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Project title:	Developing biomechanical models from initiated fall actions and reactions in frail elderly patients
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1 STRUCTURED ABSTRACT

Purpose: We identified primary actions and reactions, or corrective behaviors (CBs), during an initiated fall (“near miss”) and explored balance recovery strategies in elderly patients during egress from hospital beds. We targeted the points at which fall mechanisms are initiated during a fall risk episode (FRE) and explored how balance recovery is achieved.

Scope: We evaluated the effectiveness of recovery strategies using hand and foot CBs to prevent falls. This secondary use of our comprehensive dataset included 88 frail elderly and elderly controls (n=1442 trials) coded with 50 variables.

Methods: We visually identified CBs, FREs, and sit-to-stand-and-walk (STSW) key events and computed the biomechanical stability metrics during bed egress. CBs utilized in balance recovery were coded along with the duration of FREs. The FREs were used as proxy for a fall. These episodes were evaluated by fall-risk level, TUG score, bed height, and biomechanical metrics. Strategies for enabling STS (bouncing, scooting, leaning) were identified, along with discontinuities in rising (pausing), and were associated with fall-risk scores.

Results: Our systematic analyses of elderly fall-prone subjects during bed egress and transitions during gait revealed moments of instability. We identified corrective behaviors used by subjects to prevent a fall in a patient room setting. Strategies that have not been previously investigated, most notably bouncing-to-stand from bed and pausing upon standing prior to initiating gait, occurred most frequently at low bed heights. Identifying FREs is a useful approach for identifying moments of fall risk and to provide a basis for developing fall prevention strategies.

Key Words: elderly, fall risk assessment, fall prevention, fall biomechanics

2 PURPOSE (OBJECTIVES OF STUDY).

Despite extensive research into the biomechanical causation of falls, the group most prone to falls and fall injury—the frail elderly—has been sparse. Our extensive, and comprehensive dataset consists of 88 elderly performing bed and chair ingress, egress, and walking 6 feet. Of these, 19 elderly participants were identified as having had a Fall Risk Episode (FRE) during one or more trials, for a total of 61 FREs. These data provided incidents of fall initiation—the point of instability, the period of instability and the point of recovery, the location and mechanism of falls—evidence essential for the understanding of falls in the frail elderly and leading to the identification of appropriate interventions to improve balance recovery. Our goal for this project was to analyze the effects of corrective behaviors on 'fall initiation(s)' exhibited during bed egress and walking 3-6 feet. We achieved this by visually identifying the corrective behaviors used during essential movements and quantifying the biomechanics required for independent transfer from bed to walking. We accomplished our overall objective for this project by completing the following specific aims:

Aim 1: Evaluate weight shifting and changes in stability during bedside egress (Sit-to-Stand-and-Walk) for impaired frail elderly and controls.

Aim 2: Explore how balance recovery actions modify instability and perturb imbalance during bedside egress (Sit-to-Stand-and-Walk) for impaired frail elderly and controls.

Aim 3: Compare balance performance of frail elderly participants with balance of the control group (low fall risk).

3 SCOPE (BACKGROUND, CONTEXT, SETTINGS, PARTICIPANTS, INCIDENCE, PREVALENCE).

This is a secondary analysis of a comprehensive dataset that was collected as part of AHRQ R01HS018953 (PI-Morse). The project was completed according to the following timeline:

1) **Data preparation:** 6 months.
   a) Tasks: Locating the incidents (Jerks), selecting the period of analysis (2.5 secs prior to the Jerks and the duration of the correction); downloading these data.
1) **Data Analysis:** 8 months.
   a) Tasks: data cleaning, statistical analysis; comparison of numbers of incidence within subject and between subjects.
2) **Modeling:** 9 months.
   a) Tasks: determining the best fit by corrective actions; by time to regain balance; by physiological deficits.
3) **Preparation of Reports:** 2 months.
   a) Tasks: AHRQ final report, writing, submitting, and presenting articles

A summary table of participant characteristics is included here for convenience (Table 1).

Table 1- Demographics by Morse Fall Scale (<55 and ≥ 55) total sample

	Morse Fall Scale < 55		Morse Fall Scale ≥ 55		Total	
	n = 43		n = 45		N=88	
Characteristic	n	%	n	%	Avg or n	%
Age (years)	Av 67.57	SD 10.62	Av 70.80	SD 10.76	69.24	SD 10.75
Gender						
Female	13	30.20	12	26.70	25	28.40
Male	30	69.80	33	73.30	63	71.60
Hispanic ethnicity						
Yes	2	4.70	1	2.20	3	3.40
No	40	93.00	44	97.80	85	95.50
Race						
American Indian or Alaska Native	1	2.30	1	2.20	2	2.30
Black or African American	1	2.30	3	6.70	4	4.50
Native Hawaiian or Pacific Islander	1	2.30	1	2.20	2	2.30
White	39	90.70	40	88.90	79	89.80
Unknown or not reported	1	2.30			1	1.10
Recruitment site						
VA Inpatient			2	4.40	2	2.30
VA Outpatient	26	61.90	29	64.40	55	63.20
Fall Clinic	3	7.10	2	4.40	5	5.70
Community	8	19.00	4	8.90	12	13.60
Other	5	11.90	8	17.80	13	14.80

4 METHODS (STUDY DESIGN, DATA SOURCES/COLLECTION, INTERVENTIONS, MEASURES, LIMITATIONS).

Previous studies have shown that frail elderly were most likely to fall during the complex transitional movement of sit-to-walk (STW) [1]; however, the particular phase of STW with the greatest risk of falling has not been identified. This study evaluated balance recovery actions, referred to as Corrective Behaviors (CBs; Table 1), along with biomechanical stability metrics (Table 3), including *jerk*^{2} [2, 3], to determine the point of greatest fall risk during bed egress. CBs provide a stabilizing influence, but a significant *jerk*^{2} (S*jerk*^{2}) may indicate a potential fall risk. All 144 bed egress trials of high fall risk individuals were visually reviewed, with all CBs tagged during bed egress STW. In addition, control subjects with low and moderate fall risk levels were processed in the same manner for comparison. Biomechanical data were collected through a 3D motion capture system and processed using Visual 3D [4, 5].

Key STSW events, movement phase (Stand Preparation), and subphases (Stabilization and Gait Initiation) defined by Taylor, et al. [4] for frail individuals (Figure 1) were used to more accurately identify the temporal location of greatest fall risk.

