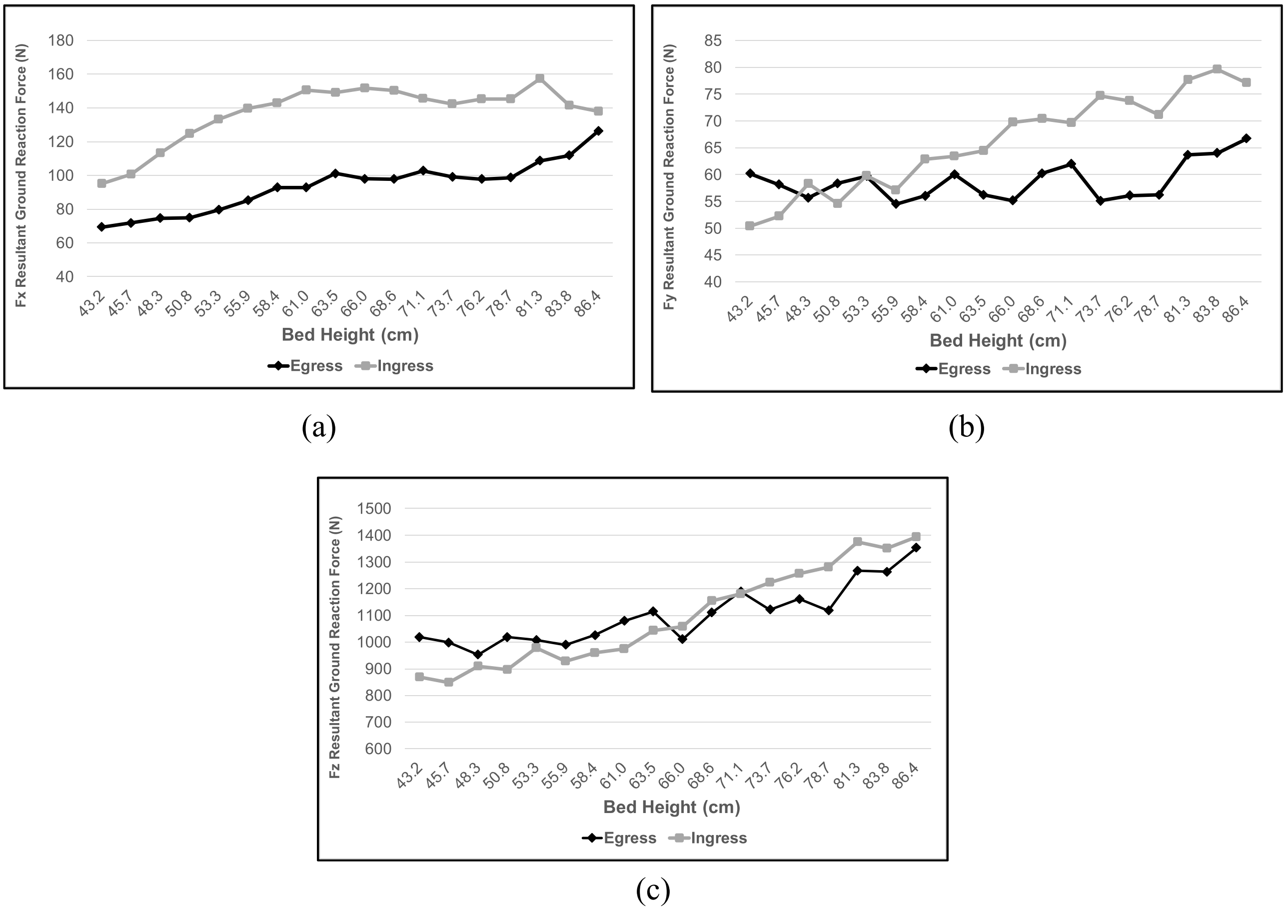

Fig. 5. Ground Reaction Force as a Function of Bed Height and Egress/Ingress for (a) Fx (anterior/posterior), (b) Fy (medial/lateral), (c) Fz (upward/downward) for the average of ingress and egress.

