CORRELATION OF OBSERVED BEHAVIORS WITH BIOMECHANICAL METRICS IN DETERMINING THE POINT OF FALL INITIATION DURING THE SIT-TO-STAND-AND-WALK OF THE ELDERLY

by

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ABSTRACT

Elderly patient falls continue to be of primary concern among hospitals worldwide. These falls frequently result in injury or death, often leading to an increase in hospital stay in the short term and a decrease in independence for the patient in the long term. Even amid the variety of fall prevention plans implemented in hospitals over the last few decades, the average patient fall rate continues to rise across the United States. This is unacceptable.

Current research has identified the majority of patient falls occur in the patient room during bed egress. Unfortunately, data surrounding these falls at the bedside are extremely limited. In order to evaluate patient falls, researchers have simulated falls in the laboratory with healthy individuals using strict protocols that have been shown to be a significantly inaccurate representation of real-world elderly falls.

Through collaborative efforts between nurses, physical therapists, hospital architects, engineers, and biomechanists, this research presents a new framework for use in evaluating elderly patient egress movement, both in the laboratory and clinically in a hospital or clinic setting. This framework includes both a new sit-to-stand-and-walk (STSW) method and a fall-proxy model. By viewing egress performance through the lens of the Taylor STSW Biomechanical Model, insights were gained regarding an elderly patient's preparation to initiate standing, corrective behaviors throughout STSW, pausing prior to initiating gait, and unsmooth movement during a fall-risk episode (FRE). This research has shown that a patient-specific bed height contributes to a successful bed egress,

keeping not only the patient safe but also the caregiver who may be assisting.

This new knowledge fills a gap in the area of fall studies and fall prevention. Future STSW studies now have a standard whereby to investigate the biomechanical mechanisms that lead to patient egress falls. By using this framework, cross-comparative analyses can be done across STSW studies of both healthy and frail individuals. Results from these studies will provide the much-needed data to drive more effective fall prevention interventions, helping the frail and elderly live healthier lives.

Twenty-five years ago, I dedicated my Master's Thesis to my husband, Brenden, and
our three children, stating, "May my commitment to education be instilled in you."
Today, Brenden has obtained an M.S. in Medical Illustration, Elise an M.S. in Civil
Engineering, Kylie an M.M. in Oboe Performance, and Chet a B.S. in Electrical and
Computer Engineering. And, returning to graduate school after eighteen years,
I have completed what I had thought might be impossible to accomplish:
a Ph.D. in Mechanical Engineering.

I dedicate my dissertation to my Savior Jesus Christ; through Him all things are possible.
May my commitment to Him be instilled in all eight of our beautiful, beloved children.

“An ounce of prevention is worth a pound of cure.”

Benjamin Franklin

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CHAPTER 1

INTRODUCTION

Elderly patient falls are the largest single category of reported incidents in hospitals [1, 2]. The cost of a patient fall to the patient includes injuries that not only cause emotional and physical pain for both the individual and their family and friends but also increase the length of hospital stay and the overall financial cost. In addition, injury from a fall may negatively impact one's independence, placing increased burdens on families and communities, or it may even cause death [2, 3]. Hospitals also incur financial costs from patient falls. Since 2008, the Centers for Medicare & Medicaid Services (CMS) has included hospital-acquired injuries from falls on their list of "Never Events," denying reimbursement to hospitals for incurred costs due to falls [4].

As a result, hospitals are making even greater efforts to reduce the rate of patient falls, despite little evidence that current fall prevention practices actually reduce the patient fall rate. Patient call buttons, bed alarms, and other mechanisms or devices that alert medical professionals or assist the patient during bed egress are often unsuccessful in preventing patient falls [4]. The patient fall rate is defined as the rate at which patients fall during their hospital stay per 1,000 patient days. Patient fall rates range from 3.3 to 11.5 falls per 1,000 patient days [2, 5-7]. Studies have shown that the majority of patient falls occur in the patient room (50-85%) on or near the bed (79%) [5, 8-12]. In addition, patients are not the only ones who suffer physical injury. Medical personnel and other caregivers who assist patients may also experience acute injury and/or musculoskeletal disorders[13]. Keeping both patients and caregivers safe is of utmost interest to hospitals.

There is a great need for a better understanding of the biomechanical context that contributes to elderly falls, along with knowledge of the factors that contribute most. While there are numerous studies on healthy sit-to-walk (STW), these studies do not translate to real-world egress of the elderly, especially frail elderly [14, 15]. Elderly egress fall data are key in identifying points of imbalance. Yet, we are limited in the laboratory to only performing studies that keep individuals safe from falls. Thus, the need for a fall proxy. **The goal of this research program is to identify key metrics that predict a fall during bed egress without actually having a fall.** This is achieved through the development of the Taylor Sit-to-Stand-and-Walk (STSW) Method, along with the Taylor Fall-proxy Model, together providing a framework for the evaluation of self-selected egress strategies and identification of potential falls. This is accomplished through three specific aims:

- AIM 1. Define appropriate and distinct phases for the self-selected egress of those at high fall risk through the development and use of visual and motion capture methods to establish key characteristics of sit-to-stand-and-walk (STSW).
- AIM 2. Differentiate between sit-to-walk (STW) and STSW by evaluating key characteristics of corrective extremity use and pausing prior to initiating gait of healthy elderly at low fall risk.
- AIM 3. Develop a fall-proxy model that can identify a fall during egress for use in laboratory settings where falls are prevented.

1.1 Participants

This research is based on data collected from 74 participants recruited by staff referral from the University of Utah Medical Center, the George E Whalen Medical Center (VA), and the local community. Participant age ranged from 50 to 94 years old. A pilot study with 21 (5 Female, 16 Male) frail (MFS>55) adults (68.0±11.2 years) with a total of 144 unique egress trials was completed to investigate the role of corrective behaviors (CBs) at 3 subject-specific bed heights and 3 rail conditions (Chapter 3) [15]. The full study using all 74 participants was performed to develop the Fall Proxy Model (Chapter 5).

1.2 DATA Acquisition

All position data were collected using a 3D motion capture system and an 80 retroreflective marker set placed at key anatomical landmarks, including the sacrum, anterior superior iliac spine, knee, lateral malleolus, heel, 2nd metatarsal head, tibial wand, femoral wand, wrist, elbow, shoulder, C7 vertebrae, and clavicle with a headband securing the markers on the head. Ground reaction force data were collected by two force plates (Bertec BP4060), one for each foot. All collected motion capture and force plate data were processed through Visual 3D. Key STSW events and CBs were visually identified and tagged in Adobe Premiere Pro (Chapter 3) [15].

1.3 Terminology

The terminology used within this research is defined in Table 1.1. Additionally, in order to facilitate comparative analyses, not only across multiple STSW studies, but also between STW and STSW studies, Key Events, Phases, and Subphases were defined that are applicable to both methods (Tables 1.2 and 1.3). This is proposed as the new standard for both STW and STSW studies.

1.4 Introduction to Dissertation

1.4.1 Chapter 2: Development of the Sit-to-Stand-and-Walk Model

Chapter 2 will address the need for a Sit-to-Stand-and-Walk method. First, the author presents a critique of the current generally accepted STW method. Limitations of this method are discussed with respect to real-world elderly egress. Second, the Taylor Sit-to-Stand-and-Walk (STSW) method is presented in which such limitations are eliminate. By using the Taylor STSW Biomechanical Model, the complex elderly egress in its entirety is represented. The Taylor STSW Biomechanical Model extends the capacity of current research for all egress studies, both young healthy and elderly frail and every ability in between. Third, through a literature review and a pilot study done by the author, variables to explicate STSW performance were selected and a biomechanical method was developed. Frail elderly individuals separate the tasks of rising and walking, frequently pausing between the two tasks. Pausing was selected as a metric of instability for the purpose of maintaining or regaining stability. The physical movement of the frail elderly is less coordinated and less smooth flowing. They have less ability to maintain stability by controlling postural changes through dynamic forces. The chapter concludes that while the traditional method used to understand STW does not apply well to the elderly population, the Taylor STSW Biomechanical Model provides a more complete characterization of elderly egress, while still maintaining applicability for STW.

1.4.2 Chapter 3: The Natural Sit-to-Walk of the Frail

Chapter 3 addresses the first aim of this research program by testing the first hypothesis:

- AIM 1 H1.1: Persons at High Fall-risk (HFR) employ a self-selected STW strategy that requires multiple Corrective Behaviors (CBs) prior to the first traditionally established STW phase (flexion-momentum) in order to achieve a successful STW.

A pilot study consisting of 21 HFR participants with 144 unique self-selected egress trials was performed. The visual coding system was developed [15] (Appendix C) and used to identify all CBs and Key Events. The exhibited preparation by the frail prior to rising is established as an additional phase to the STW task called the Stand Preparation Phase. Among the HFR, the Stand Initiation Phase had the most CBs. Significant factors in predicting CBs included bed height ($p<0.001$) and STSW phase ($p<0.001$). It is important to recall that studies in the literature were designed to explicitly eliminate possible hand and foot CBs, thus the assumption that non-frail individuals do not engage in hand CBs has not been previously validated. This will be addressed in Chapter 4.

1.4.3 Chapter 4: Use of Corrective Behaviors and Pausing During STSW: A Comparison Between Fall Risk Levels

Chapter 4 tests the validity of the previous STW assumption that healthy individuals do not use upper extremities during egress. This chapter applies the same data collection and analysis methods used in chapter three to evaluate the use of CBs and pausing during egress for all fall-risk levels. This addresses the second hypothesis of the first aim, as well as two hypotheses of the second aim:

- AIM 1 H1.2: Persons at HFR following rise, pause prior to initiating gait.

- AIM 2 H2.1: Persons at Low Fall-risk (LFR) (MFS≤25) employ a self-selected STW strategy that utilizes fewer CBs prior to and during all STW phases than persons at HFR
- AIM 2 H2.2: Persons at LFR employ a self-selected STW strategy that generates continuous forward movement from seat-off through gait.

1.4.4 Chapter 5: Developing a Fall-proxy Model for the Elderly for Use in the Laboratory

Chapter 5 develops a fall-proxy model for use in the laboratory where falls are purposefully prevented. Specifically, this chapter addresses the two hypotheses of the third aim:

- AIM 3 H3.1: Observable fall-risk episodes have a correlating significant local maximum jerk.
- AIM 3 H3.2: Observable fall-risk episodes have a corresponding critical corrective behavior (CCB).

1.4.5 Chapter 6: Creating a Safer Patient Room Environment

The impact of research is often measured by clinical application and, in the context of this research, the reduction in falls. Chapter six provides insights into patient care that not only helps to reduce patient falls, but also reduces caregiver injury. This chapter identifies a specific application of the research findings, namely patient-specific bed height for safer egress, both for the patient and for the caregiver.

1.4.6 Chapter 7: Conclusions and Recommendations for Future Research

Chapter 7 presents the main conclusions from this research and suggests areas for future research related to better understanding STSW and reducing patient falls.

1.5 Key Contributions

1. Development of a reliable and valid coding system used for ingress, egress, and research investigating falls. This coding system was developed from 74 participants performing sit-to-stand-and-walk-to-sit. The coding system can be applied to all elderly movement [15].
2. A sit-to-walk (STW) method for the elderly and frail is introduced and referred to as the Taylor Sit-to-Stand-and-Walk (STSW) Method. The Taylor STSW Biomechanical Model includes a defined Stand Preparation phase, as well as a Failed Stand Initiation subphase and a Stabilization subphase. This new phase and two new subphases differentiate the Taylor STSW from other traditional healthy STW methods. Key events that define these phases are described and can be used across future studies for ease of comparison between both STSW and STW. This method provides the context for this research and can be applied in the future to studies involving egress and/or egress fall studies of the frail and/or elderly where actual falls are prevented.
3. Due to the complexity and variation of self-selected bed egress, traditional biomechanical metrics, such as joint angles, joint torques, and peak velocity may not consistently correlate with strategies employed or with falls. Therefore, independent of the self-selected egress strategy, jerk is identified as a biomechanical metric that correlates with falls. This research develops a model that predicts a fall, based on non-traditional biomechanical metrics, assessed fall risk, and environmental features, providing researchers a way to study falls of the frail elderly without actual falls in the laboratory.

4. This research contributes to the safety of the frail elderly patient by presenting data-driven justification of a patient-specific bed height (PSBH) for the frail and elderly. In addition, when the frail patient is more able to successfully rise on their own, there is a decrease in required assistance which increases the caregiver’s safety, as well.

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Table 1.1 Terms, abbreviations, and definitions.