Table 2 Definitions with abbreviations

Terminology		
Term	**Abbreviation**	**Definition**
Lower Leg Length	LLL	Calculated as the distance from the floor to the subject's lateral tibial plateau while sitting with a 90° knee angle.
Bed height		Bed height is the bed deck height and is calculated for each participant according to a percentage of their LLL minus the compressed mattress depth while the participant is seated on the edge of the bed.
Low Bed Height	LB	Calculated at 95% LLL of the participant
Medium Bed Height	MB	Calculated at 110% LLL of the participant
High Bed Height	HB	Calculated at 125% LLL of the participant
Morse Fall Scale	MFS	A rapid method of assessing a patient's likelihood of falling
Low fall risk	LFR	MFS≤25
Moderate fall risk	MFR	25<MFS<55
High fall risk	HFR	MFS≥55
Frail	Frail	For this study, frail is defined as individuals with an MFS ≥55, or high fall-risk
Corrective Behavior	CB	Intentional positional movement of hands or feet that results in modification of performance posture to maintain or regain balance
Proximal CB	PCB	CB within 1 second of a significant *jerk*[2]
Fall Risk Episode	FRE	Visually observed moment of concern of a potential fall during bed egress, types include FRE$_{rising}$, FRE$_{stabilizing}$, FRE$_{gait}$
FRE$_{rising}$	FREr	Fall risk episode that could start and stop in any of the stand preparation, stand initiation, or stand phases
FRE$_{stabilizing}$	FREs	Fall risk episode that starts in stand phase and ends in gait phase
FRE$_{gait}$	FREg	Fall risk episode that starts and ends in gait phase
Pause	Pause	The stopping and/or reversing of forward momentum following seat-off and prior to initiating gait
Key STSW Events		
Stand Preparation	SP	First intentional movement following audible signal to perform bed egress; beginning of the Stand Preparation Phase
Stand Initiation	SI	The start of the last torso flexion just prior to successful rise; end of the Stand Preparation Phase; beginning of the Stand Initiation Phase
Seat-off	SO	Moment when buttocks is no longer in contact with seat surface; end of the Stand Initiation Phase; beginning of the Stand Phase
Zero Horizontal Velocity	ZHV	Moment when forward motion stops or reverses direction following successful rise and prior to gait initiation; end of the Stand Phase; beginning of the Stabilization Phase
Gait Initiation	GI	First step with intent to walk
Gait Initiation Foot Off Swing Step	GIFOSw	First step to initiate gait, occurring when foot leaves contact surface; end of Stabilization Phase; beginning of Gait Initiation Phase
Gait Initiation Foot Off Stance Step	GIFOSt	Second step to initiate gait, occurring when foot leaves contact surface; end of Gait Initiation Phase; beginning of Gait Phase
STSW Phases & Subphases		
Stand Preparation Phase		SP to SI (Stand Preparation to Stand Initiation)
Stand Initiation Phase		SI to SO (Stand Initiation to Seat-Off)

Stand Phase	SO to GI, (Seat-Off to Gait Initiation Swing Foot includes the Stabilization Subphase)
Stabilization Subphase	ZHV to GI (Zero Horizontal Velocity to Gait Initiation Swing Foot)
Gait Initiation Subphase	Transition between standing and steady state walking
Gait Phase	GI through to the end of walking

Table 3 Definitions for Biomechanical Outcomes Determining Stability

Term	Units of Measure	Definition
Position from bed	m	Whole-body Center of Mass (CoM) anterior-posterior distance from bed
***jerk*^{2}**	$(m/s^3)^2$	Square of the third derivative of position, indicates unsmooth movement (values greater than 2500 were rejected as model errors)
S*jerk*^{2}	$(m/s^3)^2$	Significant *jerk*^{2}; *jerk*^{2} above the threshold of 250 $(m/s^2)^2$
Head-Foot Position	m	Anterior-posterior distance between subject's head$_{CoM}$ and combined left and right ankle$_{CoM}$
Torso angle	degrees	Angle from vertical with positive in clockwise direction
Normalized Angular Momentum	m^2/s	Whole-body sagittal plane normalized angular momentum

The sit-to-walk (STW) task is described as a complex, continuous movement. STW phases include the Stand Initiation Phase (flexion-momentum), the Stand Phase (extension), and the Gait Phase (Figure 1 STW diagram illustrating the Stand Phase overlapping with the Gait Phase. ©Brenden Taylor Illustration). According to Kerr [6], the Stand and Gait phases of STW typically overlap; thus, extension continues during the first few steps of the Gait Phase. Though not consistent among all STW studies, the key events that define STW phases are frequently measured as follows: Stand Initiation begins at the start of torso flexion and ends with seat-off; Stand begins with seat-off and ends with peak vertical velocity; Gait begins with swing toe-off and continues through the duration of walking.

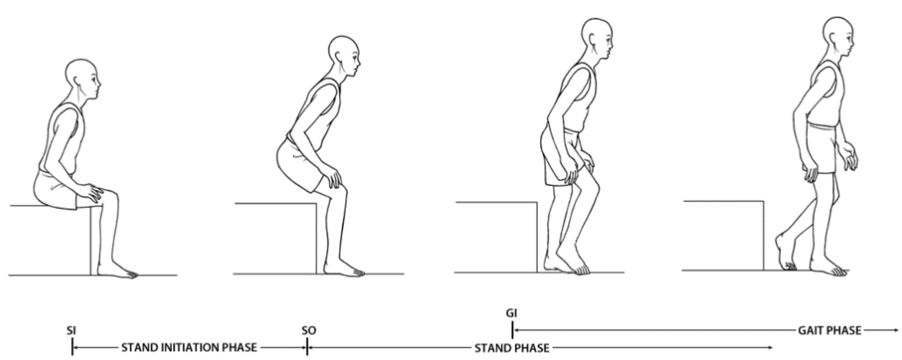

Figure 1 STW diagram illustrating the Stand Phase overlapping with the Gait Phase. *©Brenden Taylor Illustration*

Unlike the smooth, continuous STW transition observed in unimpaired populations, the frail often perform a sit-to-stand-and-walk (STSW) when rising from a seated position (Figure 2). STSW phases of the frail include STW phases as well as the stand preparation phase; stabilization and gait initiation subphases stand and gait phases do not overlap. ©Brenden Taylor Illustration). In addition to the STW phases, the STSW includes one additional phase and two additional subphases: Stand Preparation Phase, which includes movement prior to initiating a successful rise; the Stabilization Subphase, which occurs during the Stand Phase and includes the pause before Gait Initiation; and the Gait Initiation Subphase, which includes the first two steps taken to begin walking. By breaking down the complex task of STW into more refined phases, the self-selected egress strategies can be better evaluated to determine more precisely the moments of instability [1, 7]. STSW includes a pause or hesitation between the STS and GI [8], resulting in a critical reduction in forward momentum during rising. This behavior has previously been observed during STW in individuals with motor impairment [9, 10].

