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Analysis of the influence of hospital bed height on kinematic parameters associated with patient falls during egress

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Abstract

Despite the fact that falls comprise a large percentage of hospital injuries, little is known quantitatively about what induces patient falls. Our study quantified kinematic and temporal parameters at key events of the sit-to-walk movement during hospital bed egress.Sixty five older adults (67.6 +/-14.1 years) with a history of falls (Morse Fall Scale score 53.3 +/- 21.4) comprised the study population. Full-body biomechanics during unconstrained sit-to-walk movements were captured as participants exited an adjustable, instrumented hospital bed at three bed heights classified as high, medium, and low.Trunk momentum during peak vertical velocity (i.e. rising) was significantly smaller during high bed exits than the other two bed heights. Change in center of mass velocity between seat-off and first toe-off was significantly faster during medium bed exits vs low bed exits. Temporal variables in low bed conditions revealed delays in rising and gait initiation.These temporal delays indicate lack of confidence and prioritization of postural stability. Since sit-to-walk momentum values were not significantly different between bed heights, this suggests individuals are using similar strategies to generate motion but executing the motion differently in each condition. Therefore lower bed heights may be inappropriate for fall-prone individuals due to increased postural demands. If an optimal setting for hospital bed height exists, our data indicate it may lie in the range of knee height or slightly higher.

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*Keywords:*Hospital bed; Falls; Sit-to-walk; Sit-to-stand; Older adults;Kinematics

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1. Introduction

As the human population continues to grow and modern medicine produces longer life spans, the numbers of those at risk for injurious falls due to age and disease increases. While falls can occur at any age, those over 65 have greater rates and more severe consequences, including death, which is considered the sixth leading cause of mortality in this group [1-3]. Additionally, injuries sustained from falls in this age group predispose individuals to declines in motor abilities required for day-to-day life, including loss of function in independent living activities and further disease and co-morbidities [4, 5].Little is known about patient falls in hospitals [6, 7].Further underlining the need for this specialized attention is the fact that falls comprise the largest single category of reported incidents in hospitals [8].Most falls occurred in the patient’s room (50-85%) on or near the bed while unassisted (79%), citing lost balance as the most common reason (12%) [5, 9-11].While it is unlikely that all falls can be avoided, it is both possible and necessary to continue efforts at finding simple methods to reduce falls in the most vulnerable populations across a wide variety of in-patient settings.Since many falls occur proximal to the hospital bed, our study sought to examine the influence of various bed heights during the sit-to-walkmovement in a fall-prone population using quantitative methods.

Sit-to-walk (STW) is an everyday motor task and is fundamental for independence. It requires a complicated overlap of postural stability and locomotor sequences initiating a cascade of events which demand mobility. In other words, it is a dynamic movement requiring an individual to transition from sitting to standing to walking while moving the center of mass (CoM) up and over a reduced base of support (BoS). Thus, sit-to-walk can be considered a more complex motor task than sit-to-stand (STS) with greater demands on stability. It has also been far less studied [12-14].Magnan’s and Kerr’s initial works were performed on healthy young populations and concluded that by merging standing and gait initiation at the point of seat-off, an individual is able to take advantage of the inertial properties of both discrete tasks to springboard directly into gait (it is important to remember here that the original definition of gait initiation is movement beginning from quiet standing, not sitting). Research by Kerr [14, 15] and Buckley et al. [12] examined STW within elderly populations and found that many individuals do not perform the STW task as a fluid, continuous motion but rather as disjointed separations of the STS and gait initiation components. They also found that elderly at risk of falling have a greater degree of separation in these tasks than healthy elderly and a wider distribution of timing in each phase, all significantly slower.

We hypothesized that some kinematic threshold exists which should provide ideal degrees of both stability and mobility and that seat/bed height plays a significant role.While the literature still remains largely unexplored in the areas of rising failures and their relationship to fall risk, more empirical investigation has been devoted to examining components of stability during STW.A few variableswhich appear as significant within fallers:

- Drop in *linear CoM velocity* in the anterior direction between seat-off and swing-off events of up to 50%. This is in comparison with a 15-35% drop in healthy populations of all ages [13, 15-17].
- A *long time delay* in the duration of the overall task, in particular during the extension phase, which coincides with seat-off and gait initiation, indicating reduced fluidity and mobility [13, 15, 18-20].
- A large *reduction in CoM linear momentum* in the anterior direction during all STW phases[12, 19-22, 40].
- *Increased mediolateralCoM velocity* as gait becomes established. [16, 17, 23].

