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Effects of bed height on the biomechanics of hospital bed entry and egress

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Abstract.
BACKGROUND: Although a significant proportion of patient falls in hospitals occur in the vicinity of the hospital bed, little is known about the contribution of bed height to fall risk.
OBJECTIVE: To compare lower extremity joint torques and angles during hospital bed entry and egress at two bed heights.
METHODS: Twelve adults (age >55) were purposively selected and had variety of strength and mobility limitations. Biomechanical data for this pilot study were collected with three digital video cameras and processed to obtain estimates for joint torques and included angles.
RESULTS: At the low bed height, hip torque for bed entry was significantly higher, and hip, knee, and ankle flexion angles were significantly smaller. The absence of significant differences in knee and ankle torques were the result of a compensation strategy that shifts the center of mass forward by flexing the torso during low bed ingress. Torque data from the egress motion were similar, however 50% of participants were unable to rise from the low bed without assistance.
CONCLUSIONS: Healthcare providers should be aware that low bed heights pose safety risks to the population for which they were designed–elderly persons at high risk for falling.

Keywords: Patient safety, equipment safety, accidental falls, caregiver, healthcare provider

1. Introduction

In the hospital setting, a variety of studies report that patient falls at the bedside account for 12.1–77.6% of all falls [1–6]. Approximately one third of falls lead to patient harm with 4–6% of those resulting in serious injury [7, 8]. Patients who suffer injurious falls have an increased length of hospital stay and a greater rate of discharge to long term care facilities, which increases health care costs [9, 10]. Healthcare providers, including nurses, aides, and physical therapists are responsible for assessing fall risk and modifying the environment in an effort to reduce the frequency of falling [11].

In response to concerns about injury and death caused by rolling out of the bed or crawling over bed side rails, the low bed (with a bed deck height as low as 13 cm) was developed for geriatric care settings. The use of the 'low bed' has been recommended as an injury prevention strategy in several patient safety reports and clinical guideline papers for fall prevention [11–14]. However, there are serious safety concerns for individuals with muscle strength deficiencies and balance disorders (i.e.,

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individuals at risk for an anticipated physiological fall) as they attempt to get in and out of these low beds. To date no research has evaluated the ergonomics and biomechanical consequences of this recommendation. Joint collapse from muscle strength failure during bed entry (getting into bed using a stand-to-sit motion) and egress (getting out of bed using a sit-to-stand motion) and/or loss of balance as patients move away from their bed without assistance, place individuals at high risk for a bedside fall.

With an increasingly aging population there is a need to better understand fall risk associated with reductions in muscle strength. These reductions are estimated at 20–40% for people between the ages of 70 and 80 [15]. A systematic review of 12 studies calculated that muscle weakness and/or gait and balance disorders were, on average, the cause of 17% of falls in older adults (range 4–39%) [16]. In an earlier systematic review by the same author, 16 studies reported that lower extremity muscle weakness increased the odds of falling by a range of 1.5 to 10.3 (average odds ratio of 4.4) and gait problems increased the odds of falling by a range of 1.3 to 5.6 (average odds ratio of 2.9) [17]. Other studies have found that older adults with a history of falling have significantly weaker strength in the lower extremity [18, 19], gait instability [20], and balance problems [21] than those who have never fallen.

Rising from a seated position to standing (in this case rising to a standing position from a hospital bed) requires large external torques at the hip and knee and sufficient joint range of motion. This motion also requires significant postural stability and balance during the transition when the center of mass is rapidly shifting. It has been shown that limb collapse because of insufficient strength is the dominant factor influencing a failed sit-to-stand motion [22]. Knee extension moments are the largest of the required joint moments during the rise from a chair [23], therefore significant weakness in the quadriceps muscle group is often a cause of difficulty for elderly patients while rising from a seated position. Consequently, significant biomechanical stresses are expected during bed entry and egress, especially when the bed is in a low position.

The aim of this pilot study was to explore the relationships between lower extremity biomechanics and hospital bed height related to fall risk. The research question examined the differences in lower limb required torques and posture at the hip, knee, and ankle during hospital bed ingress and egress at the two bed heights (low bed vs. standard bed height).

This exploratory pilot study used a one-group design to evaluate the lower extremity biomechanics during hospital bed entry and egress among older adults. Each participant completed the testing procedures for the two randomly ordered bed heights. (1) low bed (38 cm measured from the floor to the top of the mattress) and a standard hospital bed in its lowest position (58 cm measured from the floor to the top of the mattress). During the testing procedures the bed side rails were in the lowered position and were not employed during ingress or egress movements.