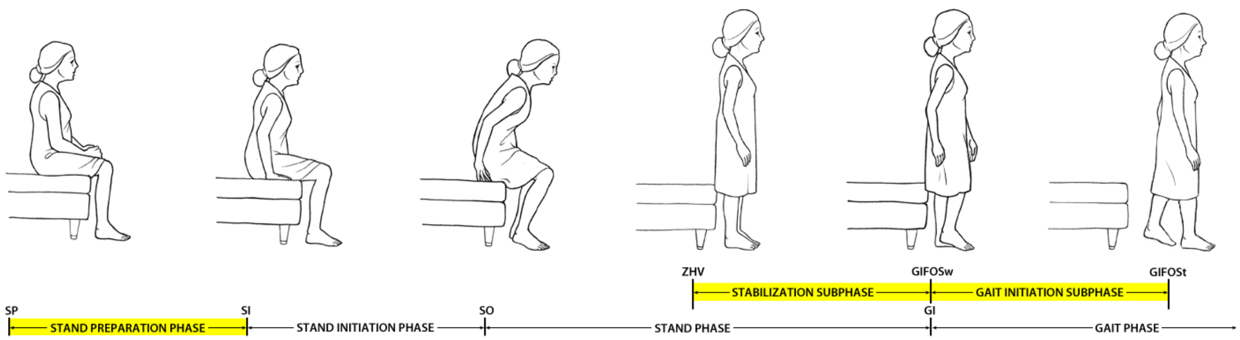

Figure 2 STSW phases of the frail includes STW phases as well as the stand preparation phase, and stabilization and gait initiation subphases stand and gait phases do not overlap. *©Brenden Taylor Illustration*

The STSW Phases are defined by key events. The *Stand Preparation Phase* begins with the first movement following the directive to stand and walk and then ends at the initiation of torso flexion to begin standing just prior to a successful stand. Stand Preparation includes shifting, scooting, rocking, bouncing, and failed attempts to stand. The *Stand Initiation Phase* begins with the last torso flexion just prior to a successful stand and ends at the following seat-off. The *Stand Phase* begins at successful seat-off and ends with swing toe-off. The *Stabilization Subphase* occurs during the Stand Phase beginning with the forward momentum stopping and/or reversing and ending with swing toe-off. The *Gait Phase* begins with swing toe-off and continues through walking. The *Gait Initiation Subphase* begins at swing toe-off and ends with stance toe-off. The Stand Initiation, Stand, and Gait Phases of STSW can be directly compared to those of a healthy STW when using the same key events to define the phases.

5 RESULTS

5.1 AIM 1: EVALUATE WEIGHT SHIFTING AND CHANGES IN STABILITY (TYPES OF FREs) DURING BEDSIDE EGRESS (SIT-TO-STAND-WALK) FOR IMPAIRED FRAIL ELDERLY AND CONTROLS.

Analysis: Fall Risk Episodes (FREs) were matched with biomechanical data and analyzed. Each time point of the trial was coded within the STSW phases (Stand Preparation, Stand Initiation, Stand, or Gait) and whether it was a time of stability or instability (Non-FRE vs. FRE). These data were analyzed with a linear mixed model for each dependent biomechanical variable (jerk, torso angle, etc.). The model included the fixed factors of stability, and phase. There was a random effect of trial to account for the correlated time measures within each trial. Each biomechanical variable was modeled as a separate outcome variable.

Results: From 436 videos, 61 fall-risk episodes (FREs) were identified within 51 trials from 19 participants. The majority of FREs occurred in the Stand and Gait phases (n = 45 and 33, respectively). A relatively small number of FREs occurred in the Stand Preparation and Stand Initiation phases (n = 5 and 8, respectively).

Table 4 FRE and Phase of Occurrence

Phase	FRE (count)
Stand Preparation	5
Stand Initiation	8
Stand Phase	45
Gait Phase	33

Many FREs spanned two phases in the same trial (hence the greater number of FREs reported for all STSW phases than the total number of FREs, N = 61). Two transition periods appeared critical: (1) rising from bed to stand (before gait is initiated), and (2) standing to gait initiation. No FRE spanned greater than two phases. We defined three different FRE types as follows:

FRE_{rising} (FRE_r): These are moments of fall risk that could start in Stand Preparation, Stand Initiation, or Stand Phase but end prior to the gait initiation.

$FRE_{stabilizing}$ (FRE_s): These moments of fall risk start in the Stand Phase and continue into the Gait Phase.

FRE_{gait} (FRE_g): These moments of fall risk start and end in the Gait Phase.

Table 5 FRE Type Counts and Duration (seconds)

	Stand Phase FRE (FRE_{rising})	Stand to Gait Phase FRE ($FRE_{stabilizing}$)	Gait Phase FRE (FRE_{gait})
N	28	18	15
Mean	3.35	2.39	1.32
Standard Deviation	2.50	1.49	0.58

The majority of fall risk episodes occurred near the bedside. Twenty-eight FREs occurred in Stand Preparation through the Stand Phase, FRE_r; 18 FREs occurred during the Stand Phase through the Gait Initiation Subphase, FRE_s; 15 FREs were in Gait Phase alone, FRE_g. The average length of a FRE was longest in the Stand phase: 3.35 (2.46) seconds. The shortest duration occurred in the Gait Initiation Subphase: 1.32 (0.58) seconds. Analysis showed statistical significance, $p = 0.005$.

Comparison of episodes of instability with the three bed heights is show on Table 5. The low bed condition had 25 FREs, the medium bed had 16, and the high bed had 20. There was a trend with the most FREs occurring at the low bed height. Suggesting that the low bed had a higher risk of falling. Chi-squared analysis showed no relationship between bed height and FRE type, $p = 0.183$.

We explored how biomechanical metrics differed between the three FRE types (Table 6). The results were stratified by bed height condition. In the high bed condition, $jerk^2$ was significantly higher in FRE_r (mean = 89.57, SD = 19.41) and FRE_g (mean = 80.07, SD = 18.6) when compared with FRE_s (mean = 5.39, SD = 18.6), $p < 0.05$. Head Feet Position was lowest in FRE_r (mean = 0.05, SD = 0.03) and highest in FRE_s (mean = 0.10, SD = 0.03). The Torso angle was high in FRE_r (mean = 25.48, SD = 2.85) and FRE_s (mean = 23.18, SD = 2.81) but lowest in FRE_g

(mean = 0.22, SD =2.81). Normalized Angular Momentum was highest in FRE_r (mean = 0.32, SD = 0.08) and lowest in FRE_s (mean = -0.20, SD = 0.08).

Table 6 FRE Type vs. Bed Height

Bed Height	Stand Phase FRE_{rising}	Stand-Gait Phase $FRE_{stabilizing}$	Gait Phase FRE_{gait}	Total
Low	16	4	5	25
Medium	6	6	4	16
High	6	8	6	20
Total	28	18	15	61

Within the medium bed-height trials: $jerk^2$ was highest in FRE_r (mean = 58.75, SD = 17.32) but equivalent between FRE_s (mean = 38.36, SD = 17.36) and FRE_g (mean = 32.18, SD = 28.15). Head Feet Position was highest in FRE_s (mean = 0.14, SD = 0.04) and lowest in FRE_g (mean = 0.06, SD = 0.06). Torso angle was highest in FRE_r (mean = 30.77, SD = 4.87) and lowest in FRE_g (mean = 10.09, SD =8.06). Normalized Angular Momentum was highest in FRE_r (mean = 0.12, SD = 0.06) and near zero in FRE_g (mean = 0.01, SD = 0.1).