This paper investigates the effects of hospital bed height on fall parameters in those with a variety of risk factors. Morse Fall Scale (MFS) score was used as a stratifying fall index for participants; it has been demonstrated to provide good clinical sensitivity and specificity [24]. Three bed heights were analysed in relation to subjects’ tibial plateau heights: “low”, “medium”, and “high”. It was hypothesized that the medium bed height would provide the ideal middle ground between creating improved mobility for fall-prone individuals during STW while also allowing them to use optimal techniques forbalance. To this end, analysis of anterior-posterior and medial-lateral CoM velocity and momentum changes between seat-off and toe-off events was deemed important to reveal perturbations in stability between the two axes. It was also hypothesized that the overall task duration as well as the durations occurring between key events of the STW task would be reduced in the bed height which createdan ideal bridge between stability and mobility.

2. Methods

2.1. Participants

Sixty five older adults with strength, gait, and mobility impairments were recruited for this study. Participants in this study were a subset of a larger study examining multiple effects of hospital bed height on mobility and stability parameters of fall-prone populations. Mean (±SD) age of 69.2±11.0 years, height of 172±10 cm, body mass of 87.3±20.2 kg, and body mass index of 29.6±6.4 kg/m^2. Women made up 31% of the population.All participants had moderate to high fall risk due to a variety of conditions including but not limited to: Parkinson Disease (PD), rheumatoid and osteoarthritis, degenerative joint disease, and neurologic deficits secondary to mechanical injury or biological disease.Inclusion criteria were: 1) Morse Fall Scale score ≥ 45; 2) weak or impaired gait or impaired mobility during sit-to-stand and stand-to-sit; and 3) able to transition between sitting and standing at the bedside, turn 180°, and walk several steps without assistance. Exclusion criteria were: 1) Limb amputation; 2) anthropometric and/or medical conditions which could preclude the use of the fall arrest system; 3) unilateral strength deficits > 50%; 4) cognitive impairments which would preclude giving informed consent or following simple instructions to perform bed entry and egress.

2.2. Experimental protocol

The study was carried out at the Nurses Education Laboratory at the George E. Wahlens Salt Lake City Veterans Administration Hospital. The space contained an instrumented, adjustable-height hospital bed and two force plates (Bertec BP4060, Columbus, OH) installed on the floor directly beneath the bed side in order to collect bilateral lower extremity ground reaction forces (sample rate 500 Hz). Kinematic data were captured using 18 optoelectric cameras (NaturalPoint, Corvallis, OR) mounted to a custom-built metal frame surrounding the bed and chair (16’ x 15’ x 8.5’). Approximately 80retroreflective markers on key anatomical landmarks and limb segments defined the segment model for 3D biomechanical data (sample rate 100 Hz).

Our independent variables consisted of three bed heights determined as a percentage of lower leg length (LLL): 1) 95% of LLL was considered a low bed (LB); 2) 110% of LLL was considered a medium bed (MB); 3) 125% of LLL was considered a high bed (HB). Each participant completed a single unconstrained STW motion trial from each bed height. Bed height order was randomized as part of the larger study data set, which was comprised of 27 total motion trials.A 15-segment, whole-body custom model was created in Visual3D (C-Motion Inc., Germantown, MD) from the 3D capture and the individual subject anthropometric data. Center of mass velocity, trunk momentum, and temporal characteristics were analysedat key events during the STW motion which required participants to sit on the edge of the bed with one foot on each force plate, rise in an unconstrained manner, and walk toward a chair opposite the bed.The variables chosen for analysis were created using temporal, kinematic, and kinetic data collected and synchronized between the 3D motion capture and the ground reaction forces after filtering each via a Butterworth low-pass at 6 and 15 Hz, respectively.