Terminology		
Term	**Abbrev**	**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.[6]
Bed height	BH	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.[6]
Low Bed Height	LB	Calculated at 95% LLL of the participant[6]
Medium Bed Height	MB	Calculated at 110% LLL of the participant[6]
High Bed Height	HB	Calculated at 125% LLL of the participant[6]
Morse Fall Scale	MFS	A rapid method of assessing a patient's likelihood of falling, based on 5 criteria: history of falling, secondary diagnosis, ambulatory aid use, IV, gait, and mental status[16]
Low Fall Risk	LFR	MFS≤25[6, 15]
Moderate Fall Risk	MFR	25<MFS<55[6, 15]
High Fall Risk	HFR	MFS≥55[6, 15, 16]
Frail	Frail	For this study, frail is defined as individuals with an MFS ≥55, or high fall risk[6, 15]
Corrective Behavior	CB	Intentional positional movement of hands or feet that results in modification of performance posture to maintain or regain balance[15]
Critical Corrective Behavior	CCB	The temporally closest Proximal Corrective Behavior (PCB) for a given STSW Phase or subphase
Proximal Corrective Behavior	PCB	Any CB within +/-0.5 second of the local maximum significant $jerk^2$ of a specified STSW phase
Fall Risk Episode	FRE	Visually observed moment of concern of a potential fall during bed egress; a perceived moment of instability with start endpoints, labeled as FRE_start; FRE_end, respectively
Pause	Pause	The period of time when a subject stops and/or reverses forward CoM velocity following seat-off and prior to initiating gait
Term	**Unit of Measure**	**Definition**
$jerk_{CoMz}^2$	$(m/s^3)^2$	Square of the third derivative of position in the vertical direction, indicates unsmooth movement (values greater than 2500 were rejected as model errors)
$Sjerk^2$	$(m/s^3)^2$	Significant $jerk^2$; $jerk^2$ above the threshold of $250(m/s^2)^2$
Torso angle	degrees	Angle from vertical with positive in a clockwise direction

Table 1.2 STSW key events defined

STSW Key Events		
Term	**Abbrev**	**Definition**
Stand Preparation	SP	Instance of first intentional movement following audible signal to perform bed egress that is not SI. This movement may include bouncing, scooting, or other adjusting prior to flexion to stand. This movement does not include tremors, shaking, or other unrelated movement.; beginning of the Stand Preparation Phase;
Stand Initiation	SI	Instance of intentional torso flexion to rise. This is followed by a successful rise; end of the Stand Preparation Phase; beginning of the Stand Initiation Phase when there is no failed stand initiation (FSI).
Failed Stand Initiation	FSI	Attempted stand initiation, followed by a fall back to the bed, requiring another stand initiation.
Seat-off	SO	Instance when buttocks are no longer in contact with seat surface following SI. This does not consider leg contact against the bed surface for support; end of the Stand Initiation Phase; beginning of the Stand Phase
Failed Seat-off	FSO	Attempted seat-off, followed by a fall back to the bed, requiring another seat-off.
Zero Horizontal Velocity	ZHV	Instance when forward motion stops or reverses direction (crosses zero threshold) following successful rise and prior to gait initiation, as measured by the center of mass velocity (v_{CoMy}=0); beginning of the Stabilization subphase
Swing Foot-off	Sw	Instance where subject's foot leaves contact surface and takes their first intentional forward step to begin gait initiation phase. This may or may not follow corrective step(s); end of Stabilization subphase and/or Stand Phase; beginning of Gait Initiation Phase
Stance Foot-off	St	Second step to initiate gait, occurring when the foot leathe ves contact surface; end of Gait Initiation Phase; beginning of Gait Phase

Table 1.3 STSW phases and subphases defined

STSW Phases & Subphases	
Stand Preparation Phase	SP to SI, or FSI, if it exists (Stand Preparation to Stand Initiation, or Failed Stand Initiation, if it exists)
Failed Stand Initiation Subphase	FSI to SI (Failed Seat Initiation 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-off, includes the Stabilization Subphase)
Stabilization Subphase	ZHV to GI (Zero Horizontal Velocity to Gait Initiation Swing Foot-off)
Gait Initiation Phase	S_w to S_t; Transition between standing and steady-state walking
Gait Phase	S_t through to the end of walking

CHAPTER 2

DEVELOPMENT OF THE SIT-TO-STAND-AND-WALK METHOD

2.1 Introduction

In order to study frail elderly Sit-to-Walk (STW) movement, a method must be developed that provides the appropriate framework where the self-selected egress strategies can be evaluated. As humans age, muscle strength and power decrease, contributing to a decreased ability to successfully perform the STW transition [1, 2]. Studies have observed that the STW performance of the frail is often asymmetric, along with frequent use of upper and lower-limb compensatory strategies to achieve a successful STW transition [3-6]. Unfortunately, current state-of-the-art methods are too limited to accommodate these compensatory strategies, as they have been simplified to torso and lower limb only, eliminating any upper extremity use [7]. In addition, STW studies commonly use restrictive position and egress strategy protocols and often analyze factors in isolation which limits the generalization of the results [8]. This chapter defines a STW method that is appropriate for frail elderly egress characteristics, referred to as the Taylor Sit-to-Stand-and-Walk (STSW) Method .

General background on the state of STW research and the current challenges with the STW method for frail elderly population are presented. A review of a commonly used STW method is presented, including corresponding biomechanical metrics used to define the STW phases. This is followed by a discussion on current metrics used to evaluate STW performance. As a result of the STW method limitations, the Taylor STSW Biomechanical Model with defined phases, subphases, and key events is presented, followed by a discussion of STSW performance evaluation metrics.

2.2 Sit-to-Walk (STW)

Rising from a seated position to standing and walking is a complex, transitional movement requiring continual adaptation to maintain dynamic stability. While there is a general agreement of the basic phases of flexion, extension, and gait (Figure 2.1), key events that mark the start and end of these phases vary widely from study to study. Simplified STW methods are used and a variety of evaluation metrics are selected depending on the focus of the study. Two main challenges exist with the current STW approach, particularly when including frail subjects: inconsistent definitions of key events and unrealistic protocols. First, unlike other areas of study, there is a lack of uniformity in the methods used across studies. For example, there are a plethora of gait studies based on uniformly-defined functions and key events that are evaluated by consistent biomechanical metrics. However, literature reviews of STW studies demonstrate there is a lack of consistent parameters [4, 9-16], making comparisons between studies nearly impossible, or challenging at best [6, 17-21]. The second challenge in STW research is the strict protocols in study methods that inhibit studying real-world STW, particularly of the frail elderly. For ease and safety, STW studies frequently recruit healthy individuals who are able to follow strict protocols. These strict protocols require specific 'ideal' posture and movement where balance control is maintained through muscular adjustments of hip, knee, and ankle joints. In contrast to this healthy transition, an individual who lacks sufficient muscular strength cannot rely solely on joint strategies alone [7, 8, 22, 23]. A successful rise and walk for these frail individuals requires alternative strategies and supports [23, 24]. These inconsistencies in biomechanical metrics, along with the limiting protocols, present the need for a new framework for evaluation of real-world STW of the frail elderly.

2.2.1 STW Biomechanical Method

In order to study the complex STW movement, simplified methods have been created that reflect a healthy egress. These STW methods describe phases that include joint flexion, followed by a momentum transfer through rotations about the hip, knee, and ankle joints into extension, and end with gait initiation [18, 25]. Magnan et al. were the first to publish on combining the sit-to-stand task with gait initiation [17]. They identified that a healthy STW was not merely a sequence of two separate tasks but, a merging of the two [17]. Later, Kerr et al. developed a STW method with 4 defined phases: flexion, extension, unloading, and stance, the former three phases potentially overlapping (Figure 2.2) [18].

Kerr's STW phases are defined by 6 key events: initiation, seat-off, peak vertical velocity, gait initiation, swing toe-off, and stance toe-off. Initiation is defined as the first instance that the vertical ground reaction force changes (>2SD) from the mean vertical ground reaction force recorded during the first second of quiet sitting. Seat-off is defined as the moment when peak vertical ground reaction force occurs. Peak vertical velocity is determined using the Center of Mass velocity. Gait initiation is the instance when the mediolateral force exceeded 5.6% of the subject's body weight. Swing toe-off is identified at the peak velocity of the center of pressure in mediolateral direction. The stance toe-off is identified at the instance when the vertical ground reaction force of the stance foot is equal to zero.

Kerr's simplified method has been used by others [6, 14]. Buckley et. al. compared STW of a healthy population to one with Parkinson's Disease. Buckley noted that the PD group did not fit Kerr's method of overlapping STW phases but, rather, the PD group consistently had a gap between the extension and unloading phases [6]. Buckley and others have suggested that further investigation is needed to understand the real-world biomechanical movement of the frail STW [9, 26-28].

While Kerr's Method is sufficient when evaluating lower limb and torso biomechanical metrics for the healthy population, it has limitations and assumptions that prohibit use with the frail population. Limitations include protocols that severely hinder successful rise of the frail by restricting upper and lower extremity use [17, 21, 25, 26]. Typical STW methods require the subject to cross their arms over their chest throughout the duration of STW. These methods also set ankle, knee, and hip angles, giving no freedom to reposition extremities to decrease the required torque, such as shifting feet backward toward the center of mass (CoM). Furthermore, assumptions are made that do not reflect reality for the frail, such as vertical ascension during seat unloading[29], bilateral symmetry[30], and/or temporal overlapping of extension and gait initiation phases[18]. While healthy individuals with strong muscle synergies are generally able to follow these strict protocols[22], frail elderly individuals who have decreased strength employ a variety of nonconforming STW strategies that result in asymmetrical use of extremities, among other postural differences[23, 24, 30]. In fact, several STW studies have concluded that the frail elderly STW, hereafter referred to as the sit-to-stand-and-walk

(STSW) [23, 31], should be considered a distinct task, differentiated from the healthy STW, and should be further investigated [30, 32-35]. A new STSW method that reflects actual frail performance is needed.

2.2.2 STW Performance Evaluation Metrics

STW performance evaluation consists of a wide variety of biomechanical metrics depending on the aim of the particular study. Some of the most common biomechanical metrics used to evaluate STW performance include power [36-38], joint angles [39], joint moments [37, 38], foot position [26, 40], center of mass (CoM) position [17, 40, 41], CoM peak acceleration [42], CoM momentum [43], and jerk [44]. Strict STW protocols, such as no upper extremity use, provide the context to obtain focused information on the torso and lower extremity biomechanics during STW. In addition, STW performance evaluation often includes assumptions to simplify the STW analysis, such as dual lower extremity symmetry. Unfortunately, such simplifications do not reflect an actual real-world STW performance, particularly for frail individuals whose egress movement is often asymmetrical and dependent on upper extremity use. In order to evaluate real-world performance of the frail elderly during self-selected egress, a new framework is needed.

2.3 Sit-to-Stand-and-Walk (STSW)

The Taylor STSW Biomechanical Model is based on observations from prior research that indicate the elderly use upper and lower extremities to compensate for lack of strength and/or other limitations [36, 45-49] and is validated by this research. At a minimum, the natural, self-selected STSW requires a framework that includes upper extremity use. While there have been previous studies that have evaluated natural STSW movement of the elderly in the course of activities of daily living [44, 50], their study primarily focused on identification of the location of elderly falls within the course of daily movement, including STSW generally. To the best of our knowledge, our STSW studies are the first to have evaluated unrestricted STSW movement during hospital bed egress that evaluates each STSW phase [23, 51, 52]. This research addresses the additional phases and characteristics specifically of STSW from a hospital bed.

2.3.1 STSW Biomechanical Model

In order to fill the gap in current literature and to provide a framework to analyze elderly egress, a STSW biomechanical model along with appropriate evaluation metrics are developed as part of this research. Based on consistently observed behaviors among frail elderly in past STW studies, the use of upper and lower extremities and the characteristic of pausing prior to initiating gait [20, 23, 53] are incorporated into the Taylor STSW Biomechanical Model. First, in order to account for movement that occurs prior to initiating a stand, the Stand Preparation Phase is added to the model. These movements include postural shifting while seated, such as scooting or bouncing which have been shown to be linked with falls (Appendix B). Also included are assistive hand placements and/or feet repositioning. Hand placements include contact with the bed, bedrail, or thighs. Feet repositioning includes both anterior-posterior and medial-lateral movement. These hand and feet movements during alternative egress strategies, including bouncing and scooting during the preparation phase, are collectively referred to as Corrective Behaviors (CBs) and are defined as intentional positional movement of hands or feet that results in modification of performance posture to maintain or regain balance. Second, to account for pausing prior to initiating gait, the Stabilization Subphase is added as part of the Stand Phase. Thus, the STSW biomechanical model includes five phases (Stand Preparation, Stand Initiation, Stand, Gait Initiation, and Gait) and two subphases (Failed Stand Initiation and Stabilization) (Figure 2.3). For the purposes of this research, only the Gait Initiation Phase was included, not the Gait Phase.

Current STW metrics used to define phases for healthy individuals are not sufficient for STSW. Kerr uses the change in vertical ground reaction force as the starting point for STW. For a healthy rise, this has been shown as a reasonable metric; however, for a person applying force with their feet on the floor to assist in shifting before standing, this is not an appropriate metric for the start of the rise. In addition, it was observed that some elderly the ground. Another reason why vertical ground reaction force is not an appropriate metric for the start of STSW.

Kerr then uses peak ground reaction force as the metric for determining seat-off. This metric cannot reliably indicate seat-off when the subject uses upper extremities to assist in the rise, thus not placing as much weight through their feet at seat-off. In addition, if the subject uses their feet to assist in bouncing prior to standing, the peak ground reaction force may occur during bouncing, not at the seat-off just before standing.

Kerr then uses peak vertical velocity to indicate the end of the extension phase. This is not a reliable metric for STSW due to reversals prior to the maximum extension as a result of falls, catches, or reach-back touches.

Next, Kerr uses the instance when the mediolateral force exceeded 5.6% of the subject's body weight as gait initiation. Again, this is an unreliable metric for STSW due to upper extremity use and/or corrective steps taken prior to initiation gait, where the full body weight of the subject is not on their feet and certain strategies employed may not result in a significant mediolateral ground reaction force.

The remaining two metrics for swing foot and stance foot toe-off use different metrics. Swing toe-off is identified at the peak velocity of the center of pressure in mediolateral direction, while stance toe-off is identified at the instance when the vertical ground reaction force of the stance foot is equal to zero. Again, both the peak velocity metric and the zero ground reaction force are unreliable as the same instance may reflect a corrective step taken by the subject prior to initiating gait, for example.

In order to identify the beginning and ending of each STSW phase and subphase, both biomechanical criteria and visual observation metrics were selected. Due to the large variability in the self-selected egress strategies among subjects, biomechanical metrics alone cannot identify key events. Both metric types must be used to differentiate between similar movements that are used for different purposes during STSW. For example, both scooting and initiating rise from a seated position use flexion followed by extension and, if followed by an unsuccessful rise, have strikingly similar biomechanical characteristics. However, the sublime differences can be identified through visual observation of the STSW performance based on overall movement and resulting outcomes that follow. STSW key events are described in Table 2.1 and are used to define STSW phases in Table 2.2. The Taylor STSW Biomechanical Model is representative of the real-world egress performance of frail individuals and provides a framework for evaluation of STSW performance.