For the low bed height trials, $jerk^2$ was high in FRE_r (mean = 68.78, SD = 18.96) and FRE_g (mean = 76.53, SD = 19.7) but low in the FRE_s (mean = -80.61, SD = 20.88). Head Feet Position was equivalent in FRE_r (mean = 0.14, SD = 0.03) and FRE_s (mean = 0.16, SD = 0.03) but was near zero in FRE_g (mean = -0.01, SD = 0.03). Torso angle was highest in FRE_r (mean = 38.48, SD = 2.75) and lowest in FRE_g (mean = 9.67, SD = 2.83). Normalized Angular Momentum was highest in FRE_s (mean = 0.22, SD = 0.03); both FRE_r and FRE_g were near zero (mean = 0.01, SD = 0.03, mean = -0.07, SD = 0.03, respectively).

A micro analysis of 3D biomechanics during bed egress was conducted. We hypothesized that movements prior to a fall-risk episode would indicate compensatory action to correct imbalance to prevent a fall. The timing of these FREs highlights the need for improvements in fall prevention strategies specifically targeted at the bedside and during transition from a seated position into gait. The majority of FREs occurred during rising. Bed height has a significant effect on the trunk posture and angular momentum of the center of mass during rising. Lower beds were accompanied by greater trunk flexion and reduced momentum during rising.

The irregularity of movement defined by $jerk^2$ was consistently greater across all movement phases for the low bed condition. The highest angular momentum during egress from a low bed occurred during the Stabilization Phase. This key finding suggests that when a patient rises from a low bed, not only is there greater fall potential defined by higher $jerk^2$ but also the head is more forward than the feet (Head Feet Position) during the Stand Phase, creating a higher risk for a forward fall prior to gait initiation. This head-forward position then requires the generation of a higher Normalized Angular Momentum to extend during the Stabilization Subphase, creating an increased risk for a backward fall, or a failed sit-to-stand movement.

Table 7 FRE Type and Biomechanical data Stratified by Bed Height

	FRE Type		
	FRE_{rising}	**$FRE_{stabilizing}$**	**FRE_{gait}**
	N = 28	N = 18	N = 15
Bed Height			
Biomechanics (metric)			
High Bed			
Position (m)	1.02^{a} (0.05)	0.95^{b} (0.04)	0.32^{c} (0.04)
$jerk^2$ $(m/s^3)^2$	89.57^{a} (19.41)	5.39^{b} (18.6)	80.07^{a} (18.6)
Head Feet Position (m)	0.05^{a} (0.03)	0.10^{b} (0.03)	0.09^{c} (0.03)
Torso angle (degrees)	25.48^{a} (2.85)	23.18^{b} (2.81)	0.22^{c} (2.81)
Normalized Angular Momentum (kg/m^2)	0.32^{a} (0.08)	-0.2^{b} (0.08)	0.25^{c} (0.08)
Medium Bed			
Position (m)	1.07^{a} (0.06)	0.84^{b} (0.06)	0.46^{c} (0.1)
$jerk^2$ $(m/s^3)^2$	58.75^{a} (17.32)	38.36^{b} (17.36)	32.18^{ab} (28.15)
Head Feet Position (m)	0.09^{a} (0.04)	0.14^{b} (0.04)	0.06^{ab} (0.06)
Torso angle (degrees)	30.77^{a} (4.87)	22.73^{b} (4.87)	10.09^{b} (8.06)
Normalized Angular Momentum (kg/m^2)	0.12^{a} (0.06)	0.09^{a} (0.06)	0.01^{a} (0.1)
Low Bed			
Position (m)	1.05^{a} (0.04)	0.99^{b} (0.05)	0.19^{c} (0.04)
$jerk^2$ $(m/s^3)^2$	68.78^{a} (18.96)	80.61^{b} (20.88)	76.53^{a} (19.7)
Head Feet Position (m)	0.14^{a} (0.03)	0.16^{a} (0.03)	-0.01^{b} (0.03)
Torso angle (degrees)	38.48^{a} (2.75)	26.81^{b} (2.95)	9.67^{c} (2.83)
Normalized Angular Momentum (kg/m^2)	0.01^{a} (0.03)	0.22^{b} (0.03)	-0.07^{c} (0.03)

*FRE Types that share same superscript are statistically equivalent at the 0.05 level.

In summary, we support the hypothesis that movements occurring prior to and during an FRE are indicative of increases in fall potential and provide guidance to suggest changes in practices that utilize a low bed condition to prevent patient falls. Future work should focus on providing stabilizing features to beds and rooms to reduce FREs during bed egress.

5.2 AIM 2: EXPLORE HOW BALANCE RECOVERY ACTIONS MODIFY INSTABILITY AND PERTURB IMBALANCE DURING EGRESS FOR IMPAIRED FRAIL ELDERLY AND CONTROLS.

In studies in which healthy subjects perform a scripted STW, hands are typically crossed over subject's chest and joint angle positions begin generally at 90 degrees [6]. The resulting STW of healthy individuals in those studies consisted of a smooth rise to walk without the possible use of hands to aid in stabilization. It is from those studies that the traditional STW phases were defined, for which no balance recovery is employed. Though this may be appropriate for the healthy population, there is a need to define additional phases in order to better characterize STW for the frail elderly [4]. As presented in the methods section, STSW includes, in addition to the STW phases, the Stand Preparation Phase as well as the Stabilization and Gait Initiation Subphases.

This aim evaluates the use of CBs during bed egress STSW with respect to fall risk level, bed height, and STSW phases. In addition, this aim evaluates the Stabilization Subphase where pausing and/or reversing of forward momentum occurs upon rising, thus separating the vertical rise from the forward gait movement. S*Jerk*[2] is then evaluated with proximal CBs identified.

5.2.1 Results: Use of Corrective Behaviors

On average, corrective behaviors were used by both the healthy control group and the frail in all phases of STSW. During the Stand Preparation Phase, CBs were employed that adjusted postural position to perform stand initiation and achieve a successful rise to stand. Results from the high-fall-risk group include a total of 678 CBs, or an average of nearly five CBs per high-fall-risk trial, indicative of instability. The majority of CBs occurred prior to and during the Stand Initiation Phase (275 [40.6%] and 343 [50.6%], respectively), with only 84 (12.4%) occurring during the Stand Phase (Figure 3 Average Number of Corrective Behaviors During Each Phase of STSW). This observation is key in beginning to understand the particular movement being performed when the frail subjects were most likely to experience a potential fall risk episode (FRE). The addition of the Stand Preparation Phase provides the ability to separate the difficulty in initiating a stand, and thereby achieving a successful seat-off, from the difficulty in standing itself (safely extending following seat-off) [4].