2.3. Variables and analysis

STW events considered important were based on phases defined and validated by Kerr et al. [15, 21] which include: 1) flexion momentum, 2) extension, 3) unloading, and 4) stance (Fig. 1). The flexion momentum phase describes the momentum generation required for STW via angular trunk and lower extremity flexion and angular acceleration. The extension phase describes the seat-off and rising action via trunk and lower extremity extension. The unloading phase describes the initiation of gait via heel-off by the swing foot and can vary in timing. The stance phase describes the transition between first and second steps. Second step toe-off completes the STW task. Events considered important for analysis were kinematic occurrences whichmarkthe phase divisions. Events were based on those described by Buckley et al. [12] and accounted for STW motor sequencing differences occurring in older, impaired persons. They include movement initiation (first detected anterior trunk displacement), begin-to-stand (first detected caudal trunk displacement), seat-off (approximated as peak anterior-posterior ground reaction force), peak

CoM vertical velocity, heel-off (first heel to rise and initiate gait), swing-off (first toe-off), and stance-off (second toe-off). All events were marked and error checked for analysis in a total of 689 unique trials.

Repeated measures analysis of variance (RM ANOVA) was used to determine the effects of each bed height on STW movements. Cut-off for significance was maintained at $p < 0.05$ ($\alpha = 0.05$). When the assumption of sphericity was violated, the Greenhouse-Geisser correction was used when $\varepsilon < 0.75$; otherwise the Huynh-Feldt correction was used. Post-hoc pairwise comparisons were conducted using the Sidak correction factor to reduce type I error but maintain power since comparisons were fewer than six. Observed power and effect size using partial eta squared were calculated. Effect size was considered small when $\eta^2_P = 0.01$, medium when $\eta^2_P = 0.09$, and large when $\eta^2_P = 0.25$ according to Cohen's d guidelines. When considered relevant, RM ANOVA was performed on sub-sets of the data.

3. Results

3.1. Temporal variables

Bed height was found to significantly influence the timing of several variables including total task time (p=0.016), the extension phase duration (p=0.001), the ratio of the extension phase normalized to total task time, aka time ratio (p=0.006), the heel-off time, the swing-off time, and the stance-off time (all p=0.006). Total task time was considered the duration between movement initiation to stance-off. Extension phase duration was considered the time between peak anterior-posterior ground reaction force(peak A/P GRF) and heel-off. Time ratio was the ratio of extension phase duration to total task time. Time to heel-off and toe-off was considered the duration between movement initiation to each respective event.

3.2. Velocity variables

Bed height was found to significantly influence the change in velocity between peak A/P GRF (i.e. seat-off in most participants) and swing-off (p=0.011). P-values were between 0.05 and 0.10 for instantaneous velocity at the swing-off event (p=0.067). The change in velocity was considered the difference in instantaneous velocities at each event.

3.3. Momentum variables

Anterior-posterior momentum occurring at peak A/P GRF was found to be significant between bed heights (p=0.047) although post-hoc pairwise comparisons did not support this result. Anterior-posterior momentum at peakCoM vertical velocity (peak VVEL) was also significantly different between bed heights (p=0.000).

Medial-lateral (M/L) stance-off momentum was found to be statistically significant between bed heights (p=0.042) but post-hoc comparisons did not bear this out.

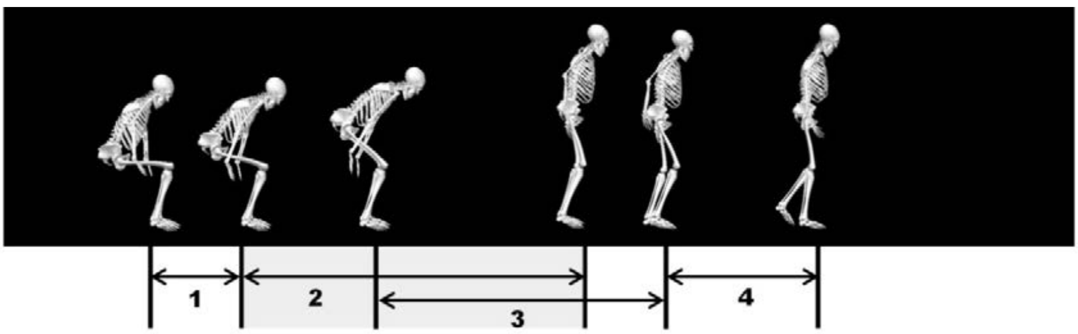

Fig.1.Phases of sit-to-walk in one fall-prone individual: The gray area between phases 2 and 3 indicates the temporal timing range possible for gait initiation.