2. Methods

2.1. Sample

Twelve adults over age 55 recruited from the inpatient setting of a hospital, a nursing home and a long term care residence were purposively selected to provide a range of stature and gait. The main inclusion criterion was that the individual require the maximum assistance of one person to ambulate, however during the study sessions, two-person assists were occasionally used due to participant fatigue, difficulty entering and exiting the low bed, and in the researcher's judgment, as a precautionary measure to prevent a fall.

The sample included ten males and two females with an average age of 76.9 ± 11.3 years (range 56 to 90), height of 166.9 ± 10.8 cm, and weight of 72.6 ± 9.5 kg. The sample included three older adults with no observable gait impairment, three with a weak or impaired gait, four with Parkinson Disease, one with stroke resulting in hemiplegia, and one surgical patient with an abdominal wound. The range of Morse Fall Scale scores was 0 to 75 with an average of 43.3 ± 24.6.

2.2. Ethics and institutional review board approvals

Ethics approvals were obtained from the University of Alberta and the local health authority, and administrative permissions were obtained from health care facility supervisors and the participants' primary physician. Consents obtained from all participants included the use of videotaping and the release of photographs for research and educational purposes. Institutional Review Board approval was also obtained at the University of Utah for the use of the videos in this biomechanical analysis. A vinyl floor mat was used for participants that were considered fall prone; however, use of this safety mat was discontinued part way through the study because its beveled edge created a safety hazard [24].

2.3. Data collection instruments

The Morse Fall Scale, used to assess fall risk, applies a score based on a person's history of falling (yes/no), presence of a secondary diagnosis (yes/no), use of an ambulatory aid (no assistance, bed rest or nurse assistance; crutches, cane or walker; holds onto furniture), presence of an intravenous catheter (yes/no), gait (normal, bed rest, wheelchair; weak; impaired), and mental status (knows own limits; overestimates or forgets limits) (see Morse [8] for scoring rubric). Previous falls research has established Morse Fall Scale sensitivity of 78%, specificity of 83%, positive predictive value of 10.3%, and negative predictive value of 99.2% [25, 26]. Morse Fall Scale scores range from 0 to 125; scores > 45 indicate that a patient is at an increased risk for falling.

Four consumer grade 60 Hz digital cameras were used for capturing body movements; two lateral, one central, and the fourth at floor level to determine how the foot struck the floor. The cameras were synchronized by flashing a laser pointer at a target prior to each data collection session.

2.4. Data collection procedures

Each participant was asked to complete one trial for each of the randomly ordered bed heights; each trial involved an approach to the bed from a chair positioned 10 feet from the bed, bed entry (stand-to-sit motion), specific in-bed movements, and finishing with bed exiting (sit-to-stand) and return to the chair. One additional trial at the standard bed height with side rails in the raised position was part of the protocol, but not included in this analysis since there was no comparable condition at the low bed height. Participants were, for the most part, elderly patients with mobility challenges who were unable to complete more than one trial per bed height.

2.5. Data capture and processing

The sample was originally recruited for a qualitative, observational study of mobility related to bed height and design. This biomechanical study was conducted as a secondary analysis. Three images, one from each tracking camera, were used to identify the posture of each subject and identify postural angles. Biomechanical data were analyzed only at the point during bed entry at the instant prior to making contact with the bed while sitting or the instant following the last contact with the bed while standing. Static postures from the video frame images were analyzed using the University of Michigan's 3D Static Strength Prediction Program (3DSSPP™, Ann Arbor, Michigan), a widely used biomechanical modeling tool, which has the capability of providing the percent strength capability and joint torque at each joint required to perform a particular task. The 3DSSPP uses anthropometric norms and Newtonian mechanics based on body segments weights and external forces applied to the hand to compute moments and forces at each major body joint. The use of muscle strength norms are then used to compute strength moment capabilities for a specific anthropometry and posture [27, 28]. The joint centers and segment inertial properties were a function of gender, weight and height as defined by the population parameters in the 3DSSPP. The markers in this model were not used for 3D rigid body tracking of segments, rather as reference points between joints to identify postural angles. The direction and magnitude of the joint torques for right and left lower limbs was estimated from the model since no external forces were collected during this study. The link segment model used in the 3DSSPP provides detailed force, torque, balance, and population strength capability values as a function of posture. Conservative support forces from assistants, walking aids or handrails were estimated, as no direct force measurements were recorded in the study. Since the static strength capabilities produced from 3DSSPP represent strength capabilities of healthy adults in the work force, not older, frail adults, they were not included in this analysis.