Compared with healthy controls, those at high fall risk had more than twice the total CBs per trial. For high-fall-risk individuals, the largest number of CBs generally occur during the Stand Initiation Phase, when the participant is attempting to achieve seat-off (Figure 3 Average Number of Corrective Behaviors During Each Phase of STSW). Multiple CBs were employed, depending on the type of strategy chosen. A variety of egress strategies were observed, including bouncing, rocking, scooting, and leaning, all with multiple CBs [1]. These strategies will be evaluated more during ongoing research (R18 HS025606-01). The highest number of CBs on average occur for those at high fall risk in every STSW phase when exiting the low bed (Figure 3). In addition, the Stand Initiation Phase has the most CBs when exiting a low bed. *This suggests that the frail subjects (high fall risk) largely compensate for the increased effort required when standing from a low bed height prior to and during rising by using CBs.*

Statistical analysis indicates that the fixed factors of bed height, phase, and their interaction are significantly related (p-value<0.05) to the number of CBs for HFR individuals (Table 8).

Table 8 Estimated fixed effects from gee: total CBs (high fall-risk)

	Wald Chi-Square	df	*p*-value
Bed Height	13.81	2	0.001
Phase	110.01	2	< 0.001
Bed Height and Phase	14.30	4	0.006
TUG	3.58	1	0.059

[1] NOTE: This observation held true for the no-fall-risk (MFS=0) control subjects as well, for the low bed condition in which hands were often used to assist in bed egress. In addition, a variety of self-selected STSW strategies employed among the frail subjects while preparing to initiate stand were observed and will be investigated in the future. These strategies include bouncing, rocking, scooting, sliding, and repositioning of hands and feet.

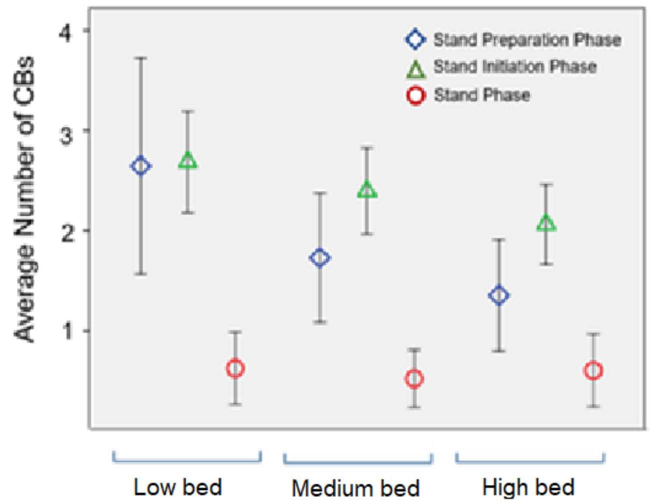

Figure 3 Average Number of Corrective Behaviors During Each Phase of STSW

Following the initial evaluation of CBs for the HFR group, results were compared among LFR, MFR, and HFR groups (Table 9 Average number of CBs for a given Bed Height, level of fall risk, and egress phase).

Table 9 Average number of CBs for a given Bed Height, level of fall risk, and egress phase

STSW Phase		Stand Preparation Phase			Stand Initiation Phase			Stand Phase		
Fall-Risk Level # (st dev)		LFR	MFR	HFR	LFR	MFR	HFR	LFR	MFR	HFR
Bed Height	Low Bed	0.1 (0.7)	0.6 (0.9)	3.4 (3.9)	2.0 (1.2)	2.4 (1.4)	2.7 (1.8)	0.1 (0.5)	0.1 (0.2)	0.9 (1.4)
	Medium Bed	0.9 (1.9)	0.3 (0.6)	2.1 (2.5)	2.0 (1.1)	2.8 (1.2)	2.3 (1.6)	0.0 (0.0)	0.0 (0.0)	0.7 (1.1)
	High Bed	0.2 (0.9)	0.4 (0.8)	1.8 (2.3)	2.5 (1.1)	2.1 (1.2)	2.1 (1.4)	0.0 (0.0)	0.3 (0.8)	0.9 (1.4)

Note: Colors in table header indicate corresponding phases analyzed for HFR (Figure 3 Average Number of Corrective Behaviors During Each Phase of STSW).

These results indicate that the greatest number of CBs occurs during the Stand Preparation Phase for the HFR group and are highest at the low bed condition. CBs are used during the Stand Preparation Phase to assist in rising from the bed, including adjusting using hands to push off the bed, legs, or rail; adjusting foot position to align CoM closer to their feet to minimize the moment required to stand; and using these CB strategies in multiple attempts until successful rise is achieved. During the Stand Initiation Phase, MFR and HFR groups have an average greater than 2 CBs at all bed height conditions. During the Stand Initiation Phase, both hand and feet CBs are employed to maintain and/or regain balance as the subject achieves a successful seat-off. The Stand Phase only shows concern of increased CBs for the HFR group and is reflected in all bed conditions. The CBs in the Stand Phase include touching back with a hand to the bed or rail and/or small side or forward steps to maintain or regain balance prior to initiating gait.

5.2.2 Results: Pausing during bed egress

Following a successful rise from the hospital bed, elderly participants of all fall risk levels tend to pause following seat-off and prior to initiating gait. It is possible that this pause provides the opportunity to visualize the next target where they are walking to, the purpose of ensuring stability, or possibly both. The purpose of the pause is being investigated in our ongoing research (R18 HS025606-01). This behavior of pausing not only increases the duration of the traditional Stand Phase and overall STW time when compared with a healthy STW but also leads to the possibility of overcorrection (rocking back on heals), leading to FREs or falls.

Results indicate that, the greater the fall risk level, the more likely an individual is to pause during bed egress. HFR individuals paused during 48.7% of their bed egress trials, whereas MFR and LFR individuals paused during 35.9% and 17.4% of their bed egress trials, respectively (Figure 4 Percent of trials with pausing by fall-risk level). The number of trials with pausing increased on average by 15.65% between low to moderate and moderate to high fall risk groups.

When evaluating the effect of bed height on pausing, all fall risk levels had some trials with pausing for each bed height condition except the LFR group with a medium bed height condition (Figure 5 Average pause time by bed height and fall risk). The low bed height condition had the greatest percentage of trials with pausing for moderate and high fall risk levels. Consistently across all bed heights, the HFR group had the most trials with pausing, followed by the MFR. The average pause time was greatest for the HFR group and averaged 2.35 seconds at the low bed height.