4. Discussion

No known study to date has examined STW kinematics and temporal characteristics as they relate to differing seat or bed heights. The strategy with this research was to fill a gap between existing hypothesized fall-prone population risk factors and their interactions with bed height in an unfamiliar environment.

4.1. Temporal variables

Most temporal variables of significance revealed a performance schism between LB and that of HB and MB conditions. All effect sizes for temporal variables fell between the range of 0.09 to 0.25 and are considered medium by Cohen's d cut-offs. Observed power was good for all variables, being 0.8 or higher. In the case of total task time, pairwise comparisons revealed LB to be significantly different from HB (p=0.024) and MB (p=0.016). Participants took, on average, 2.4 seconds longer to complete the STW task from the LB. These delays in STW execution may mean more postural accommodations to maintain balance were required in the LB condition [15] and are in agreement with data produced by Buckley [13] on PD patients and Frykberg[18] in stroke patients.

Table 1.Summary of repeated measures ANOVA. N varies between analyses due to occasional missing data and listwisedeletion. * Indicates p<0.05 compared to one other bed height. ** Indicates p<0.05 compared to two other bed heights. † Indicates statistical significance was not found with post-hoc testing.

Bed Height Main Effects - Within Subjects							
	Condition	Mean(SE)	95% CI	N	F (p)	η^2_P	Power
Temporal							
Total task time (s)	H*	3.7(0.3)	3.2-4.2	61	7.899(0.006)	0.116	0.950
	M*	3.9(0.3)	3.3-4.5				
	L**	6.3(1.0)	4.4-8.2				
Extension phase time (s)	H*	1.3(0.1)	1.0-1.5	61	10.570(0.001)	0.150	0.988
	M*	1.4(0.2)	1.1-1.8				
	L**	2.4(0.4)	1.7-3.1				
Time ratio %	H*	32.4(1.5)	29.4-35.3	61	6.227(0.006)	0.094	0.812
	M	35(1.5)	32.0-38.1				
	L*	38.8(2.3)	34.3-43.3				
Heel-off time (s)	H*	2.6(0.3)	2.3-3.4	61	7.878(0.006)	0.116	0.798
	M*	3.1(0.3)	2.5-3.7				
	L**	5.4(1.0)	3.5-7.3				
Swing-off time (s)	H*	3.1(0.3)	2.5-3.6	61	7.871(0.006)	0.116	0.798
	M*	3.3(0.3)	2.7-3.9				
	L**	5.6(1.0)	3.7-7.5				
Stance-off time (s)	H*	3.7(0.3)	3.2-4.2	61	7.899(0.006)	0.116	0.800
	M*	3.9(0.3)	3.3-4.5				
	L**	6.3(1.0)	4.4-8.2				
Velocity and Momentum							
Δ velocity: seat-off to swing-off (+cm/s)	H	9.9(2.3)	5.2-14.6	65	4.722(0.011)	0.069	0.781
	M*	15.1(2.5)	10.0-20.2				
	L*	9.9(2.3)	5.3-14.5				
A/P momentum at seat-off (kg*m/s)†	H	1.2(0.6)	0.0-2.3	64	3.221(0.047)	0.049	0.582
	M	0.3(0.6)	(-)0.8-1.5				
	L	(-)0.9(0.5)	(-)1.1-0.9				
A/P momentum at peak v_vel (-kg*m/s)	H**	4.1(0.4)	4.8-3.4	65	29.785(0.000)	0.318	1.000
	M*	6.2(0.5)	7.2-5.3				
	L*	7.1(0.5)	8.0-6.2				
M/L momentum at stance-off (kg*m/s)†	H	5.0(0.5)	4.0-6.0	65	3.254(0.042)	0.048	0.611
	M	4.8(0.4)	3.9-5.6				
	L	5.5(0.5)	4.5-6.5				