The Taylor STSW Biomechanical Model is representative of the real-world egress performance of frail individuals. Described by key events that define the STSW phases and subphases, this method provides a framework for evaluation of STSW performance. By applying the Taylor STSW Biomechanical Model to the real-world frail, elderly egress, analyses can be done not only on the egress biomechanics of the successful portion of the rise to walk (SI to S_w), but also the preparatory movement (SP to FSI or SI), any failed rise attempts (FSI to SI), and any pausing that may occur (ZHV to S_w). The Taylor STSW Biomechanical Model provides information that helps to diagnose more specifically and, therefore, may provide more timely and effective intervention. **In addition to reflecting real-world elderly egress, the Taylor STSW Biomechanical Model provides a framework whereby key events of both healthy and frail individuals, can be applied consistently for cross study comparisons.**

Figure 2.4 shows an example of a high fall risk subject performing STSW. This ample includes scooting as a preparatory movement, along with two unsuccessful attempts at rising where the subject fell back to the bed (Fall1 and Fall2). This was followed by a successful rise, pause (ZHV to S_w), and initiation of gait. The center of mass forward velocity (CoM_y) and the mediolateral ground reaction force are also shown for comparison to the Kerr STW Method.

2.3.2 Selecting Metrics to Evaluate STSW Performance

Now that the Taylor STSW Biomechanical Model is developed with key events defined, we consider biomechanical metrics and observable quantitative data to evaluate STSW performance. Due to the complex and varied movement among STSW strategies, traditional STW performance metrics, such as joint angles and peak vertical CoM velocity, would not be sufficient to determine successful rise and walk. Rather, metrics should be selected that can assess dynamic stability of STSW.

Drawing on past evaluated biomechanical metrics for STW, STS, and Gait analyses, several metrics were considered for use in STSW evaluation. One of the first biomechanical metrics considered as a measure of dynamic stability was the base of support (BoS) and the position of the CoM relative to the participant's BoS perimeter (Appendix A) [51]. The BoS is the projected area defined by the points in contact with either the ground or another supportive surface. For standing, this is simply the area between and including one's feet when there are no other points of contact. The calculation of the BoS becomes more complex with more bodily features in contact with multiple supporting surfaces. For this research, the BoS was calculated in Visual 3D using the 2-dimensional convex hull method [54]. The convex hull is computed using the vertically projected reflective marker positions that are in contact with a surface (Figure 2.5). The results from the convex hull method were verified by using Heron's formula (3.1) [55] to compute the area of each triangle (K_i) based on the length of the three sides (a_i, b_i, c_i) and the semi-perimeter (s_i) in terms of the side lengths. This is done by taking the sum of all triangle areas, as follows:

$$\sum_{i=1}^{n} K_i = \sqrt{s_i(s_i - a_i)(s_i - b_i)(s_i - c_i)}\text{, where } s = \frac{a+b+c}{2} \tag{3.1}$$

Substituting in terms of the side lengths a, b, and c, for s_i, the sum is calculated using only the side lengths (3.2).

$$\sum_{i=1}^{n} K_i = \sqrt{\left(\frac{a_i + b_i + c_i}{2}\right)\left(\frac{-a_i + b_i + c_i}{2}\right)\left(\frac{a_i - b_i + c_i}{2}\right)\left(\frac{a_i + b_i - c_i}{2}\right)} \tag{3.2}$$

The final form of Heron's formula that was used to calculate BoS is equation 3.3.

$$\sum_{i=1}^{n} K_i = \frac{1}{4}\sqrt{2{a_i}^2{b_i}^2 + 2{a_i}^2{c_i}^2 + 2{b_i}^2{c_i}^2 - \left({a_i}^4 + {b_i}^4 + {c_i}^4\right)} \tag{3.3}$$

Calculated values from Heron's formula confirmed that the convex hull method within the Visual 3D software program was giving correct values for the BoS area.

Traditionally, to determine instances of imbalance, the CoM position relative to the BoS perimeter is calculated to identify the point of imbalance, or instance when the CoM crosses over the BoS perimeter. Unlike when standing on two feet, where the point of imbalance can easily be determined, a pilot study by the author [51] confirmed an earlier study by Maki [35] that the CoM is maintained well within the BoS perimeter during STSW. Thus, CoM exceeding the BoS perimeter was not an effective metric for assessing stability during STSW.

Rather than a biomechanical imbalance, as humans age, experience disease, or encounter a debilitating injury, their decreased strength, along with environmental factors, influence STSW performance. Previous studies have shown that successful sit-to-stand is associated with strength of the knee extensor/flexor muscles, the ankle flexor muscles and with joint motion, balance, proprioception, reaction time and tactile sensation [56, 57]. Several metrics were evaluated and were found not to correlate with falls, including normalized forward angular momentum, anterior-posterior distance between forehead and mediolateral center point between feet, torso angle and temporal metrics, such as CoM Time to Contact, STSW duration and individual phase durations. These metrics appear to be more closely linked with the egress strategy which may not be directly correlated to falls. Current literature indicates that the most commonly observed elderly STW characteristics associated with poor egress performance are upper extremity use, pausing, and lack of continuous, smooth movement [23, 58-61]. Based on the previous findings, discussion, and these observations, three metrics were selected to assess dynamic stability of STSW: corrective behavior (CB) use, pausing prior to gait initiation, and high jerk magnitude.

Contrary to traditional views, the use of corrective behaviors are not just a last resort to regain balance, but they are often initiated well before the CoM is near the stability limits of the BoS [35] (Appendix A.1). Corrective Behaviors (CBs) are defined as an intentional positional movement of hands or feet that results in modification of performance posture to maintain or regain balance. CB counts are used as a quantitative measure of instability, with higher counts indicating a greater in instability. Unlike the healthy blending, even overlapping, of rising and walking by healthy individuals, frail individuals separate the two tasks. This separation often includes pausing between the two tasks. Pausing, therefore, was selected as a metric of instability. Also, unlike the healthy STW, physical movement of the frail elderly is less coordinated and less smooth-flowing. Smooth movement indicates a subject's ability to maintain stability by controlling postural changes through dynamic forces [62, 63]. One measure of unsmooth movement that has proven useful in motor control studies is jerk, defined as the rate of change of acceleration or the third time-derivative of position with respect to time (3.4) [64, 65].

$$jerk = \frac{da}{dt} = f'''(t) = \frac{d^3s}{dt^3} \tag{3.3}$$

Previous biomechanical studies have shown that jerk is associated with real-world imbalance and falls [28, 44]. One study demonstrated the use of $jerk^2$ as an indicator of a fall initiation point [58]. By squaring the jerk magnitude, the value is always positive and the difference between low and high jerk is magnified to more readily identify unsmooth movement. Normalization of jerk was considered; however, unlike ground reaction force, for example, where a person's body weight is directly related to the resulting ground reaction force, distance and time are not directly related to a subject's anthropometrics. Instead of normalizing the metric, the statistical methods used take into account subject variation. With this in mind, $jerk^2$ is included as a metric of instability.

2.4 Results and Discussion

An initial review of all 74 elderly subjects in our study revealed that not only did the frail subjects fit the Taylor STSW Biomechanical Model, but also the healthy elderly. Even the healthy, low fall-risk elderly individuals (n=12) had some demonstration of STSW characteristics. In fact, 98.6% of all participants in our study, including healthy LFR, fit the Taylor STSW Biomechanical Model better than the STW method due to extremity use in the Preparation and/or Stand Initiation Phases, since STW protocols restrict the use of upper extremities.

To demonstrate the usefulness of the Taylor STSW Biomechanical Model in better understanding elderly movement during egress, Figure 2.6 compares the Kerr and Taylor Methods by superimposing results from a representative healthy individual (black curves) with a frail individual (red curves), respectively. Due to strict STW laboratory protocols, any potential preparation performed by the healthy individual is unknown and, thus, cannot be compared to the frail STSW. What can be compared is the successful egress of both subjects. Since Kerr does not include the timing of events, we cannot compare directly, but only curvature trends. Healthy and frail performance curves are aligned at the Stand Initiation point for both subjects. Recall that for the STW, stand initiation is marked at the change in vertical ground reaction force greater than 2SD from quiet sitting. For STSW, stand initiation is marked at the sagittal plane torso flexion change of 5° prior to a successful seat off. Potentially, both of these metrics could be occurring at initiation; however, it is likely that the torso flexion of the STSW subject occurs slightly before the vertical ground reaction force of the STW subject. Either way, we can see that the healthy individual STW is shorter than the frail individual's attempt. The frail subject scoots and bounces in preparation to stand. This is followed by torso flexion, initiating a failed stand due to falling back to the bed. This rising and falling back to the bed is repeated, then a successful rise is achieved with the third attempt. It is interesting to note, though not surprising, that both the mediolateral force magnitude and the forward velocity magnitude for the healthy subject are greater than that of the frail individual, as the more frail subject is likely moving slower and likely has less muscle strength, among other potential difference, such as weight. Also note that the frail individual pauses for roughly four seconds upon rising and before initiating gait.

Another comparison can be made between the healthy STW and frail STSW forward center of mass (CoM) velocity. The forward velocity increases with a slight slowing during extension followed by increasing velocity through gait initiation for the healthy STW. For the frail individual, forward velocity starts slowing with flexion at stand initiation and continues to slow through seat-off until there is a reversal of CoM forward movement, followed by an increase in velocity of forward movement again due to anterior-posterior sway prior to initiating gait. The difference between subjects in the change in forward velocity may, in part, be due to the difference in the definition of SI. While Kerr uses the peak GRF to define SI, this research has defined SI as the point at which a 5º change in forward torso flexion angle prior to successful seat-off. It is not known if these two events align, but is used here only for general overall STW/STSW comparison purposes.

Superimposing a healthy LFR elderly subject egress trial onto a frail HFR elderly subject egress trial, both from this author's research study (Figure 2.7), demonstrates a clearer temporal representation of real-world elderly egress. Here we can see that the forward velocity of the LFR subject peaks at more than double that of the frail subject. The successful SI-SO duration is practically identical for both the frail and healthy individual though the two metrics both have higher magnitudes for the HFR subject. The mediolateral force is positive for the HFR, yet negative for the LFR, indicating that while the HFR subject is pushing more medially, the LFR subject is pushing more laterally. The peak horizontal forward velocity occurs near SI for the HFR subject; however, for the LFR subject, the peak occurs after seat-off. Forward velocity of the LFR subject peaks at more than double the magnitude of the frail subject.

This is an example of the comparisons that can be made using the Taylor STSW Biomechanical Model , not only for frail individuals, but also healthy and everyone in between. As individuals age, there is a decrease in neuro-musculoskeletal coordination and function. Using the Taylor STSW Biomechanical Model , future research may identify specific changes in STSW that correlate with a frailty continuum.

2.5 Conclusion

The proposed Taylor STSW Biomechanical Model provides the framework for evaluating egress of the elderly, both individuals considered to be healthy and those that are frail. STSW consists of five phases: Stand Preparation, Stand Initiation, Stand, and Gait

Initiation, and Gait Phases, and two subphases: Failed Stand Initiation and Stabilization. Key events define the start and end of each phase and subphase. Evaluation criteria for STSW performance includes number of CBs, pausing prior to initiating gait, and jerk^2.

Traditional methods used to understand STW do not apply well to the elderly population. The Taylor STSW Biomechanical Model provides a more complete characterization of elderly egress and, thus, enables egress performance classification beyond simply 'abnormal'. With a clearer, more detailed, understanding of elderly egress movement, specific, individualized intervention may prove to be key in reducing falls. As observed in literature, there appears to be an onset of these characteristics as an individual ages and may be an indicator of frailty level and frailty progression [66, 67].

In addition to providing a framework that can be used as a standard for comparison across STSW studies, this model can also be mapped onto STW studies for comparison of successful Stand Initiation, Stand, and Gait Initiation Phases which may also provide insight into the progression of frailty. The Taylor STSW Biomechanical Model provides the framework for the remainder of this research, in which a fall-proxy is identified for use in laboratory studies and key factors in predicting falls are identified.

The implications of the ability for researchers and clinicians alike to classify egress performance level is far reaching. By providing missing information, the Taylor STSW Biomechanical Model increases understanding of movement during egress and the potential for fall-risk. Fall intervention methods could be more appropriately determined, given the specific type and timing of the dysfunctional movement during egress. Therefore, further investigation of STSW is merited on the basis of this new knowledge.

2.6 References

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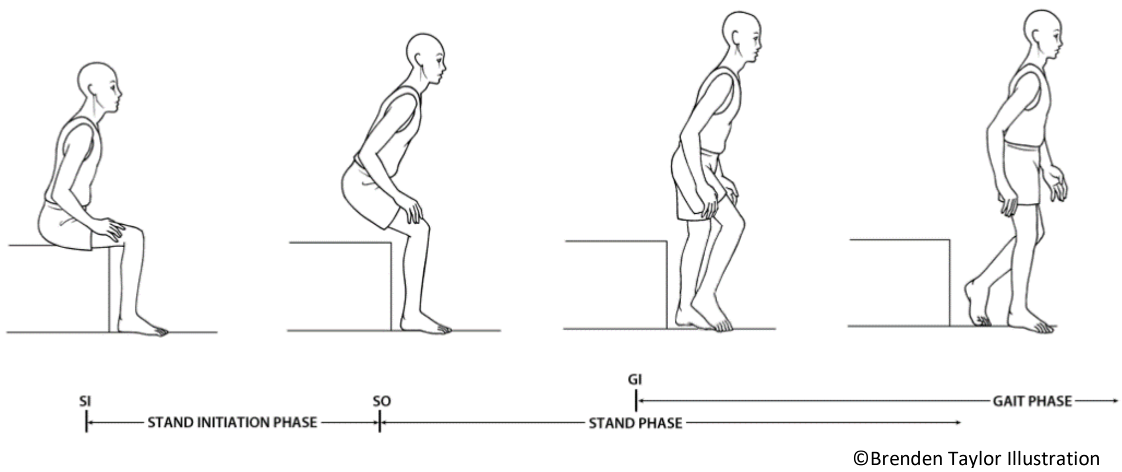

Figure 2.1 Generally accepted STW phases: flexion/stand initiation phase, extension/stand phase, and gait phase with overlap between extension and gait.