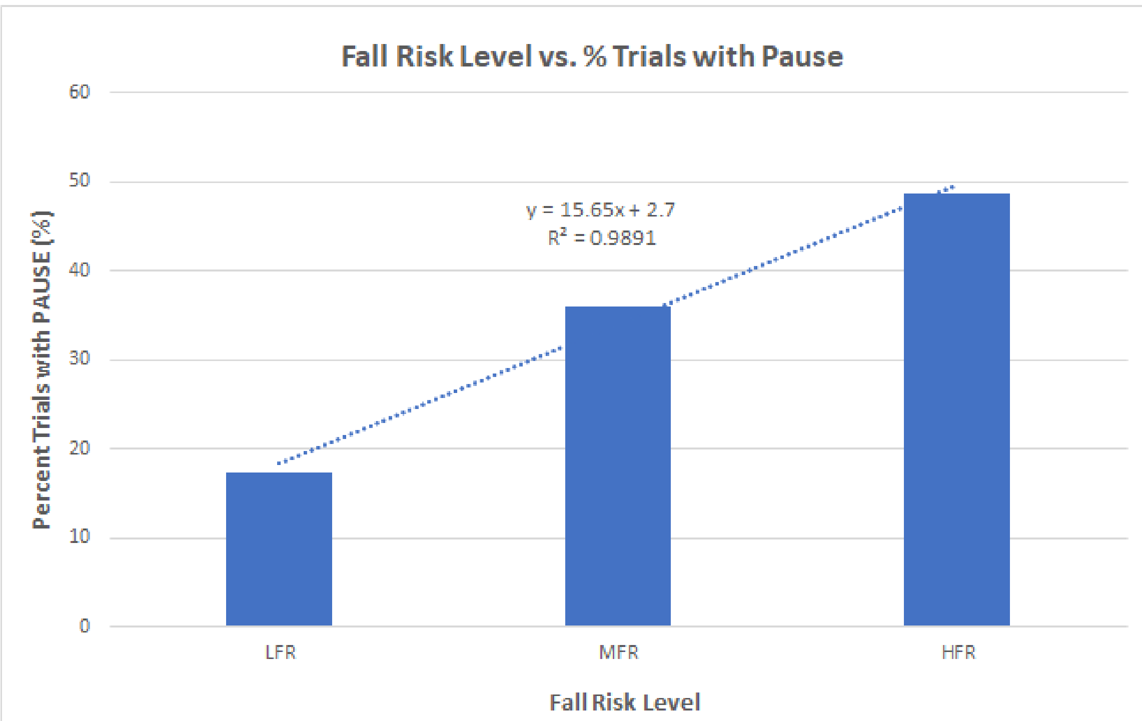

Figure 4 Percent of trials with pausing by fall risk level

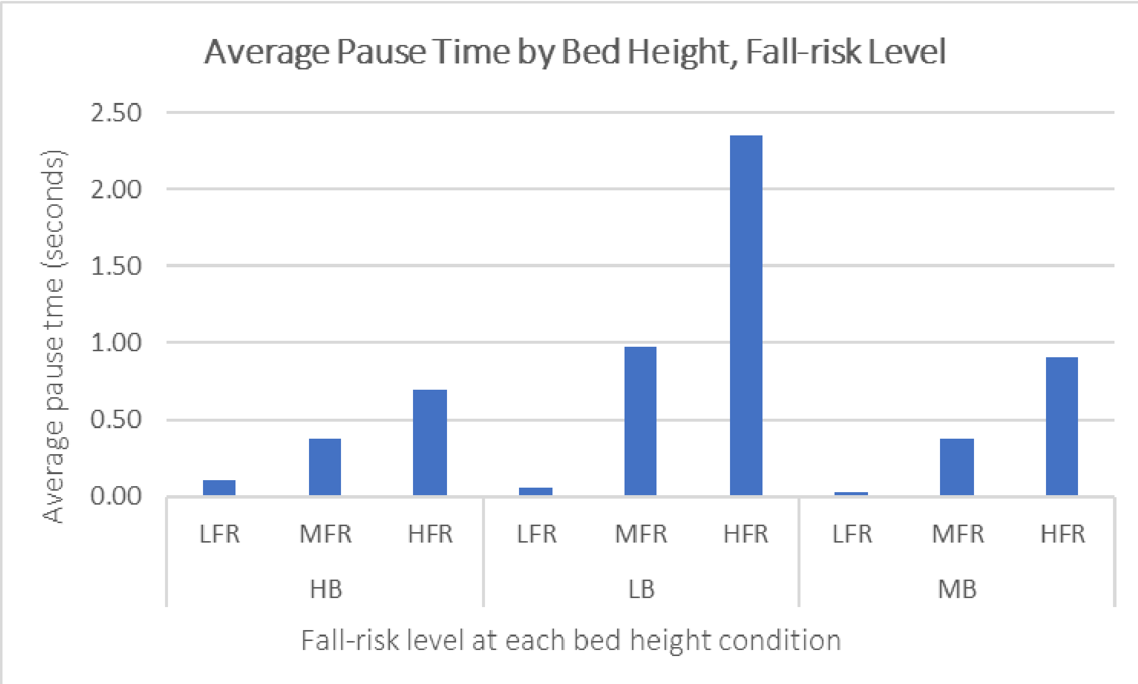

Figure 5 Average pause time by bed height and fall risk

5.2.3 Results: Significant Jerk2 with correlating CB

As humans age, experience disease, or encounter a debilitating injury, physical movement is less coordinated and smooth flowing. Jerk, the time derivative of acceleration, is often used to quantify smoothness [11]. Previous studies have demonstrated the use of $Jerk^2$ as an indicator of a fall initiation point [2]. We hypothesized that when there is S$Jerk^2$, there will either be a fall or a CB that follows, or potentially both if the CB is unable to effectively correct the instability. An initial evaluation was completed on a sample group of HFR trials to determine if a CB could be located within 1 second of a S$Jerk^2$. Figure 6 (Example of HFR subject's low bed condition trial with multiple SJerk2 events and CBs) is a visual example of the data. Here, the continuous $Jerk^2$ trajectory is plotted, along with the STSW key events, phases, and temporal locations of CBs and S$Jerk^2$ events. All S$Jerk^2$ are identified by a blue triangle, and each CB is uniquely identifiable according to CB type. Proximal CBs were identified for each S$Jerk^2$ event. The results for % of S$Jerk^2$ events with a proximal CB can be seen in Table 10 SJerk^2 events with proximal CB. Overall, the majority of S$Jerk^2$ events did associate with a CB. This relationship between S$Jerk^2$ and proximal CBs will be investigated more in our ongoing research.

Table 10 SJerk^2 events with proximal CB

Bed Height	Average Number of S$Jerk^2$/trial (St Dev)	% S$Jerk^2$ events with proximal CB<1s
Low Bed	8.5 (4.6)	97
Medium Bed	5.8 (4.4)	100
High Bed	2.5 (0.7)	80