Extension phase durations were also significantly different between LB and HB (p=0.002) and between LB and MB (p=0.013). HB and MB extension phase durations were, on average, 1 second faster than LB. The extension phase characterizes the time spent rising as it overlaps into gait initiation and may be the most demanding transition of the task due to the dynamic use of the body's inertial properties and the need for simultaneous postural control. Also, longer time-to-rise phases are typically present in fall-prone individuals and may be a hallmark of the need for increased postural adjustments to accommodate a lack of stability and poor motor coordination between lower extremity muscles [13, 18,25]. If we extrapolate this to the LB time-to-rise performance, we can interpret this to mean that individuals deliberately separate their movements into more perfunctory STS and gait initiation event divisions.

It was also important to consider the extension phase duration relative to the total task time in order to normalize this variable between bed heights as a percentage of the entire STW duration. It was found that the time ratio was significant between HB and LB only ($p=0.009$). HB and MB had a p-value between 0.05 and 0.10 and there was no significance between MB and LB. This means that participants spent more time in the extension phase when rising from the LB condition even when considered as a percentage of the total task time. This could indicate HB requires the least posturally challenging transition prior to the start of gait and the best use of generated kinetic energy (in this case, "posturally challenging" indicates challenges to an individual's ability to effectively maintain balance within the BoS). Alternatively, it could mean that individuals have a harder time controlling the rate of postural overlap between sitting and standing and thus they perform "quickly" by default. The MB condition appeared to offer the most flexibility either way.

Heel-off, swing-off, and stance-off times were all statistically significant between the LB and HB ($p\leq0.016$ for all three variables) and the LB and MB ($p\leq0.025$ for all three variables). LB conditions showed the largest delay in gait initiation by an average of 2.4 seconds, a result that is consistent with the total task time increase for the same condition.

Interestingly, no difference in seat-off timing was found, even when the data was stratified to examine only individuals with a MFS score of 50 or higher.This result indicates that seat-off timing is identical for any given bed height and the diverging temporal parameters come into play only upon rising.

4.2. Velocity and momentum variables

Some studies have concluded that fall-prone individuals have higher lateral velocities and momentums than their healthier counterparts [16, 17, 23]. This is theorized to be associated with a lack of postural control and thus contribute to instability and fall risk. This study found most velocity and momentum parameters to have no significant differences between bed heights. One exception was the change in velocity between seat-off and swing-off. Pairwise comparisons revealed differences in MB and LB ($p=0.012$) as well as a borderline significance between MB and HB ($p=0.057$). There was no difference between HB and LB, interestingly, because of the nature of the metric: HB started fast and stayed fast while LB started slow and stayed slow.

Momentum variables found to be significant include A/P values at peak VVEL. The HB condition produced markedly different results from both other bed heights ($p=0.000$ in each case). All trunk momentum values were negative during this event due to the fact that it occurs during rising. HB required less negative momentum at this event, indicating a potential difference in timing and/or a decreased need for forceful trunk extension to rise. This may mean a high bed height could allow more momentum to be channeled into an anterior direction for forward mobility or simply reduce de-stabilizing posterior momentum. This particular result had high observed power and large effect size although there are virtually no literature sources which investigate kinematic details (beyond the Z axis) occurring at this event. Fig. 2 illustrates this outcome, as well as the fact that anterior momentum at gait initiation is slightly higher.

RM ANOVA revealed statistical significance between bed height for A/P momentum at peak A/P GRF ($p=0.047$) but post-hoc testing did not bear this out. It is possible this parameter may have been confounded by differing signs. HB and MB momentum means were (+) for the event while the LB momentum mean was (-).

While this study cannot make any claims on the baseline measurements of the participants' M/L velocity or momentum parameters, it is important to note that no M/L variables were found to be significant between bed heights for any STW event - with one exception: M/L trunk momentum at stance-off was found to differ between conditions with RM ANOVA ($p=0.042$). However, post-hoc testing did not confirm this.