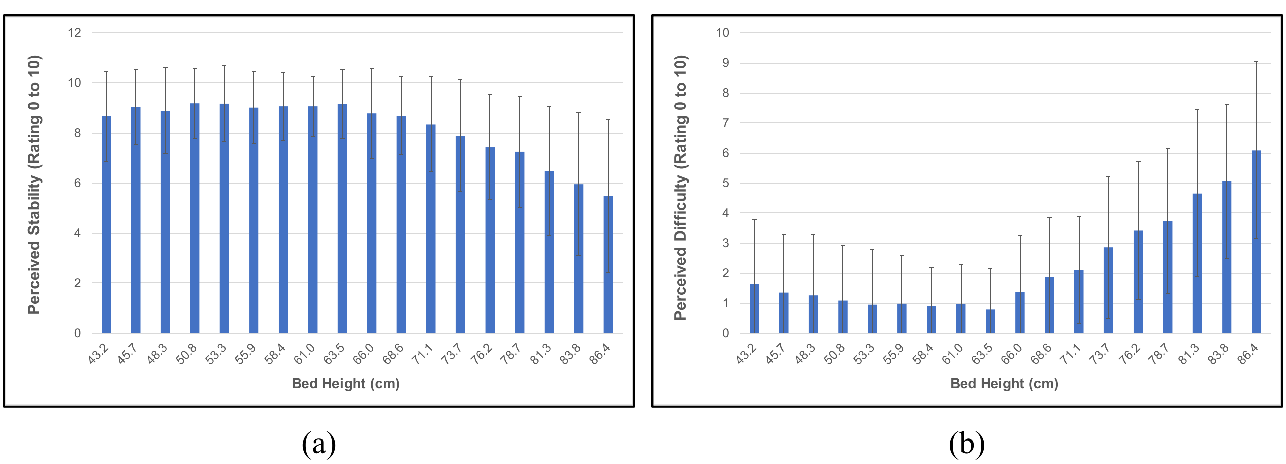

Fig. 6. Perceived Stability (a) and Difficulty (b) as a Function of Bed Height.

as well as the perception of the subjects, instead of determining the optimal bed height based on the perceptions of caregiver.

The results of this study clearly depicted that the lower heights of hospital bed involved greater ground reaction forces, more difficulty, and less stability for ingress and egress tasks. This might be because the lower bed heights force the knees to be in a biomechanically disadvantageous position, which in turn result in the individual being required to stimulate a considerably higher motion of the upper body. The maximum AP and ML COP were found to be considerably lower when the hospital bed was at the height between 51 cm and 66 cm from the ground. The maximum AP and ML COP were a measure of imbalance for subjects during their ingress and egress trials from hospital bed. The results indicated that the subjects were least likely to lose their balance during ingress and egress at medium bed heights.

The results of perceived stability and difficulty further strengthened the ergonomic optimization of the medium bed heights as this range was perceived to be more stable and less difficult than the lower or higher heights. The results supported the conclusion of the Buckley et al. study (Buckley et al., 2009) that rising from a lower height of bed demand greater torque at the knee joint and the hip joint and requires an

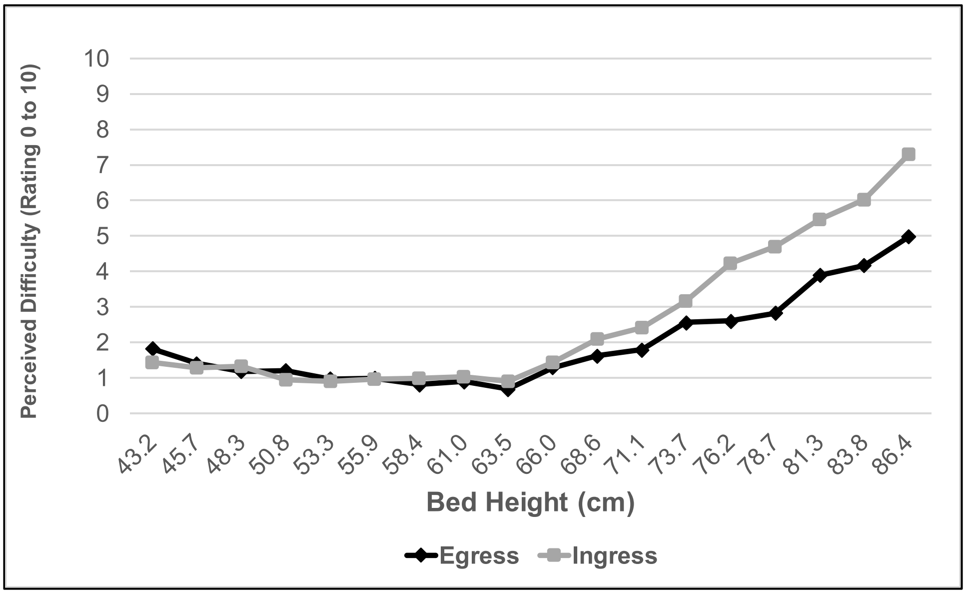

Fig. 7. Perceived Difficulty as a Function of Bed Height and Egress/Ingress.

adequate joint range of motion. Sufficient balance along with postural stability will be required when the center of mass of the subject would shift rapidly for egress from a low height bed.