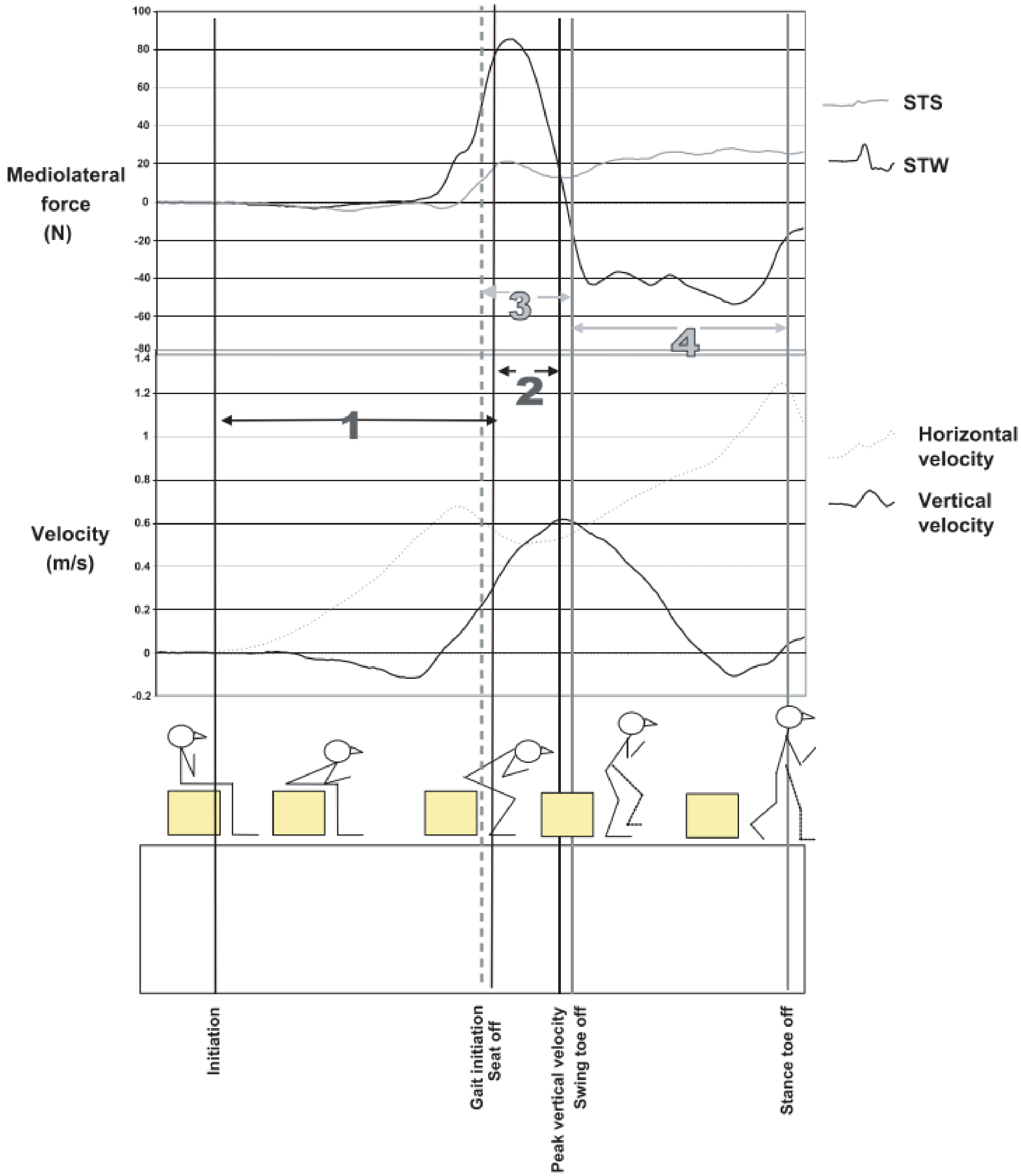

Figure 2.2 Kerr STW method with example performance of one subject.
Reprinted from Clinical Biomechanics, 19(4), Andy Kerr, B. Durward, and KM Kerr, "Defining phases for the Sit-to-Walk movement", pp. 385-390., 2004, with permission from Elsevier.

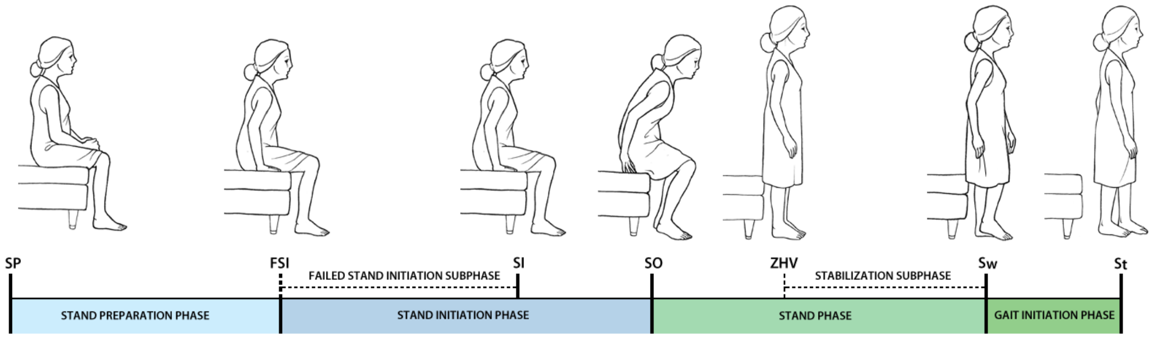

Figure 2.3 Taylor STSW biomechanical model with stand preparation, stand initiation, stand, and gait Initiation phases and failed stand initiation and stabilization subphases.

Table 2.1 Definition of key events during STSW

Key Event	Abbrev.	Definition	Metric
Stand Preparation	SP	Instance of first intentional movement following audible signal to perform bed egress that is not SI. This movement may include bouncing, scooting, or other adjusting prior to flexion to stand. This movement does not include tremors, shaking, or other unrelated movement; beginning of Stand Preparation Phase	Visual determination
Stand Initiation	SI	Instance of intentional torso flexion to rise. This is followed by a successful rise; when there are no falls, it marks the end of Stand Preparation Phase; when there are no falls, it marks the beginning of Stand Initiation Phase. Provides a similar point of biomechanical and temporal comparison with healthy SI.	Visual determination, torso angle increase from vertical of ≥5° just before instance
Seat-off	SO	Instance when buttocks is no longer in contact with seat surface following SI. This does not consider leg contact against bed surface for support; beginning of Stand Phase	Visual determination
Failed Stand Initiation	FSI	In the case where a subject falls back to the bed, the FSI is the failed stand initiation which leads to a FSO. In order to stand, another SI-SO attempt will need to be made.	Visual determination
Failed Seat-off	FSO	In the case where a subject falls back to the bed, the FSO is the failed seat-off. In order to stand, another SI-SO attempt will need to be made.	Visual determination
Zero Horizontal Velocity	ZHV	Instance when forward motion stops or reverses direction (crosses zero threshold) following successful rise and prior to gait initiation, as measured by center of mass forward velocity; beginning of Stabilization subphase	$v_{CoM_y} = 0$
Swing Foot-off	Sw	Instance where subject takes their first intentional forward step to begin gait initiation phase. This may or may not follow corrective step(s); beginning of Gait Initiation Phase	Visual determination and $F_{Sw_z} = 0$
Swing Foot-contact	FCSw	Instance where the subject first makes foot contact with the floor with their swing foot following Sw	Visual determination and $F_{Sw_z} > 0$
Stance Foot-off	St	Instance where the subject takes their second intentional forward step to continue gait initiation. This may or may not follow corrective step(s)	Visual determination and $F_{St_z} = 0$
Stance Foot-contact	FCSt	Instance where the subject first makes foot contact with the floor by their stance foot. This ends gait initiation	Visual determination and $F_{St_z} > 0$

Table 2.2 STSW phases and subphases with start and end key events

STSW Phase or Subphase	**Start**	**End**
Stand Preparation Phase	SP	SI
Stand Initiation Phase	SI	SO
Stand Phase	SO	GIFOSw
Stabilization Subphase	ZHV	GIFOSw
Gait Initiation Phase	GIFOSw	GIFCSt

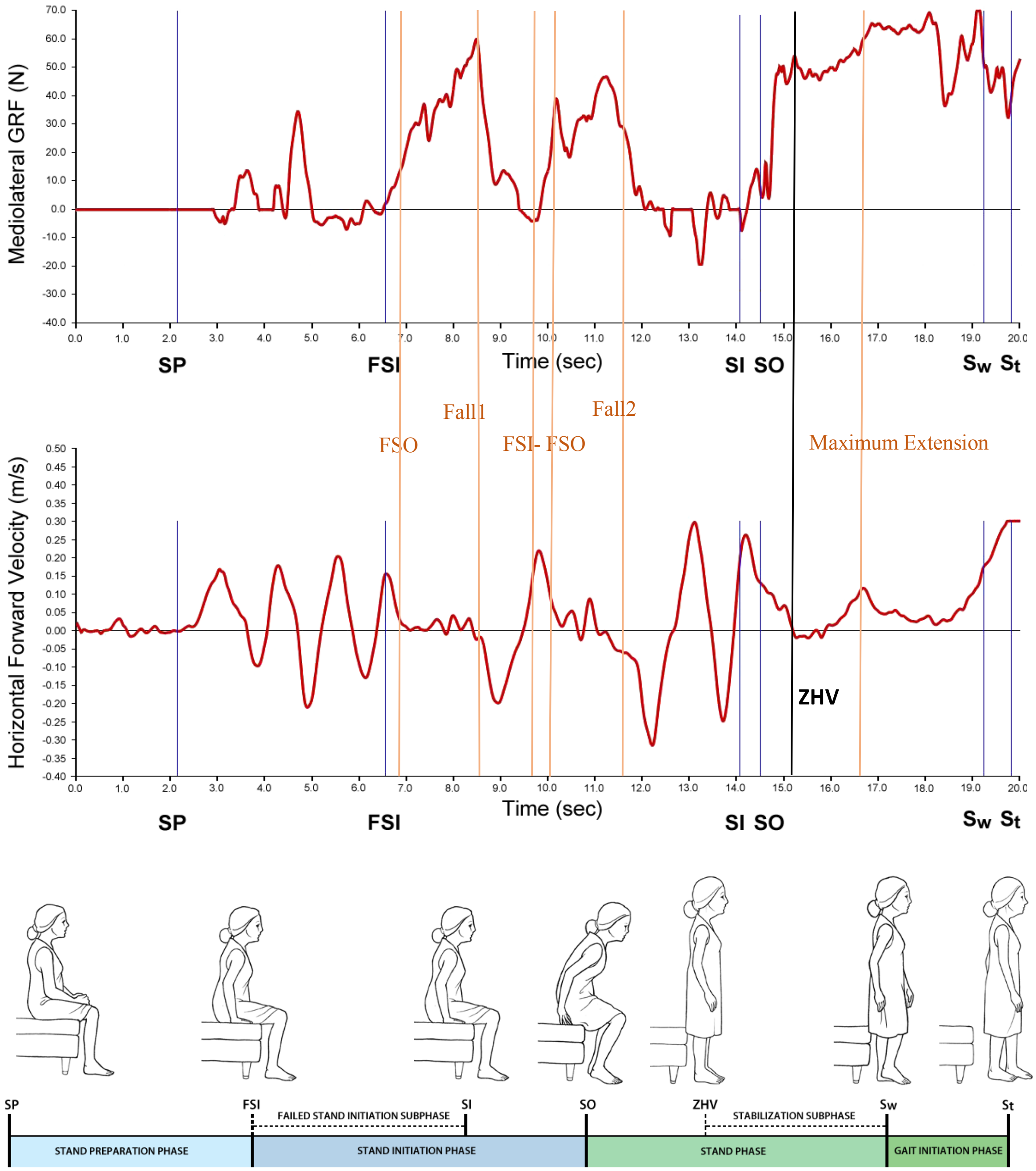

Figure 2.4 Taylor STSW biomechanical model with example performance of HFR subject during LB egress. This trial has scooting prior to two falls back to the bed (Fall1 and Fall2) followed by a rocking/bouncing movement before successfully rising. There is also pausing marked by ZHV to Sw, with the maximum extension point noted.

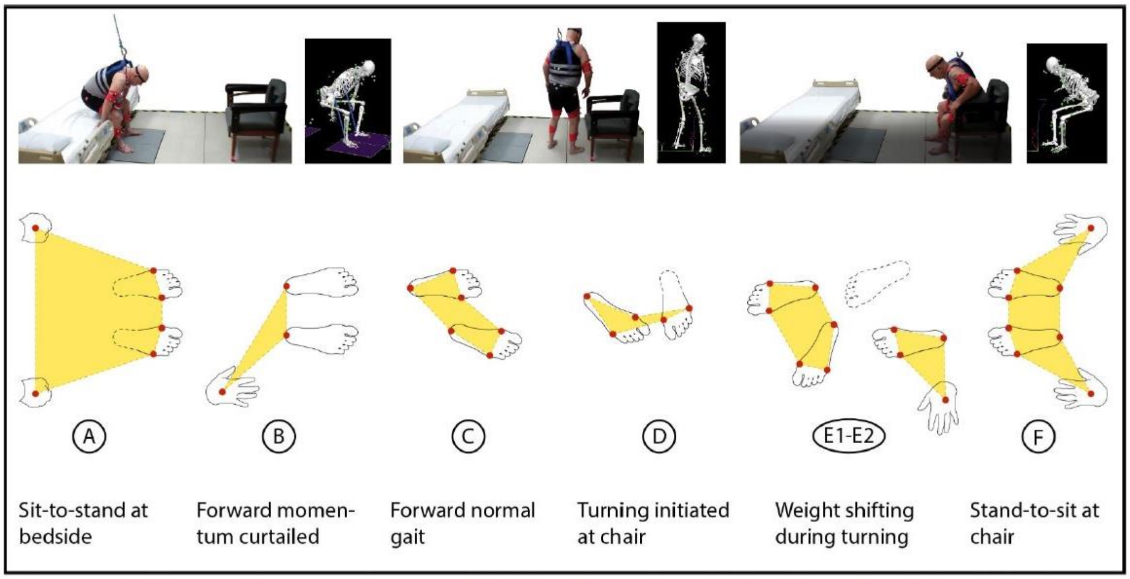

Figure 2.5 Changing base of support area (yellow) defined by points of contact (red dots) during full length trial of bed egress, walk, turn and chair ingress (A-F).