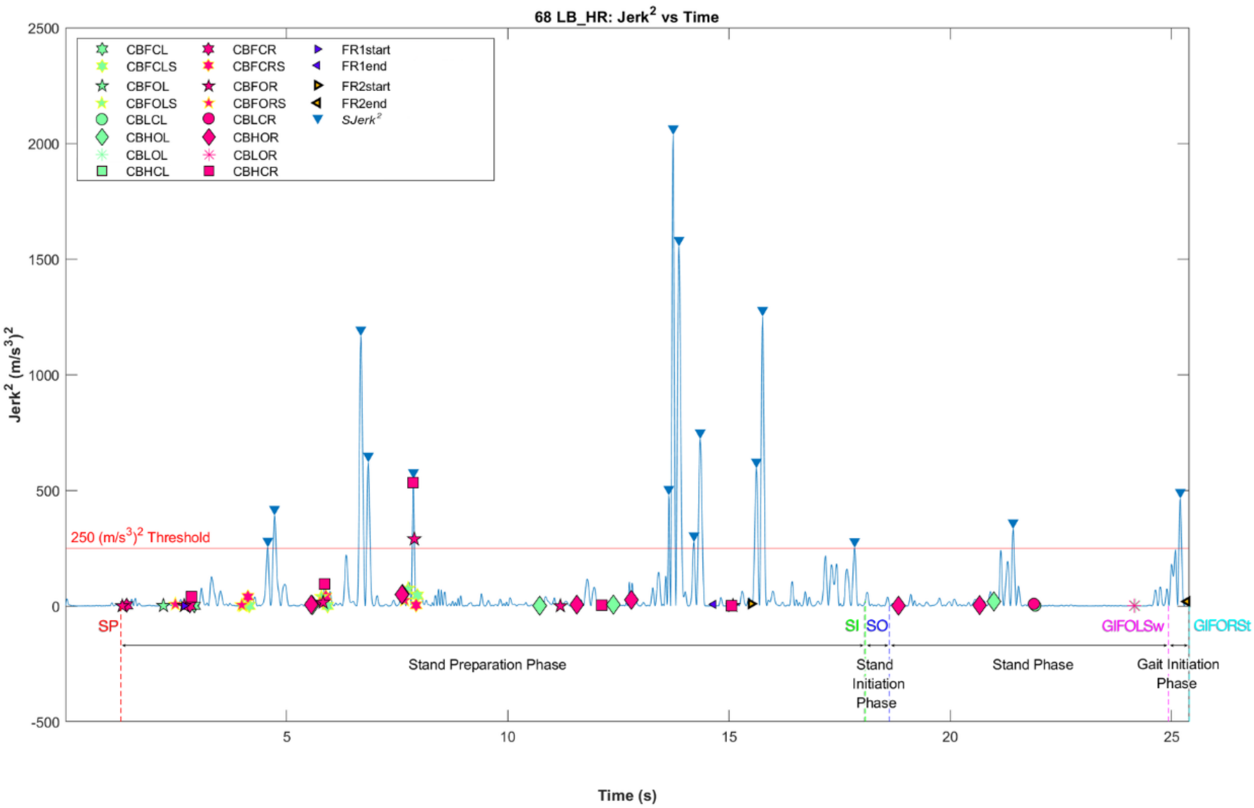

Figure 6 Example of HFR subject's low bed condition trial with multiple SJerk2 events and CBs

5.3 DISCUSSION

Through visual identification and analysis of CBs during bed egress, we have shown that the average number of CBs increases as fall risk increases. The greatest number of CBs used correlates with the low bed condition for all fall-risk levels. In addition, the percentage of trials with a pause also increases with increased fall risk. Finally, we have shown that S*jerk*^{2} generally coincides with a CB within 1 second. These findings suggest that, as an individual's fall risk level increases, they increasingly compensate for instability during STSW by using CBs and pausing prior to initiating gait. These characteristics could be monitored for deterioration in STSW performance. Identification of this change could trigger a warning to caregivers to increase support for successful STSW transitions. In addition, when performing a TUG test, clinicians could identify those who demonstrate STSW characteristics with a notable pause between STS and Gait Initiation.

5.4 AIM 3: COMPARE BALANCE PERFORMANCE OF FRAIL ELDERLY PARTICIPANTS WITH BALANCE OF THE CONTROL GROUP (LOW FALL RISK).

Investigation of demographic characteristics of those individual participants that had a FRE vs. participants who did not have a FRE (stable vs. unstable).

Analysis: Independent t-tests were used to assess mean differences on strength variables, BMI, age, and physical performance. Chi-square was used to assess categorical variables (gender, race, etc.) Mixed modeling was used to compare stable vs. unstable participants on biomechanical outcomes data.

Results: Comparison between stable vs. unstable participants showed differences in Timed up and go performance. Unstable participants were slower than stable participants (20.48 vs. 13.94 seconds, p<0.001.) The participants were not statistically different in demographic characteristics.

Table 11 Stable vs. Unstable Participants Demographic and Performance

	Stable	Unstable
	N = 69	N = 19
Age in years (SD)	69.88 (10.8)	69.95 (10.5)
Morse Fall Scale	46.77 (20.7)	55.26 (19.0)
Timed Up and Go (sec)	13.94 (6.4)	20.48 (7.5)***
Leg strength (lb)	40.64 (19.80)	46.21 (30.22)
Tricep strength (lb)	25.47 (10.34)	24.87 (15.48)
Grip strength (lb)	64.3 (24.48)	62.26 (26.89)
BMI	29.19 (6.59)	30.41 (5.17)
Gender		
Male	48 (69.6%)	15 (78.9%)
Female	21 (30.4%)	4 (21.1%)
Ethnic Background		
Not Hispanic or Latino	66 (95.7%)	18 (94.7%)
Hispanic, Latino, or of Spanish Origin	2 (2.9%)	1 (5.3%)
Unknown or refused	1 (1.4%)	0 (0.0%)
Race		
American Indian, Aleut, or Eskimo	1 (1.4%)	1 (5.3%)
Native Hawaiian or Pacific Islander	2 (2.9%)	0 (0.0%)
African-American	3 (4.3%)	1 (5.3%)
White/Caucasian	62 (89.9%)	17 (89.5%)
Unknown or Refused	1 (1.4%)	0 (0.0%)

Table 12 Stable vs. Unstable Participants Comparing Biomechanical Outcomes

	Stable	Unstable	
	N = 69	N = 19	p-value
Biomechanic (metric)			
Phase			
Position from bed (m)			
Stand Preparation	1.3 (0.01)	1.24 (0.01)	< 0.001
Stand Initiation	1.21 (0.01)	1.15 (0.01)	< 0.001
Stand	1.02 (0.01)	0.98 (0.01)	< 0.001
Gait	0.1 (0.01)	0.11 (0.01)	0.854
jerk^2 $(m/s^3)^2$			
Stand Preparation	39.18 (3.72)	48.04 (5.63)	0.552
Stand Initiation	60.76 (3.77)	60.91 (6.86)	0.848
Stand	37.31 (1.85)	33.59 (3.08)	0.146
Gait	74.24 (1.89)	63.57 (3.18)	0.560
Head Feet Position (m)			
Stand Preparation	-0.36 (0.01)	-0.33 (0.01)	0.002

Stand Initiation	-0.08 (0.00)	-0.08 (0.01)	0.644
Stand	0.19 (0.00)	0.16 (0.01)	< 0.001
Gait	0.06 (0.00)	0.05 (0.01)	0.069
Torso angle (degrees)			
Stand Preparation	13.39 (0.45)	16.08 (0.73)	0.002
Stand Initiation	35.83 (0.35)	35.06 (0.62)	0.280
Stand	41.27 (0.53)	35.39 (0.91)	< 0.001
Gait	-6.43 (0.36)	-5.36 (0.62)	0.139
Normalized Angular Momentum (kg/m^2)			
Stand Preparation	0.05 (0.00)	0.05 (0.01)	0.359
Stand Initiation	0.39 (0.01)	0.37 (0.02)	0.313
Stand	0.28 (0.01)	0.20 (0.01)	< 0.001
Gait	0.1 (0.00)	0.09 (0.01)	0.133

Analysis showed that stable participants' average position in each phase (stand prep, stand initiation, and seat-off) was nearer to the bed than unstable participants: 1.3 (0.01) vs. 1.24 (0.01), 1.21 (0.01) vs. 1.15 (0.01), and 1.02 (0.01) vs. 0.98 (0.01) meters, respectively.