Bed height plays a role in kinematic and temporal fall risk parameters. The low bed height created the largest delays in temporal parameters after seat-off occurred but displayed no significant differences in A/P velocities or momentums at most key events. This indicates that low beds pose a more posturally challenging transition and require more time to accommodate balance impairments while using the same momentum strategy as the other bed heights. These results are illuminating in that a slightly lower bed height significantly influenced mobility (low bed was on average only 2.5 (±0.1) inches below the medium bed and only 0.9 (±0.1) inches less than tibial plateau height). Fig. 2 illustrates A/P momentum values as they occur at 6 STW events for each bed height (indicated with markers). The study population was divided into groups as a function of MFS scores (lower scores indicating less impairment).As bed height gets lower, momentum magnitudes tend to increaseduring rising for both groups, indicating individuals may need to use more speed during extension in order to develop the needed hip moment to rise. This is probably because individuals place their CoM further over their BoS as seat height drops.

The medium bed height had the least significantly different kinematic or temporal parameter outcomes in pairwise comparisons with both other bed heights, indicating it may provide a middle ground for patients to utilize either stabilization or mobilization strategies. These two kinematic expressions are often seen as non-complementary yet it is imperative to use both in a fluid manner for successful STW [26]. The medium bed height allowed for time-to-rise phases to be longer or shorter as needed, yet gait initiation timing was similar to HB (i.e. sooner). It also provided the greatest increase in velocity between seat-off and swing-off. Thus the potential beauty of a medium bed height is that it allowed participants to rise at a rate which felt stable yet enter into gait with a fairly high degree of fluidity.

The high bed height had many of the same kinematic and temporal characteristics as the medium bed height with slightly faster event times. Since M/L kinematic parameters were statistically the same as medium bed heights, high bed heights in the range of 3 inches beyond tibial plateau height may pose little hazard for individuals with fall risk during bed egress.

This study supports qualitative literature findings that low bed heights do not appear to reduce fall risks during bed exit; rather, they may exacerbate them. Additionally, it gives evidence that fall risks may be reduced in high risk populations by setting a bed deck height that compliments the balance strategies commonly used to compensate for deficits in strength and mobility. More work is needed to establish clear guidelines to determine and set more accommodating bed heights for bed entry and exit.

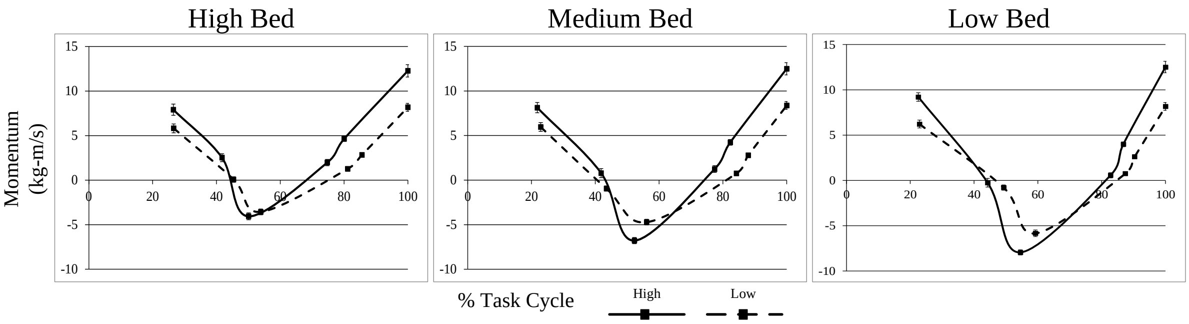

Fig.2. Three graphs highlighting A/P trunk momentum in six STW events for each bed height. MFS score ≤ 50 made up the low scoring group and reflects less impairment. MFS score > 50 made up the high scoring group and reflects more impairment. Events shown are in order of: 1) begin-to-stand; 2) seat-off; 3) peak VVEL; 4) heel-off; 5) swing-off; 6) stance-off. Event timing is reflected as a percent of task cycle, beginning with movement initiation and ending with stance-off.

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