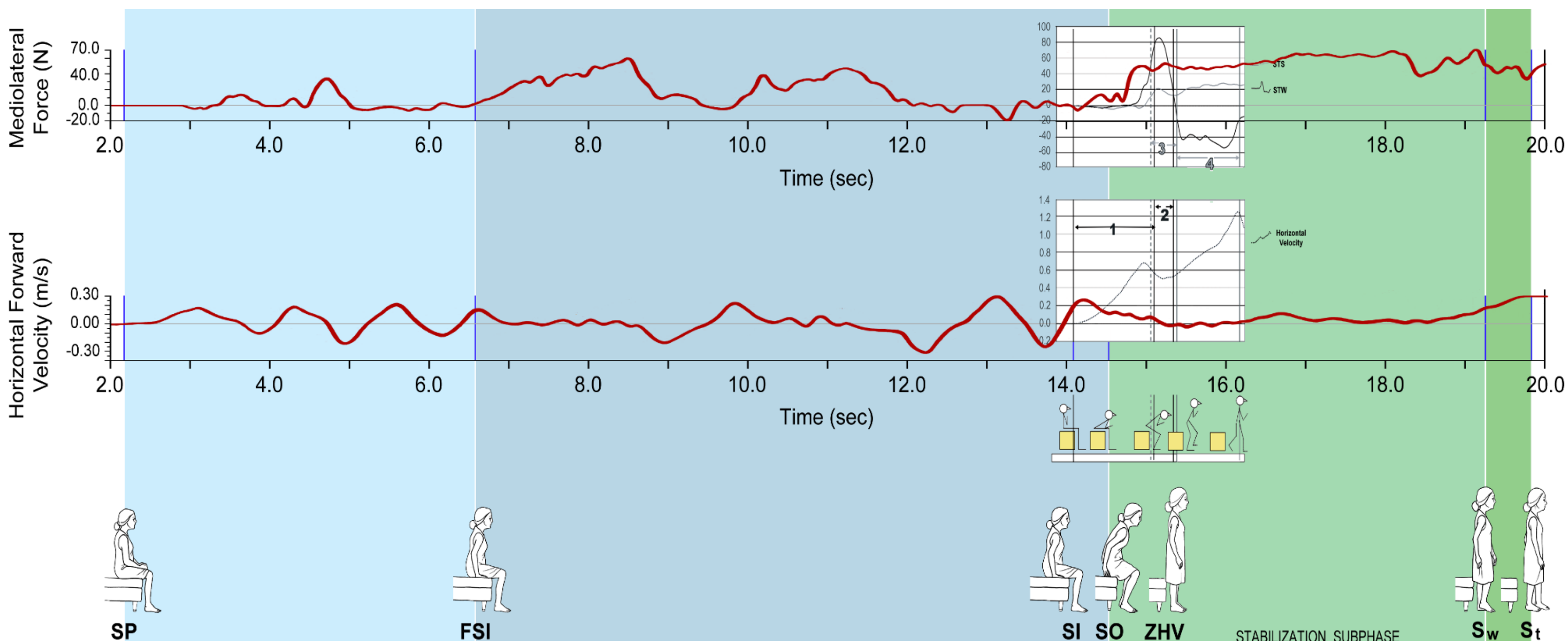

Figure 2.6 Superimposed Kerr/Taylor models with representative individual STW/STSW data. Key events and phases are labeled for STSW. GIP is the Gait Initiation Phase. SI for STW and STSW are synced, with the remaining events relative to that.

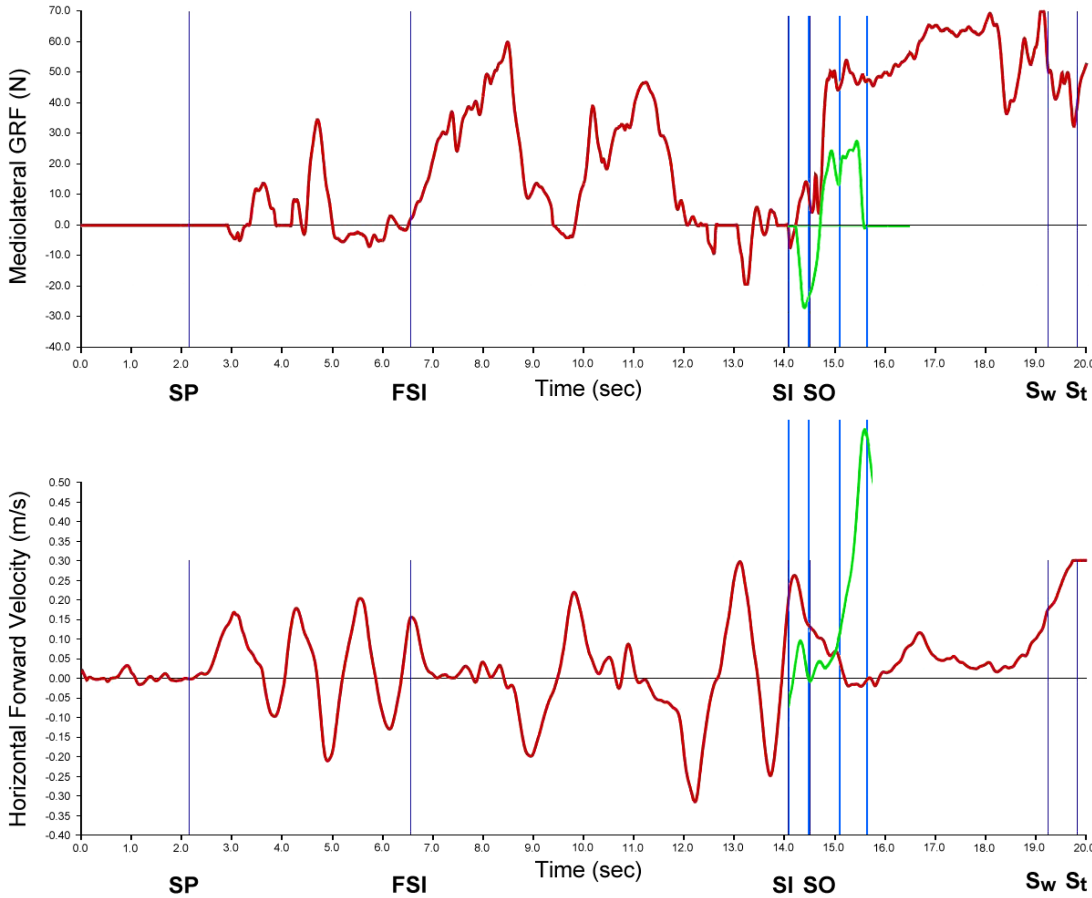

Figure 2.7 Horizontal Forward Velocity and Mediolateral GRF for LFR, HFR subjects
LFR LB trial (green) superimposed over HFR LB trial (red) synced at SI.
forward velocity of the LFR subject peaks at more than double that of the frail subject.

CHAPTER 3

THE NATURAL SIT-TO-WALK OF THE FRAIL

In this chapter we investigate the self-selected sit-to-walk (STW) of the frail. Unlike the traditional methods for evaluating healthy STW, where strict protocols negate the use of arms and hands[1], this study allows the high fall-risk participants to employ full use of their upper and lower extremities during a variety of bed egress trials. Corrective Behaviors (CBs) and STW key events are defined. A coding method is developed that identifies CBs and key STW events through visual observation. These coded events, combined with the 3D biomechanical model generated from collected marker position data, provide the foundation of collected data for kinematic analysis throughout this dissertation. This chapter found that Aim 1 Hypothesis 1.1: Persons at high fall-risk (MFS≥55) employ a self-selected STW strategy that requires multiple corrective behaviors (CBs) prior to the first traditionally established STW phase (Flexion-Momentum, or Stand Initiation Phase) in order to achieve a successful STW is fully supported.

This part of the dissertation was presented at the ASME International Mechanical Engineering Congress & Exposition 2019, Salt Lake City, Utah.

This research was primarily completed by myself, under the guidance of Dr. Andrew Merryweather, Dr. Janice Morse, and Dr. Bob Wong. Coding was performed by undergraduate research assistants Parker McAdams and Savanna Bennett. Additional

assistance with post processing was provided by undergraduates Ryan Wilcox and Katrina Cernucan.

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THE NATURAL SIT-TO-STAND-WALK OF THE FRAIL

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ABSTRACT

Sit-to-stand-walk (STW) is a complex task that sequentially transitions an individual from sitting through standing to walking. In this study we evaluate the unrestricted, natural pattern of movement of the STW task from a hospital bed of 21 (5 Female, 16 Male) frail (MFS>55) adults (68.0±11.2 years) with a total of 144 unique trials. Bed height (low, medium, high) and bed rail condition (no rails, Hill-Rom®, Stryker®), were varied, generating 9 potential trial types per participant. A new STW phase, Stand Preparation, is defined specifically for the frail that occurs just prior to the Flexion Momentum Phase, also named here as the Stand Initiation Phase. In conjunction with the newly defined Stand Preparation Phase, movements used by the frail to maintain or regain balance during STW task are newly defined as corrective behaviors (CBs). These include hand, foot, leg and torso CBs. In 144 unique STW trials, 678 hand and foot CBs were observed and recorded. The most frequent CB type was the hand CB (335), followed by the foot CB (316). A coding system for use in the kinematic analysis of the natural STW task was developed that identifies CBs through visual observation. In addition, a 3D biomechanical model was generated from collected marker position data and will be used in future biomechanical analyses with the visually observed CB data. The Stand Initiation Phase contained the most CBs. Significant factors included bed height and phase, as well as their interaction (all with p-values≤0.006). This is the first study to establish a more accurate and complete STW of the frail elderly, as well as to define CBs employed during their natural STW. The dataset from this coding system, along with the newly established STW phases of the frail, are currently being used for further analyses to determine the exact timing and position of fall initiations during STW of the frail.

Keywords: sit-to-walk, sit-to-stand, sit-to-stand-walk, frail, fall

1. INTRODUCTION

As the frail elderly population continues to increase, falls among the frail are becoming a major public health concern worldwide. [1,2] Recent fall research has identified the sit-to-stand-walk (STW) task as a high-risk task where falls are most likely to occur among the frail elderly. [3-7] As a result, an understanding of the STW process in frail individuals, including the elderly, would have substantial impact on overall injury and lifespan, and is therefore a research area of high interest.

STW is a complex task that sequentially transitions an individual from sitting through standing to walking. The task of STW for healthy subjects has been previously described by Kerr in four phases: flexion momentum, extension, unloading, and stance. [8-10] Healthy adults tend to perform the STW in one smooth motion. As they stand, around the point of seat-off, they are able to use the horizontal momentum to carry them through to gait initiation; they continue to move upward and forward simultaneously.

However, distinct differences between the STW process in healthy and frail individuals have been reported. For example, Buckley, et. al. reported that the frail perform various movements before they even initiate standing that have not been observed in healthy subject studies. [11-12, 18] These preparatory movements vary depending on the type of STW strategy employed, but include things such as scooting to the edge of the bed/chair, bouncing, and grasping and/or applying force with one or both hands to support rising. In addition to these preparation movements, the frail do not have a continuous motion from seat-off to gait. Rather, the frail rise to stand and then stop forward motion prior to initiating gate. [11-15] Hence, the frail perform the STW task in two distinct sequential tasks: first, sit-to-stand (STS), followed by a distinct pause and then gait initiation (GI). [11] Such key differences between observed healthy and frail individuals indicate that the STW process must be separately studied in frail individuals.

Previous analyses of STW processes observed subjects as they performed an experimentally prescribed STW task; they were instructed to rise with hands crossed over their chest and both feet resting parallel on the floor. [8-9] However, in more natural, spontaneous STW processes, individuals have their hands and feet free to engage in behaviors to promote balance that were not included in these previous studies. Hence, it is also of high utility to track the STW process under less scripted conditions.

We have designed a series of experiments that observe the unscripted natural STW processes in subjects during egress from a hospital bed, as they rise and begin walking. Both motion capture position data and visual observation data were recorded for future analyses of individual motions during the STW process. No instructions were given to the patients about what motions or supports they should use; hence, the study can be used to describe the spontaneous movements individuals use in their natural STW process.

Here we present analyses through video observation of unscripted STW of frail individuals. We also observed corrective behaviors (CBs) not previously described. For frail individuals, such motions could help compensate for both lack of muscle strength needed for rising and lack of balance that can otherwise lead to falls. With this new understanding, using CBs as a proxy for fall in these participants, new insights into the mechanics of fall initiation and fall risk may be obtained.

2. METHODS

2.1 Participant Selection

Participants were recruited by staff referral from the University of Utah Medical Center, the George E Whalen Medical Center (VA), and the local community.

Inclusion criteria included:

1. Morse Fall Scale score: MFS >55 for frail elderly
2. Able to stand at bedside and walk without assistance, including assistive devices for 10 feet

Exclusion criteria included:

1. Unilateral strength deficits >25%
2. Lower limb amputation
3. Medical conditions that preclude the use of the safety system for falls prevention (i.e., osteoporosis, morbid obesity)
4. Cognitive impairments that preclude giving informed consent or following simple instructions to perform bed egress

This study included 5 (23.8%) female and 16 (76.2%) male with an average age of 68.2±11.2 years old. Approval was obtained from the Institutional Review Board (IRB 00107043). All subjects consented to participate in the study and to be videotaped. All participants were tethered to mitigate against a fall.

2.2 Natural STW from Hospital Bedside Setup

In order to simulate a variety of bed and rail combinations, a Hill-Rom® hospital bed was stripped and two upper side rails (Hill-Rom® and Stryker®) were retrofitted to be interchangeable with the bed. The side rails were instrumented with a multi-axis load cell (6 dof). Load cell data are used to determine the direction and magnitudes of forces being applied to the side rails by the participant.