The assignment of positive or negative values to the joint torque and included angles was an indication of the limb being observed and associated joint coordinate system, therefore an absolute value for each was used in the analyses in order to compare magnitudes. Required torques at each joint on the left and right sides were not significantly different from each other (paired t values ranging from 1.23 to 2.20, df = 11, p values ranging from 0.05 to 0.22), and were subsequently averaged. Included angles for each joint on the left and right sides were not significantly different from each other (paired t values ranging from 0.36 to 1.4, df = 11, p values ranging from 0.18 to 0.73), therefore the angles were also averaged.

Since the patients self-selected the technique used in entering and exiting the bed, a large range of values for

Table 1
Comparison of required joint torques during bed entry ($N = 12$) and egress ($N = 6$)

	Mean Torque (N·m)					
	38 cm bed height	58 cm bed height	95% CI of the difference (N·m)	Paired t	df	p
Bed Entry						
Ankle	42.8 ± 28.1	45.3 ± 24.9	−18.8–13.9	−0.33	11	0.75
Knee	59.4 ± 6.2	60.3 ± 7.1	−14.1–12.3	−0.15	11	0.89
Hip	58.3 ± 14.7	43.8 ± 13.2	3.1–26.0	2.79	11	0.017
Bed Egress						
Ankle	23.6 ± 12.7	21.2 ± 12.5	−7.7–12.6	0.62	5	0.56
Knee	45.9 ± 19.7	41.5 ± 7.7	−16.7–25.6	0.54	5	0.61
Hip	48.2 ± 19.0	27.5 ± 8.1	2.5–38.8	2.93	5	0.03

joint angle and torque were produced. It was determined that the large range of values was largely a result of twisting that occurred as the patient transitioned from standing to sitting. For example, if a patient twisted to the right he/she had a lower knee joint torque on the left knee than the right knee. If the subject twisted to the left the values would reverse, creating a higher knee joint torque on the left side while the right side would be lower. This change was related to the degree of twisting that was observed; the more a subject twisted, the greater the difference between limbs.

2.6. *Statistical analysis*

The goal of the statistical analysis was to examine differences in lower limb required torques and included angles at the hip, knee and ankle during hospital bed ingress and egress at the two bed heights. Bed entry and egress were analyzed separately, as were the torques and angles at each joint. Univariate statistical analyses were conducted using IBM SPSS Statistics Version 20 for the Macintosh. Alpha was set at 0.05 for all analyses; an adjustment to alpha for multiple comparisons was not made due to the exploratory nature of this study and small sample size. Biomechanical measures were compared at the two bed heights using paired *t*-tests for each joint location. A series of non-parametric, bivariate correlations between 1) the average torque and angle at each joint and 2) participant age, height, and Morse Fall Scale score were conducted.

3. Results

3.1. *Bed entry: Stand-to-sit motion*

For bed entry (i.e., stand-to-sit), as bed height decreases the required torques at the hip joint increases (Table 1). There was no statistical difference in required ankle or knee torques between the low and standard bed heights. Included angles at the hip and knee were significantly smaller at the low bed height when compared to the standard bed height (Table 1).

There was a strong, significant correlation between Morse Fall Scale score (a measure of fall risk) and the average torque at the knee when participants were entering the low bed (Spearman rho = 0.69, $p = 0.012$). Other than this one finding, there were no significant correlations between joint torques among the two bed conditions and age, height, and Morse Fall Scale score.

Six of the 12 participants were unable to complete the bed egress movement (i.e., sit-to-stand) from the low bed without significant assistance from one or two assistants. Four of these participants were also unable to rise from the standard bed height without assistance. Therefore, biomechanical data characterizing required torques and included angles could not be calculated for these participants because it was difficult to estimate the forces applied by the assistants and views of participants were occluded in the camera images.

For the remaining six participants, required torque at the hip during egress was significantly greater at the low bed height than it was at the standard height, suggesting that as bed height decreases the torques at the hip increase during egress (Table 2). This difference was not present at the ankle or knee. The angle at the hip was significantly smaller at the low bed height when compared to the standard bed height; this difference was not present at the ankle and knee (Table 2).

For egress, there was a strong correlation between Morse Fall Scale score and the average torque at the hip when participants were rising from both bed heights (Spearman rho = 0.79, $p = 0.059$). Other than this one finding, there were no significant correlations between joint torques for the two bed conditions and age, height, and Morse Fall Scale score.