Head Feet Position, Torso Angle, and Normalized Angular Momentum were all significantly higher in the stable participants during the Seat-Off phase: 0.19 (< 0.01) vs. 0.16 (0.01), 41.27 (0.53) vs. 35.39 (0.91), and 0.28 (0.01) vs. 0.20 (0.01), respectively.

Findings suggest that rising from the bed to a standing position is a key transition time, marked by differences in biomechanical data and distinguishing stable participants from unstable participants.

These results are informing our grant, "Reconfiguring the patient room using a fall protection strategy to increase patient stability during ambulation for the estimation of fall risk) in hospital rooms" (R18 HS025606-01). Finally, we will compare the results from our analyses with results published by other researchers.

5.4.1 Discussion

We compared key biomechanical metrics during different movement phases between elderly adults during stable and unstable periods for movement transitions between sitting on a hospital bed and walking. Prior work has highlighted the risk associated with balance transfers and turning during gait [1]. We found a significant difference in TUG score between groups from the perspective of a clinical evaluation.

Our detailed analysis of movement during transitions that are represented in the TUG also reveal a significant difference between groups for head-feet position, trunk angle, and angular momentum during the stand phase. The stable movements involved greater trunk flexion and angular momentum. There were no significant strength deficits between groups, but the coordination of the movement as measured using 3D motion analysis revealed these important differences.

These findings highlight the need for future fall interventions at the bedside, specifically during the transfer of momentum and balance from sitting to standing during the stabilization phase described in Aim 2. This additional time to become stable prior to initiating gait represents the criticality of providing support to establish a stable stance prior to gait initiation.

Future work will study STSW with an unstable elderly population and which object features (i.e., graspability, movability, height) affect balance during STSW, Gait, and Turning.

6 OVERALL CONCLUSION

In this study, we explored the biomechanics of fall initiation in the frail elderly by identifying actions and reactions during an initiated fall (a "near miss"), and the balance recovery strategies in frail elderly patients, during ingress and egress when transferring from a hospital bed and chair. Data were a secondary analysis of the performance of 22 frail elderly and controls during bed and chair ingress/egress in a hospital room (AHRQ #1R01HS018953).

The data set included 1442 unique trials from 88 frail, elderly participants that were coded using 50 variables. Focusing on the fall mechanisms of these frail elderly patients with an extremely high risk of injury makes this research unique, significant, and highly important.

The purpose of Aim 1 was to evaluate weight shifting and changes in stability during bedside egress for impaired frail elderly and controls. We targeted the points at which fall mechanisms are initiated during a fall risk episode (FRE), and periods of instability were identified. The majority of the 61 FREs occurred during rising. Bed height has a significant effect on the trunk posture and angular momentum of the center of mass during rising. Lower beds were accompanied by greater trunk flexion and reduced momentum during rising. Normalized Angular Momentum during rising was lowest during an FRE on the low bed condition, which would suggest an increased risk for a backward fall or a failed sit-to-stand movement. Statistical analysis indicates the fixed factors of bed height, phase, and their interaction are significantly related (p-value<0.05) to the number of CBs for HFR individuals. There was a trend with the most FREs occurring at the low bed height, suggesting that the low bed had higher risk of falling during egress.

In Aim 2, we explored the balance recovery actions used to modify instability during egress. We investigated how balance recovery was achieved using foot and hand corrective behaviors (CBs) to prevent a fall. The CBs were an indication of instability (i.e., potential fall) prior to and during the stand initiation phase. We observed that frail subjects paused after rising and prior to initiating gait. This behavior of slowing or reversing forward momentum upon rising may lead to rocking back on heals and thus create an instable moment and potential fall risk, particularly at low bed height condition.

Compared with the healthy control subjects, those at high fall risk had more than twice the total CBs per trial. For high-fall-risk individuals, the largest number of CBs generally occurred during the Stand Initiation Phase, when the subject is attempting to achieve seat-off. Strategies that have not been previously investigated, most notably bouncing to stand from bed or chair and pausing upon standing prior to initiating gait, appear to be critical for identifying moments of fall risk and developing preventative strategies. These egress strategies, primarily bouncing, rocking, scooting, and leaning, use multiple CBs and indicate that the frail subjects (high fall risk) must compensate for the increased effort required when rising from a low bed height. Statistical analysis indicates the fixed factors of bed height, phase, and their interaction are significantly related (p-value<0.05) to the number of CBs for HFR individuals.

Finally, in AIM 3, we compared balance performance of frail elderly participants with balance of the control group. We found that rising from the bed to a standing position is a key transition time marked by differences in biomechanical data, distinguishing stable participants from unstable participants. We found a significant difference in TUG score between groups and for head-feet position, trunk angle, and angular momentum during the stand phase. Unstable participants were further from the bed than stable participants. In conclusion, there was a trend with the most FREs occurring at the low bed height, suggesting that the low bed had higher risk of falling. This will be investigated in our ongoing grant (R18 HS025606-01). Future work will focus on providing stabilizing features to beds and rooms to reduce FREs during bed egress to prevent patient falls.

7 List of Publications and Products

Conference Presentations:

Taylor, D., Merryweather, A., & Morse, J. (2018, June). Biomechanical Characterization of the Hand Touch Corrective Behavior in the Frail Elderly During Bed Egress. In Proceedings of the International Symposium on Human Factors and Ergonomics in Health Care (Vol. 7, No. 1, pp. 237-239). Sage India: New Delhi, India: SAGE Publications.

Taylor, Dorothy, Merryweather, Andrew, Morse, Janice. “Corrective Behaviors During the Sit-to-Stand-and-Walk Task of the Frail Elderly Correlate with Fall Risk and Fall Initiation.” *9th Annual Rocky Mountain American Society of Biomechanics Conference* (pp. 42-43). 5-6 April 2019.

Taylor D, Merryweather A, Morse J, Wong B. “Natural Sit-to-Stand-Walk of the Frail.” Podium Presentation at the American Society of Mechanical Engineers International Mechanical Engineering Conference and Exposition (ASME IMECE), Salt Lake City, UT, 11-14 November 2019.

Taylor D, Merryweather A, Morse J, Wong B. “Decreasing the Frequency of Frail Elderly Patient Falls by Limiting Exposure Risks in Hospital Patient Rooms.” Podium Presentation at the NIOSH Regional Conference, Auburn University, Auburn, AL, 27-28 February 2020.

Peer-reviewed Publications:

Taylor D, Morse J, Merryweather A, Wong B, “Natural Sit-to-Stand-Walk of the Frail.” Proceedings of the American Society of Mechanical Engineers International Mechanical Engineering Conference and Exposition, SLC, UT, November 2019.

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