A wooden platform was constructed along the length of the bedside with two force plates (Bertec® BP4060) installed to collect bilateral lower extremity ground reaction forces (sample rate 500 Hz). Linoleum flooring, similar to common hospital flooring, was then placed over the entire platform. A large steel frame was constructed (16'x15'x8.5') around the hospital bed and chair to secure 18 optoelectric cameras (NaturalPoint®) and 1 reference video camera.

A fall intervention safety device consisting of an iron frame (8'x8.5'x5'), with two degrees of freedom for planar translations, and a belay system was located above the bed. The belay system was connected to the patient's harness to ensure no patient would fall to the ground.

Participants rose from the bed and walked approximately 3.2 ft to a chair. A potential maximum of nine trials/participant are performed which vary the 2 parameters (bed height and side rail) each having three levels. The bed heights (low, medium, and high) were set for each subject according to their leg length. Leg length was measured from the floor to the subject's lateral condyle of the tibia. The low (LB), medium (MB), and high (HB) bed heights were calculated at 95%, 110%, and 125% of the subject's lower leg length, respectively. [20] The three rail conditions were Hill-Rom®, Stryker®, and no rail. Each unique trial, with a set bed height and rail condition, was performed in a randomized order. No assistive devices were used by the participants during the trials. Some participants were unable to complete all nine trials.

2.3 Motion Capture Data Collection

During the trials, participants wore black cycle shorts, tank top and a restraint vest. Movement was measured by optoelectric cameras recording 80 retroreflective markers placed at key anatomical landmarks on each participant. These include the sacrum, anterior superior iliac spine, knee, lateral malleolus, heel, 2nd metatarsal head, tibial wand, femoral wand, wrist, elbow, shoulder, C7 vertebrae, and clavicle. A headband secured markers on the head. A custom user interface and accompanying software was designed using Labview® (National Instruments) for analog data acquisition and synchronization with the motion tracking software (AMASS®, C-Motion Inc.).

The continuously recorded position data, along with the individual's anthropometric data, were used to define a three dimensional, 15-segment, whole-body custom skeletal model in Visual3D (C-Motion, Inc®.) Collected data were filtered with a Butterworth low-pass filter at 6 and 15 Hz, and synchronized between the 3D motion capture and the ground reaction force, respectively. All data were encrypted, and transferred via a secure RedCap server to the University of Utah College of Nursing Statistics Department and to the Merrill Engineering Building for analyses. A single video camera recorded each trial. These recordings were used when performing observational coding of key events and corrective behaviors.

2.4 New Definitions: Frailty, Stand Preparation Phase, Key Events of STW Phases, and Corrective Behaviors

Frailty is a complex subject and has been evaluated in a variety of ways depending on the context [14]. For simplicity, this study equates frailty to fall risk and uses the Morse Fall Scale (MFS) score as a measure of frailty, where frail >55 MFS. [16] All participants used for this study have an MFS>55 and, therefore, all participants are considered frail.

Based on previous studies and preliminary observations, a new STW phase for the frail is established here, named the Stand Preparation Phase. The Stand Preparatior
preparatory movement prior to the torso fl
successful stand. By defining the end of the Stand Preparation Phase in this way, the actual rise from seat-off to gait initiation can be compared between the
including biomechanical and bal

In this study, key events that indicate the beginning and end of each STW phase were visually identified and coded. They are described here.

Stand Preparation (SP): SP is defined as the first movement, which may include feet, hands, torso, etc., following directive to begin STW. This includes any physical adjustments such as bouncing, scooting, shifting, and/or unsuccessful standing (falling back to a seated position) prior to a successful stand initiation.

Stand Initiation (SI): SI is defined as torso and lower extremity flexion that is followed by a successful rise to stand. If a participant generates torso flexion that produces bouncing or scooting, stand initiation is specified as the torso flexion just prior to a successful rise to stand.

Seat-Off (SO): SO is defined as the moment just after the buttocks leave the seat surface and the majority of the participant's body weight is supported by feet and/or hands, following stand initiation.

Gait Initiation (GI): GI is defined as the first heel off (HO) by the swing foot with forward movement and the intention to walk. Other foot movements that adjust base of support prior to gait are preparatory, and are classified as foot corrective behaviors.

In addition to the key events of STW for the frail, the authors also define additional assistive movements of the frail during STW. These movements are called corrective behaviors (CBs), and are defined here as a movement performed to maintain or regain the necessary balance needed to perform a task, such as STW. In this study, these corrective behaviors have been observed to include the use of hands, feet, legs and torso. Such balance corrections generally include making contact with surfaces, such as a hand reaching to touch or grasp a bedrail, while other corrections do not, such as raising arms or a quick movement of the torso to realign the center of mass (CoM) to be more centered within their base of support (BoS).

2.5 New Method for Coding Key Events and CBs

A detailed protocol handbook for coding CBs and key events was developed and used to train 2 coders. These coders tagged all CBs and key events that indicate all STW phases of the frail for each trial video. Table 1 includes all CB types that were coded when present. These visual observations were recorded stamp in Adobe Premiere®. In
risk phase rating (1-4, with 1
ement and 4 being the jerkiest or most unstable motion) was recorded.

, both coders coded nine randomly selected
initial IRR check was performed, with a resulting good interrater consistency (Cronbach's alpha > 0.80). [17] During the coding process, two additional checks were run to check for IRR. At the conclusion of coding, all coded trials were reviewed by an expert coder to locate and correct any typos, incorrect labeling, and any other problems prior to using the codes for calculations and analyses.

2.6 Statistical Analysis of Corrective Behaviors

The total number of CBs occurring during all STW trials and its association with bed height (low, medium, high), phase (Stand Preparation Phase, Stand Initiation Phase, Stand Phase), and the interaction between bed height and phase were analyzed by regression models using generalized estimating equation (GEE) with an independent correlation structure and an identity link function. GEE is a suitable method to analyze repeated measures within an individual (correlated outcomes) and can accommodate missing values. [20] To account for individual differences in frailty we included a participant's timed up and go (TUG) as a pre-trial measure of performance.

TABLE 1. CB CODES WITH CB NAMES AND DEFINITIONS

CB Code	CB Name	CB Definition
CBFCL/R*⁺	Corrective Behavior Foot Contact (L for Left or R for Right)	Extra step, other than normal stand or gait (indicate L or R).
CBFOL/R*⁺	Corrective Behavior Foot Off (L for Left or R for Right)	Extra step release, other than normal stand or gait (indicate L or R).
CBHCL/R*	Corrective Behavior Hand Contact (L for Left or R for Right)	Hand is in intentional/force applied contact with surface, other than at rest (indicate L or R).
CBHOL/R*	Corrective Behavior Hand Off (L for Left or R for Right)	Hand is no longer in contact with surface (indicate L or R).
GIFOL/R*	Gait Initiation Foot Off (L for Left or R for Right)	First step, starting at heel/foot off, after (not including) any CB Foot (indicate L or R).

*Add an 'S' to the end of a foot code if the foot does not completely leave the floor, i.e. Slides, slips or shuffles.
⁺Any foot movement/contact prior to stand initiation or once the subject is seated will be marked as a CBF.

3. RESULTS AND DISCUSSION

To more fully investigate movements employed by frail individuals during STW, we used both visual observation and motion capture to track spontaneous movements of 144 unique STW trials involving 21 individuals. Each unique trial, with a set bed height and rail condition, was performed in a randomized order. This study reports specifically on the visual observations of STW. We observed CBs not previously described. These behaviors of the frail reflect the need to compensate for reduced balance and/or strength to achieve a successful STW.

3.1 STW stages of frail individuals

We observed and coded all movements in each of the 144 trials. These movements included 678 CBs, with the largest number of CBs occurring prior to and during the Stand Initiation Phase. This observation is key in understanding how the frail perform the STW and led us to suggest adding a new STW phase called the Stand Preparation Phase. We also observed discontinuous vertical and horizontal motion during STW of the frail, as previously reported by Buckley, et. al. [12]. We confirmed that, unlike the continuous rise and forward movement observed by Kerr [13] in healthy individuals, frail subjects pause after finishing their upward motion prior to initiating gait. This behavior increases the duration of the Stand Phase when compared to a healthy STW.

Definitions of key events that indicate the beginning and end of each phase were described in the Methods section. Proposed STW Phases include the newly described Stand Preparation Phase (SP-SI), as well as the previously described Stand Initiation (SI-SO) and Stand phases (SO-HO) (Figure 1).

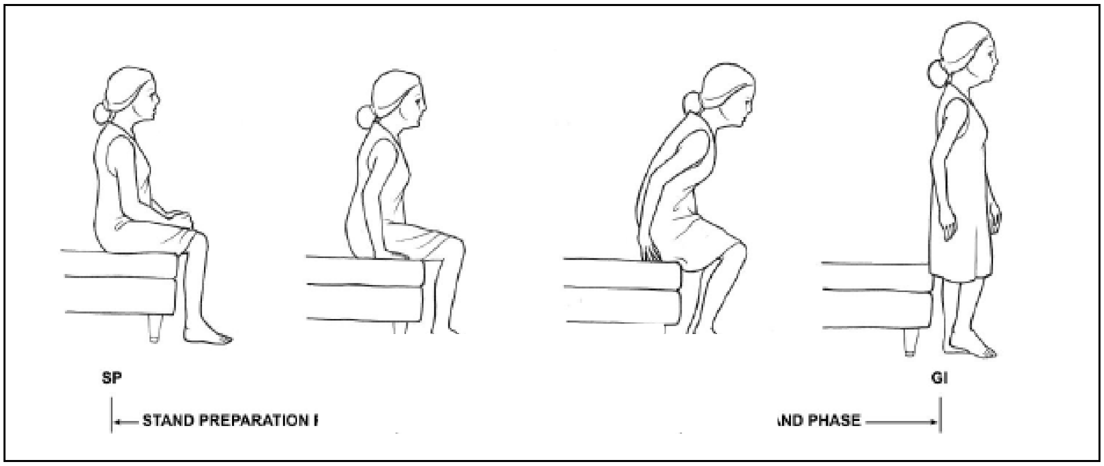

FIGURE 1. STW PHASES OF THE FRAIL WITH NEWLY PROPOSED STAND PREPARATION PHASE ©Brenden Taylor Illustration

3.2 Corrective Behaviors

Since our experimental design tracked the natural and spontaneous motions undertaken by frail individuals during the STW task, we were able to observe and quantify CBs. For frail individuals, such motions are often used to compensate for lack of strength and/or loss of balance, and include movements by hands, feet, legs, and torso. These CBs include making contact with surfaces, such as a hand reaching to touch or grasp a bedrail, while other corrections do not, such as raising arms or a quick movement of the torso to realign the center of mass (CoM) to be more centered within their base of support (BoS). Categories of CBs and the codes used to refer to them are described in more detail in the Methods section.

Since all individuals in the study can be classified as frail (MFS>55), no distinguishing correlation between MFS score (frailty) and number of CBs during STW phases can be made. However, we can draw conclusions about types and quantities of CBs per STW phase for this frail population. When the number and type of CBs are tabulated over the course of the STW process in the 144 trials, some trends emerge (Table 2).

For all 21 subjects, there were a total of 678 hand and foot CBs during the three evaluated STW phases. The greatest number of CBs occurred in the Stand Initiation Phase (343), followed closely by the Stand Preparation Phase (275), while the Stand Phase had a much lower CB count (84). Overall hand and foot CBs were similar in count (335 and 367, respectively). Whether such hand and/or foot motions would also naturally occur in healthy individuals cannot be determined, since previous studies on the STW process for healthy individuals were designed to explicitly exclude extraneous hand and foot motions.

TABLE 2. PREVALENCE OF CBS PER STW PHASE

CB Code	Stand Preparation	Stand Initiation	Stand
CBHCL	67	70	6
CBHCLS	3	2	0
CBHCR	83	69	23
CBHCRS	5	3	4
CBFCL	38	66	27
CBFCLS	22	35	3
CBFCR	38	67	17
CBFCRS	21	31	4
TOTAL = 678	275	343	84
Total Hand CBs = 335	158	144	33
Total Foot CBs = 367	117	199	51

The prevalence of total CBs as a function of bed height (Figure 2) illustrates the interaction between bed height and phase for the total average number of corrective behaviors. As expected, a low bed results in a higher number of CBs in each STW phase, particularly in the Stand Preparation and Stand Initiation phases. This suggests that the frail largely compensate for the increased effort when standing from a low bed height prior to and during rising. It was observed that a variety of strategies were employed among the frail subjects while preparing to initiate stand, such as bouncing, scooting and/or shifting, and leg and hand placement. These different strategies employ different biomechanics that will be evaluated in a future paper.

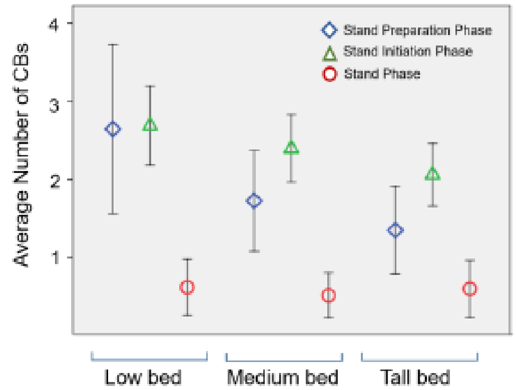

FIGURE 2. AVERAGE NUMBER OF CORRECTIVE BEHAVIORS DURING EACH PHASE OF STW, AS A FUNCTION OF BED HEIGHT. ERROR BARS REPRESENT 95% CONFIDENCE INTERVALS.

All 144 trials by 21 participants were analyzed with GEE to determine whether CB prevalence was statistically correlated with phase or bed height. Results indicate the fixed factors of bed height, phase, and their interaction were significantly related to the number of CBs (Table 3).