A study (Dehail et al., 2007) suggested that the ability to egress the bed is impacted for elderly people because of the loss of strength in the quadriceps muscles. This strength decrease will further increase the risk of falls for elderly patients trying to egress from a lower bed height. Also, younger individuals with muscle strength issues or orthopedic problems may also have issues egressing the bed at lower heights. From these lower bed heights, individuals will have reduced hip angles that require them to position their torso over their knees to maintain stability and upright posture (Merryweather et al., 2015). The results of the current study also support changes in body mechanics that result in changes at the foundation of the body (e.g. ground reaction forces and COP) (Pavol et al., 2002).

Gender, as a singular predictor, also was found to impact ground reaction forces, perceived stability, perceived difficulty, and maximum COPs. This difference of the ground reaction forces, and perceptions of stability and difficulty may partially result from differences in body weight (males (78.1 kg) were considerably higher than females (70.5 kg)). The gender differences UP/DN ground reaction forces were likely directly related to body weight differences. However, the females displayed a lower tendency to topple towards the anterior (forward) as compared to males, which likely is not completely related to body weight differences. Therefore, gender differences do exist when egressing and ingressing the hospital bed, which should be further explored to determine the actual underlying biomechanical differences.

The effect of the nature of the trial (ingress or egress) impacted the ground reaction forces, perceived difficulty, and maximum center of pressures. The ingress trials had higher ground reaction forces (in AP and UP/DN directions) and were perceived as more difficult by the subjects as compared to the egress trials, indicating a biomechanically more challenging transition for ingress. Ingressing had greater medial-lateral (ML) COP than egressing, indicating a tendency towards more imbalance to the side. For ingressing, it is likely that the knees and hips must provide a greater amount of torque to maintain the balance of the body. Future work is needed to investigate the actual body movement and joint torques during ingress and egress of beds.

Overall, the results indicate the medium heights of bed require less forces on the ground, especially for egress. As a result, egressing from lower bed heights is ergonomically more challenging likely due to higher knee and hip torques as well as greater motion in the upper body. These results were further supported by the perception at different bed heights (perceived difficulty and stability). It is clearly depicted that the perceived difficulty was least when the height of hospital bed was around 63 cm from the ground (both ingress and egress). It was also demonstrated that it was more difficult to ingress the bed as compared to egressing the bed.

Limitations

There are a few potential limitations of the study that need to be considered when interpreting the results. The subjects in this study were all healthy individuals and young which represented the optimal situation. Future work will need to investigate the impact of compromised individuals (e.g. patients, joint conditions, joint replacements, etc.) on the ability to ingress and egress. Individuals who have had an amputation may be specifically of interest as no research has been conducted for egressing/ingressing with a missing limb. Individuals in hospitals or long-term care facilities would likely be compromised by their health status, thus the lower and higher bed heights might be more detrimental. The health status of the patient might have significant ramifications of the "true" optimal position, but it is still not likely to be in the lower or upper heights. One of the other limitations was that the patients were not lying in the bed for long periods and then trying to get out of the bed, which might have significant impact on the biomechanics and the physiological response. Also, this study did not investigate the real impact of patient height (future analysis will look at height of patient and whether that is true indicator). Moreover, the type of surface of the bed and environmental factors may also impact the ability to egress and ingress. Finally, requiring the participants to land with one foot on each force plate during egressing could have influenced the results. However, the force plates were wide enough that the restriction likely had minimal impact. This study has provided a foundation for understanding the biomechanical effects of hospital bed height, and the subsequent studies can address these limitations and contribute more for knowing what height is best to ingress and egress from a hospital bed.

Conclusion

Bed height played a vital role in determining the ability of ingress and egress from a hospital bed. The medium height of hospital bed (around 51–66 cm from the ground) was found to be the best height for most of the outcome variables for both ingressing and egressing the hospital bed. The low height hospital beds pose a considerable biomechanical challenge to perform the egress trial. Nonetheless for ingress, the lower bed heights did not impose a higher ground reaction force but were certainly perceived as more difficult to complete than the medium heights of the hospital bed. The higher bed height imposed a higher ground reaction force for ingress and egress, as well as was perceived as more difficult and least stable by the participants. The medium heights (51–66 cm) of hospital bed turned out as biomechanically viable for ingressing and egressing the bed without assistance. Future work will need to investigate the underlying biomechanics, body postures, joint torques, and relative heights to body heights to truly understand the impact of bed height on the ability to egress and ingress the bed. Other clinical conditions such as position on the bed (e.g. side sitting), clinical treatments (e.g. physical tehrapy), and patient status (e.g. impaired) will also need to be investigated.

Declaration of Competing Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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