Table 2
Comparison of included joint angles during bed entry ($N = 12$) and egress ($N = 6$)

	Mean Angle (degrees)					
	38 cm bed height	58 cm bed height	95% CI of the difference (degrees)	Paired t	df	*p*
Bed Entry						
Ankle	73.6 ± 3.0	81.6 ± 1.6	−16.3–0.20	−2.15	11	0.055
Knee	95.3 ± 2.9	113.1 ± 10.7	−25.3–−10.3	−5.20	11	<0.001
Hip	70.2 ± 3.7	88.9 ± 14.7	−30.8–−6.6	−3.39	11	0.006
Bed Egress						
Ankle	79.2 ± 10.1	71.8 ± 10.1	−3.3–18.0	1.77	5	0.14
Knee	112.8 ± 17.2	122.2 ± 15.4	−25.6–6.9	−1.48	5	0.20
Hip	74.3 ± 18.5	116.5 ± 25.3	−69.9–−14.3	−3.90	5	0.01

4. Conclusion

Getting in and out of the bed is a challenging and risky endeavor for elderly patients, especially those with impaired gaits and muscle weakness. Despite strong evidence that falls and fall-related injuries at the bedside continue to be a serious concern, the biomechanics of bed-related activities as a factor contributing to fall risk and other forms of injury have not been well characterized. This leaves an important aspect of falls related to adjustable height hospital beds unexplored.

In this study two main biomechanical differences were observed at the low bed height during entry and egress. First, the low bed height induced smaller hip angles and it was observed that patients position the torso more over the knees and ankles during both ingress and egress. This posture could lead to additional balance concerns, especially as the person attempts to rise from the bed. Second, patients appeared to find an optimal torque for ankle and knee, then compensated their balance with additional torque at the hip. The videos showed that this compensation was accomplished by moving the center of mass of the body away from the hip joint center, closer to the joint center of the knee and ankle (i.e., greater trunk flexion). An additional finding was that patients at higher risk for falls generated higher torques in the hip joint during bed entry and egress, and in the knee during bed entry at the low bed height.

These findings can be used to help nurses and other caregivers understand that bed height may influence the strength required to get in or out of a hospital bed and anticipate balance issues. However, if the magnitude of the required torques are at or near a patient's capability, the ability to recover stability in the event of a slip or loss of balance would be reduced [29, 30]. A suboptimal bed height may contribute to a bedside fall because the strength requirements of the task and/or the strength required to recover from a slip or loss of balance exceed the normal strength capability level of hospital bed users.

The primary limitation of this study was that the biomechanical measures were estimated using static postural modeling, rather than measuring with three-dimensional motion analysis and actual forces. Lack of empirical force data also limited the ability to detect differences resulting from the presence and absence of bed side rails. Other studies investigating strength and balance requirements performing sit-to-stand motions and the presence/absence of hand rails during sit-to-stand motions have indicated that significantly different muscle recruitment and strength requirements exist between conditions when hand rails are used [31]. A second limitation was the small sample size and the decision not to adjust alpha for multiple comparisons. The results of this study should therefore be considered with some caution, given the increased risk of type-1 error.

Understanding that biomechanical compensation occurs with changes in bed height helps clinicians and caregivers identify those who might have difficulty accomplishing these movements safely. For example, because of pain or decreased mobility, individuals with back or abdominal injuries may be less likely to increase torques at the hip when sitting especially into a lower bed. They may compensate by increasing torques at the knee which could cause the center of mass to shift more posteriorly leading to increased risk of falls, which is similar to what was demonstrated by Pavol [32]. Older adults, especially the frail elderly and those over 80 years of age, may not be able to compensate adequately for the increase torque if improper sit-to-stand technique is used, resulting in an increased fall risk.

Recommended fall prevention strategies and interventions when using adjustable height hospital beds include both administrative and engineering controls. Administrative measures should include setting the bed at a height that increases included joint angles, although the optimal height for entry and egress has yet to be determined. Currently there are motorized beds that can adjust height from the low bed to a standard bed height, however the patient would need the awareness and cognitive ability in order to operate the bed under the aforementioned conditions. Additionally, nurses and other caregivers may need more training to provide additional assistance or supervision to patients who suffer back or abdominal pain, or recent surgeries that might affect the ability to generate hip torque. Engineering interventions may include the design of a sit support bar for stability during entry and egress.

The results of this study also raise serious concerns about the use of the low bed for older adults, especially those who have muscle strength deficits and balance disturbances that place them in a high fall risk category. Although the low bed may reduce the risk of injury should a patient roll out of bed, there is a high probability that 1) they may not be able to get out bed unassisted, for example, if they have to use the bathroom in the middle of the night, and 2) if they are able to rise they are at risk for loss of balance or limb collapse leading to a fall while completing the rise or while attempting to get back into bed. In most instances, nurses or nurse administrators make the decision to place a hospitalized or nursing home patient in a low bed. They should be aware that low bed heights pose safety risks to the population for which they were designed–elderly persons at high risk for falling.

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Conflict of interest

None of the authors has a financial conflict of interest.

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