Estimated marginal means are included in Annex A. The estimated marginal mean in CBs is highest in the Stand Preparation and Stand Initiation Phases/Low Bed Height configuration (EMM = 2.66 and 2.7, SE = 0.61 and 0.31, respectively). The next highest measure of CBs occurred in the Stand Initiation Phase/Medium Bed Height configuration (EMM = 2.38, SE = 0.35). The least amount of variability in CBs is for the Stand Phase/Medium Bed Height configuration (EMM = 0.51, Std. Error = 0.14), followed by the Stand Phase/High Bed Height configuration (EMM = 0.61, Std. Error = 0.20). (Annex A)

Hospital beds are typically equipped with side rails. For trials with bed rails, the participants had the option of choosing to employ the raised rails as an assistive device for rising or to stabilize gait initiation. When we evaluated the significance of the presence or absence of the bed rail to the number of CBs employed, we observed no statistical correlation for any of the evaluated STW stages. In fact, only 14.3% of participants consistently employed bed rails during STW; the majority used the bed itself when employing hand CBs. As a result, employment of bed rail was not included in our model.

We also evaluated a possible link between the degree of frailty for each patient and the number of CBs employed using the Timed Up and Go test (TUG), a pre-trial measure of frailty. As shown in Table 3, TUG time is trending toward significance with the total number of corrective behaviors ($p = 0.059$). The STW process takes longer as the number of CBs increases.

TABLE 3. ESTIMATED FIXED EFFECTS FROM GEE: TOTAL CBS

	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

Covariate: TUG average (seconds)=17.59

4. CONCLUSIONS & FUTURE WORK

Unlike the healthy population, the frail use a variety of movements both to prepare for and to achieve STW. The exhibited preparation by the frail prior to rising is established as an additional phase of the STW task for the frail called the Stand Preparation Phase. Assistive movements performed by the frail during STW are classified as Corrective Behaviors (CBs) and are defined as behaviors used to maintain and/or regain balance to avoid a fall.

While previous studies have only been able to identify the STW task as a high fall risk task, we have shown the specific STW phases that have the greatest fall risk for the frail persons based on the number of CBs employed, in particular during the Stand Initiation Phase of STW. In addition, we have shown that the highest concentration of CBs employed by frail persons occurs during the Stand Initiation Phase, followed closely by the Stand Preparation Phase. The CBs used in the Stand Preparation phase possibly are used to optimize positions for standing rather than balance correction. This analysis supports the need for a new STW phase: the Stand Preparation Phase.

It is important to recall that previous studies were designed to explicitly eliminate possible hand and foot CBs, thus the assumption that normal non-frail individuals do not engage in hand CBs has not been validated. It remains to be seen whether this assumption will be born out in direct observations of normal (non-scripted) STW in non-frail individuals. We are currently involved in analyses to test the validity of this assumption.

A new method has been developed to study STW of the frail that includes both visual observation and motion capture position data. Future analyses of biomechanical measures will lead to a better understanding of strategies used by the frail during STW, including bouncing and scooting STW strategies.

These analyses and additional learning from the natural movements and adaptation strategies of the frail during STW will provide insights for rehabilitation therapy, as well as assistive product designs that can facilitate safe STW transitions during activities of daily living. In addition, interventions to reduce falls can build upon these results through use of wearable inertial sensors in natural settings that quantify movement to help assess fall risk, including changes in functional status during STW and over time. Finally, by precisely identifying the task, timing, and position of the subject when an imbalance occurs, an environment can be designed where CBs are most effective at preventing loss of balance, and thus preventing falls.

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ANNEX A

ESTIMATED MARGINAL MEANS

				95% Confidence Interval	
Bed Height	**Phase**	**Mean**	**Std. Error**	**Lower**	**Upper**
LB	Stand Preparation	2.66	0.61	1.47	3.85
	Stand Initiation	2.70	0.31	2.09	3.31
	Stand	0.64	0.22	0.20	1.07
MB	Stand Preparation	1.72	0.39	0.95	2.48
	Stand Initiation	2.38	0.35	1.69	3.07
	Stand	0.51	0.14	0.23	0.79
HB	Stand Preparation	1.36	0.38	0.60	2.11
	Stand Initiation	2.07	0.21	1.66	2.47
	Stand	0.61	0.20	0.22	0.99

CHAPTER 4

USE OF CORRECTIVE BEHAVIORS AND PAUSING DURING STSW: A COMPARISON BETWEEN FALL RISK LEVELS

4.1 Introduction

Chapter 4 applies the same data collection and analysis methods used for the high fall-risk group in Chapter 3 for a larger data set of the low (control), moderate, and high fall-risk groups [1]. This chapter specifically evaluates three hypotheses: Aim 1 Hypothesis 2: Persons at HFR pause following rise, prior to initiating gait; Aim 2 Hypothesis 1: Persons at LFR (MFS≤25) employ a self-selected STW strategy that utilizes fewer Corrective Behaviors (CBs) prior to and during all STW phases than persons at HFR (MFS≥55); and Aim 2 Hypothesis 2.2: Persons at LFR (MFS≤25) employ a self-selected STW strategy that generates continuous forward movement from seat-off through gait initiation. Results are presented, along with discussion and conclusions.

4.2 Method

Recruitment, set-up, and collection of biomechanical information follows the same method as described in Chapter 3 [1]. This study includes 74 participants classified into three fall risk groups: low (LFR), moderate (MFR), and high (HFR). Complete demographic data for all fall risk levels is reported in Table 4.1. CB counts were evaluated according to fall risk level, bed height, and STSW phase, consistent with Chapter 3.

In addition to CBs, pausing was also evaluated for differentiation between fall risk groups. Pausing has been observed in prior studies as an indicator of frailty [2]. Pausing was determined by the first instance of whole-body center of mass (CoM) anterior-posterior velocity achieving or crossing a threshold of zero following successful rise and prior to gait initiation, indicating a stopped or reversal of forward movement.

4.3 Results

4.3.1 Corrective Behaviors

The CB count results indicate that the greatest number of CBs occurs during the Stand Initiation Phase for the HFR group and are highest at the low bed condition (Table 4.2). CBs are used during the Stand Preparation Phase to assist in repositioning and rising from the bed, including, for example, any hand contact with the bed, legs, or rail. CBs are also used to adjust foot position, often to align the body's center of mass (CoM) closer to one's feet to minimize the moment required to stand. During the Stand Initiation Phase, MFR and HFR groups have an average greater than 2 CBs/trial at all bed height conditions. Both hand and feet CBs are employed to maintain and/or regain balance as the subject achieves a successful seat-off. Additionally, these CB strategies are used in multiple attempts until successful rise is achieved. The Stand Phase shows higher CBs/trial for the HFR group than LFR or MFR and is reflected in all bed height conditions. The CBs in the Stand Phase include a catch, defined as two hands contacting the bed prior to maximum extension; a touch back, defined as one hand reaching back to contact the bed or rail; and/or side or forward steps to maintain or regain balance prior to initiating gait. Overall, the highest CBs/trial occurred during the Stand Initiation Phase at the low bed height for the HFR group, the Stand Initiation Phase at the high bed height for the LFR group, and the Stand Initiation Phase at the low bed height for the MFR group.

4.3.2 Pausing

Following a successful rise from the hospital bed, elderly participants of all fall risk levels displayed some frequency of tendency to pause following seat-off and prior to initiating gait. It is possible that this pause provides opportunity to visualize the next target where they are walking to, or for the purpose of ensuring stability, or possibly both. This behavior of pausing not only increases the duration of the Stand Phase and overall STSW time when compared to a healthy LFR STW, but also leads to the possibility of over correction (rocking back on heals) leading to a potential fall. HFR individuals paused during 48.7% of their bed egress trials, while MFR and LFR individuals paused during 35.9% and 17.4%, respectively. The number of trials with pausing increased on average by 15.65% between low to moderate and moderate to HFR 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 medium bed height condition (Figure 4.1). The low bed height condition had the greatest percentage of trials with pausing for MFR and HFR levels. Consistently across all bed heights, the HFR group had the most trials with pausing, followed by the MFR group. The average pause time was greater for the HFR group, averaging 2.35 seconds at the low bed height.

4.4 Statistical Analysis

Table 4.3 summarizes the independent variables, CBs and Pause, by the categorical variable (FRE). P-values are calculated based on two methods and are indicated with a superscript: 1. Linear ANOVA and 2. Kruskal-Wallace. Both CBs and Pause are significant in predicting a Fall-risk Episode (FRE).

4.5 Conclusion

The results support H2.1. The LFR group utilizes fewer CBs during the Stand Preparation than the HFR group. However, H2.2 was not supported by the results. HFR individuals egressed with a pause in 48.7% of all trials. The LFR individuals also egressed with a pause in 17% of all trials. Similarly, MFR individuals egressed with a pause in 35.9% of all trials. While not a characteristic entirely contributable to HFR, these results indicate that the greater the fall-risk level, the more likely an individual is to pause during egress.

The results indicate that an increase in both number of CBs and frequency of pausing is associated with an increase in fall risk, and, therefore, will be included as potential contributing factors in developing the fall-proxy model in Chapter 5.

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Table 4.1 Demographics table

Fall Risk Level		**LFR MFS≤25**		**MFR 25<MFS<55**		**HFR MFS≥55**		**Total**	
Characteristic		Ave	*St Dev*	Ave	*St Dev*	Ave	*St Dev*	Ave	*St Dev*
Age (years)		66.3	*10.8*	67.9	*10.5*	72.2	*10.9*	69.3	*11.0*
		n	%	n	%	n	%	n	%
Gender	Female	3	*23.1*	11	*31.4*	8	*27.6*	22	*28.6*
	Male	10	*76.9*	24	*68.6*	21	*72.4*	55	*71.4*
MFS Score		17.9	*7.5*	41.6	*6.6*	69.6	*12.0*	48.4	*20.7*
# Trials		95		276		227		598	

Table 4.2 Average number of CBs/trial for bed height, level of fall risk, STSW 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)	2.2 (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)

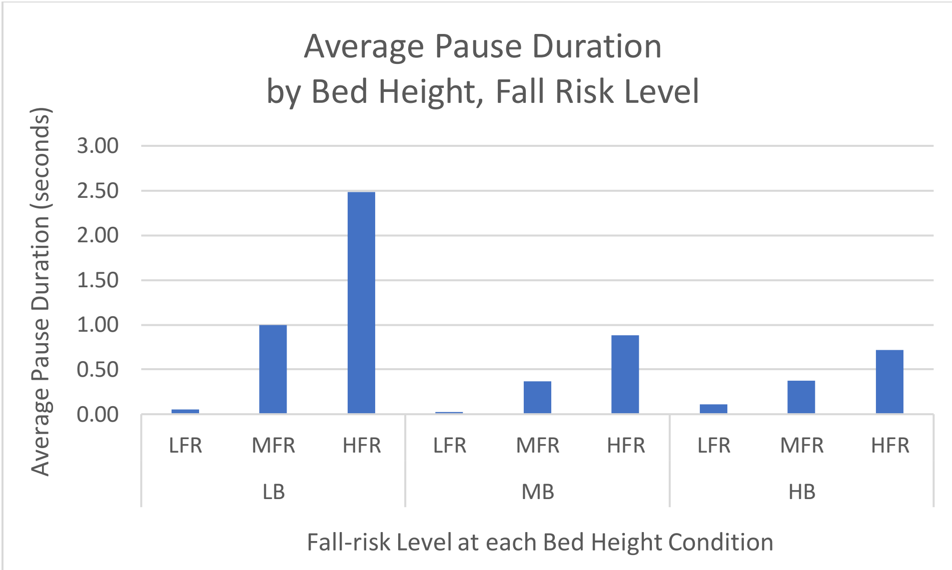

Figure 4.1 Average pause time stratified by bed height and fall risk level

Table.4.3 Summary table of independent variable contribution to FRE

FACTOR	**FRE (N=80)**	**NON-FRE (N=519)**	**TOTAL (N=599)**	**p-value**
CBs				<0.001[2]
Mean (StDev)	2.15 (1.15)	0.665 (0.98)	0.863 (1.13)	
Range	0-6	0-5	0-6	
Pause	# of trials	# of trials	# of trials	<0.001[1]
No Pause	11 (13.8%)	426 (82.1%)	437 (73.0%)	
Pause	69 (86.2%)	93 (17.9%)	162 (27.0%)	

CHAPTER 5

DEVELOPING A FALL-PROXY MODEL FOR THE ELDERLY FOR USE IN THE LABORATORY

5.1 Introduction

In the context of the proposed Taylor STSW Biomechanical Model and an increased understanding of potential performance metrics as established in the previous chapters, this chapter develops a fall-proxy model through evaluation of STSW metrics as potential predictors of patient falls during bed egress. The resulting fall-proxy model is for use in the laboratory where falls are purposefully prevented. Thus, this fall-proxy model, along with the Taylor STSW Biomechanical Model, provides a framework for researchers to study the mechanisms leading to a fall without actually having a fall.

This chapter specifically addresses Aim 3: H3.1: Observable fall-risk episodes have a correlating significant local maximum $jerk_{CoMz}^2$ (Sjerk^2) during STSW and H3.2: Observable fall risk episodes have a critical corrective behavior (CCB). First, background and definitions are presented. This is followed by the method, results, and conclusions.

5.2 Background and Definitions

This research uses current state-of-the-art methods of assessment and definitions for frailty, fall types, and fall identification as described in this section.

5.2.1 Fall Risk as Indicator of Frailty

Frailty is a complex topic that requires a multifaceted assessment and can be defined differently depending on the area of study. Among researchers and clinicians alike, frailty is considered to be a dynamic process defined as a geriatric syndrome characterized by declines in physiological reserve and function across multiorgan systems resulting in increased vulnerability to stressors and, therefore, is associated with adverse health outcomes [1, 2]. These adverse outcomes include falls, delirium, and disability [3-5]. Existing literature describes the causes of frailty as multidimensional based on the interplay between genetic, biological, psychological, social, emotional, and environmental factors [1, 4, 6].

For over the last three decades, there has been and continues to be much debate among both researchers and clinicians on how to measure frailty [4, 7-9]. The challenge has been that not all frail elderly experience the same symptoms and that frailty can be present in the absence of specific diseases, but is more likely present in combination with or as a consequence of comorbidity [6, 10].

Two main models of frailty in the literature are the phenotype model and the cumulative deficit model. The phenotype model includes five indicators of frailty: weight loss, self-reported exhaustion, low energy expenditure, slow gait speed, and weak grip strength. Any person with three or more indicators is considered to be frail [3]. The cumulative deficit model is a mix of comorbidity, cognitive impairment, and disability [11, 12]. Rockwood et. al. developed a frailty index in which the proportion of potential deficits that are present in a given individual is calculated based on 40 or more potential deficits of which were said could be selected at random [6]. The ratio of present to potential deficits is the frailty index and the greater the index number, the greater the frailty level of an individual. Additional literature suggests that falls are an indication of frailty[13]. These methods provide a way to identify frailty but is this sufficient?

Ultimately, the ability to measure frailty is only relevant if effective health promotion, prevention, treatment, rehabilitation, and care interventions can be identified and implemented. One key prevention goal for the frail is fall prevention. Multiple studies have linked falls with frailty [2, 5, 14]. Elderly individuals who are fall prone are considered frail. And those who are classified as frail, by any definition, are considered to be at a HFR. This much is widely agreed upon within the literature [4, 5, 14]. For this reason, a fall risk assessment tool was used to define frailty for this research.

This research program uses the Morse Fall Scale (MFS) fall risk assessment tool (Figures 5.1 and 5.2) [15, 16] as a metric for frailty. MFS aligns more with the cumulative deficit model by assigning a quantitative fall-risk score to various deficits and then computing a total score for an individual. These deficits include mental status, gait, IV status, assistive aids, multiple diagnoses, and history of falling. The MFS scale values range from 0 to 125. Cut-off scores broadly categorizing fall-risk are low ($MFS \leq 25$), moderate ($25 < MFS < 55$), and high ($MFS \geq 55$) fall-risk levels, where the higher the fall-risk score the greater the probability of a fall.

5.2.2 Fall Types

For the purposes of this research, a fall is defined as an event in which the subject unintentionally moves downward from a higher to a lower position. Falls have been classified into three general categories: physiological anticipated, physiological unanticipated, and accidental [13]. A physiological anticipated fall includes observable physical characteristics, such as disorientation or difficulty in ambulating (weak/impaired gait, poor balance, and/or use of walking aids). Physiological unanticipated falls cannot always be identified in advance; they include such things as fainting, heart attack, or other sudden physiological reaction that may not be anticipated. An accidental fall is defined as occurring due to extrinsic environmental factors or hazards; it is an adverse engagement with the environment resulting in a fall, such as slipping, tripping, or rolling off of the bed. This research focuses on the physiological anticipated falls, as they are falls that can be eliminated with proper interventions.

Physiological anticipated falls occur as a result of known conditions, such as muscle weakness, poor eyesight, or impaired gait and can be prevented with appropriate interventions. It is estimated that nearly 80% of elderly patient falls are of this type [13]. While there are a variety of physiological impairments, this research focuses on the physical biomechanical movement that leads to a real-world fall. Other physiological impairments are accounted for in the fall risk assessment.

5.2.3 Fall Identification in the Laboratory

Due to the safety requirements in the laboratory, actual falls among the frail elderly are purposefully prevented and, therefore, no falls data can be collected for the frail elderly. This, however, does not preclude the frail elderly from performing movements in the laboratory that may lead to a fall. Literature in both human biomechanics and industrial and humanoid robotics have validated jerk[2] as an appropriate metric for identifying unsmooth movements and have shown that jerk at higher magnitudes can indicate a fall

[17-19]. In addition, recent studies suggest periods of elevated jerk may indicate a fall initiation where there could have been a fall, but the subject was either able to recover themselves or the system in place, such as a harness, was able to restrict the participant and, thus, there was no actual completed fall [20, 21].

The large majority of current laboratory falls studies are based on simulations of falls using healthy, young subjects [22]. This approach is problematic because, as a recent study has shown, simulated elderly falls by healthy, young adults are not representative of real-world elderly falls [23]. In fact, there were significant differences in jerk magnitude between fall simulations and real-world elderly falls. This research identifies actual and potential falls through both visual observation of collected video and by using $jerk_{CoMz}^2$ above a threshold of 250 $(m/s^3)^2$, indicating a potential fall. This threshold was determined by a pilot study that analyzed falls back to the bed during bed egress.

5.3 Method

5.3.1 Recruitment and Data Collection

Recruitment and data collection for this study follows the same method outlined in Chapter 3. This study includes a larger sample size of 74 individuals and a total of 599 bed egress trials. Both male (53) and female (21) participants were included in the study with an average age of 69.6 years. Participant demographics are included in Table 5.1.

5.3.2 Data Filtering

Fundamental to the study of biomechanics is the measurement of forces and position in an effort to understand the often-complex movement that results. Position data are recorded at discrete points in time using retroreflective markers and a 3D motion capture system. Kinematic variables, such as velocity, acceleration, and jerk, are derived through differentiation of collected position data. While some error can be minimized by using highly calibrated equipment and careful experimental procedures, position data will still contain random errors (noise). This noise in the position data must be smoothed through filtering prior to performing inverse dynamic analyses or there will be considerable inaccuracies in the derived data.

The standard practice to smooth biomechanical data is to apply a lowpass Butterworth filter. The Butterworth filter is a recursive filter described by equation 5.1.

$$y_n = a_0 x_n + a_1 x_{n-1} + a_2 x_{n-2} + b_1 y_{n-1} + b_2 y_{n-2} \quad (5.1)$$

where x_n is the raw acquired signal, y_n, is the filtered signal and a_0, a_1, a_2, b_1, and b_2 are the constants of the filter. The recursive character of the filter introduces a phase lag into the signal. To remove the phase lag, a dual pass (both forward and backward) filter is run on the data. The constants are dependent on the sample rate and the desired cutoff frequency. For this research, to remove noise in the position signal, a bidirectional lowpass 4^{th}-order Butterworth filter was applied with a cut-off frequency at 6 Hz [24]. In addition, the force plate data was also filtered with a 4^{th} order Butterworth filter applied with a cut-off frequency at 15 Hz [24].

5.3.3 Identifying FREs

A visual review of all bed egress trials in this study identified trials with actual falls back to the bed (excluding bounces), as well as moments where there was concern that the subject might fall but was able to recover. Both actual falls and potential falls in this research are referred to as a Fall Risk Episode (FRE). One individual was trained and identified moments of concern for instability during STSW. Each FRE has a start and end tag. Each trial has the potential of having multiple FREs.

5.3.4 Locating Significant Jerk^2 and Critical Corrective Behaviors

Significant jerk ^{2} (*S*jerk^2) is defined for this research as a $jerk_{CoMz}^2$ value that is above a specified threshold of 250 $(m/s^3)^2$ indicating a potential fall initiation. A literature search was performed to identify any previous publications on potential $jerk_{CoMz}^2$ threshold values for a fall during egress. A few related studies were identified. One pilot study of one subject proposed a possible threshold for involuntary lateral jerk at 140 m/s^3 during a variety of daily movements [25]. Another study looked at increasing jerk over time, using the median as a threshold for indication of a fall initiation [20]. A pilot study by the author indicates local maximum $jerk_{CoMz}^2$ magnitude of falls during bed egress has a range between about 250 and 2500$(m/s^3)^2$. Therefore, for this study, *S*jerk^{2}is defined as any $jerk_{CoMz}^2$ value above a threshold of 250 $(m/s^3)^2$.

Once *S*jerk^{2}is identified for each STSW phase of a specific trial, the proximal CBs are located within +/-0.5 seconds of *S*jerk^2. These proximal CBs are referred to as Critical Corrective Behaviors (CCBs). Figure 5.3 shows an example of a LB trial performed by a HFR subject with the continuous $jerk_{CoMz}^2$ trajectory plotted, along with the STSW key events, phases, and temporal locations of CBs and *S*jerk^2 events. All *S*jerk^2 events 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. This chapter evaluates the maximum *S*jerk^2 per STSW phase as the most likely instance for fall initiation during that phase and then identifies CCBs. These events are compared to the timing of the tagged FRE duration.

We can see that $Sjerk^2$ occurred in each STSW phase for this trial, while FREs were noted only in the Stand Preparation and Stand Initiation phases. For the purposes of this research, evaluations were performed on the Stand Initiation and Stand phases, as these were the phases with the majority of the identified FREs. Further studies should be done to confirm appropriate $Sjerk^2$ thresholds for the remaining STSW phases, as there may be different thresholds depending on the type of movement being performed, and may correlate with frailty.

5.3.5 Akaike Information Criterion (AIC)

AIC is used for model selection, particularly when there is uncertainty surrounding what variables may account for variation in predicting the dependent variable [26]. Prior to selecting a model, independent variables are selected based on knowledge of the study system from pilot studies and literature. The concept of parsimony, based on Occam's razor, suggests that all else being equal, the simplest model is the best one. Thus, AIC penalizes over parameterization and a lower AIC indicates a better-fit model. AIC is calculated as follows in equation 5.2:

$$AIC_i = 2K_i - 2\ln(L_i) \quad (5.2)$$

where K_i is 2 + number of independent variables in the i_{th} model and L is the log-likelihood estimate of the i_{th} model, or the likelihood that the model could have produced the observed y-values [27]. The AIC of multiple models are then compared and the model with the lower AIC is generally selected as the better model. When there is a difference of more than 2 AIC units, the model with the lower AIC is considered to be significantly better.

Multiple models were run beginning with individual factors and then adding factors in various combinations. The purpose of this approach was to identify which model resulted in the lowest AIC with a difference of at least 2.

5.3.6 Generalized Linear Mixed Model

Statistical analysis was performed in R version 4.1.2 using a generalized linear mixed model (GLMM) approach. This approach develops a model based on one or more predictor variables (Equation 5.3), where β_i is a parameter estimate used to generate the linear curve and β_0 is the y-intercept.

$$y = \beta_0 + \beta_1 * x_1 + \beta_2 * x_2 \ldots + \beta_n * x_n \quad (5.3)$$

This approach extends linear model theory to model a categorical response variable, such as FRE, and accommodates random and/or repeated effects, such as trials with multiple FREs. Based on previous literature and pilot studies by the author discussed in previous chapters, bed height, fall risk level, Sjerk^2, CCBs, and pausing were selected as potentially being significant in predicting an FRE. Odds ratios (OR) for each independent factor were calculated by exponentiating the beta estimates. The 95% confidence intervals (CI) were determined using the OR and standard error (SE) to calculate the upper limit (UL) and lower limit (LL), as follows (Equations 5.4-5.6):

$$95\%\ CI = OR \pm 1.96 * SE \quad (5.4)$$

$$UL = OR + 1.96 * SE \quad (5.5)$$

$$LL = OR - 1.96 * SE \quad (5.6)$$

5.4 Results and Discussion

5.4.1 Fall Risk Episodes

FREs were identified in Stand Preparation (SP), Stand Initiation (SI), Stand (Stand), and Gait Initiation (GI) phases of STSW. The majority of FREs (80/83, 96.3%) occurred in the SI (18/80, 21.7%) and Stand Phases (62/80, 74.7%), with only 2 in the SP Phase and 1 in the GI Phase. It is not surprising that nearly all of the FREs occurred in the SI and Stand Phases, as they require the most challenging movement of shifting weight from a seated position and extending to a standing position. In this motion of multi-joint flexion-extension, the entire body is involved, requiring multi-muscle coordination [28, 29]. The lower extremity extension upon rising alone has been shown to require coordinated activation of tibialis anterior, gastrocnemius, soleus, biceps femoris, rectus femoris, as well as the vastus lateralis when feet are not placed sufficiently underneath the CoM [30]. This multi-muscle coordination becomes even more complex as muscles deteriorate and compensatory strategies involve upper extremities, as well.

These compensatory strategies replace the once familiar flow of healthy movement and lead to more frequent falls. It is this difference in movement by the frail elderly during STSW which is not well understood. Because the biomechanical motion varies between each of the STSW phases, the indicators of a fall may differ or have different thresholds. For example, non-smooth movement during extension while rising may have a different magnitude of jerk that indicates a potential fall than the movement of initiating gait where an individual shifts weight from two feet onto one foot. Because there simply is not sufficient data to analyze FREs in the SP and GI phases of STSW, this research focuses on the analysis of the SI and Stand Phases.

Table 5.2 compares the FRE and NON-FRE by subjects and trials for the SI and Stand phases. There are 40.5% (30/74) of all elderly subjects with at least one FRE trial. There are 80 FREs. Eleven FRE trials had multiple FREs. Nine of the multiple FRE trials had 2 FREs/trial and two trials had 3 FREs/trial for a total of 80 FREs among 67 trials. Of the subjects with FREs, the majority of the subjects 40(59.7%) were in the HFR group, with MFR and LFR groups at 24(35.8%) and 3(4.5%), respectively. In addition, the majority of FREs occurred at the low bed condition 54(67.5%), while high and medium bed heights had 16(20%) and 10(12.5%), respectively. No subject had an FRE in every trial performed. Only one subject had FREs in 8 out of 9 trials performed, or 89%. This individual was 80 years old and in the HFR group.

During an FRE, either a fall occurred or corrective measures were taken to prevent a potential fall. For each of the 80 FREs, the type of corrective method was noted. Table 5.3 summarizes the number and percent of falls and corrective methods. Corrective methods were categorized into three types: catch, step, and touchback. A catch is defined as both hands making contact for momentary support and then continuing with the STSW task. A step is defined as one foot taking a side, forward, or backward step to reposition prior to initiating gait. A touchback is defined as one hand reaching back and making contact with either the bed or the rail and then continuing with the STSW task. The most frequent FRE corrective method type is the catch (42.6%), followed by the step, touchback, and actual fall (each at 22.5%).

5.4.2 Significant Jerk^2 and Critical Corrective Behaviors

Of the 80 FREs, 78/80 (97.5%) had a Sjerk2. This can be contrasted with the Non-FRE trials where only 154/519 (29.7%) had a Sjerk2. While 30% may seem to be a large percentage of false positives, this is acceptable given the importance of being able to identify FREs. Although some non-FREs will be identified as FREs, that is better than not identifying an actual FRE. Of the FRE trials with Sjerk2, only one FRE did not have a Critical Corrective Behavior (CCB). Overall, the majority of trials with Sjerk^2 events (98.8%) did associate with a CCB. Aim 3 H3.1 and H3.2 are nearly fully supported.

5.5 Statistical and Sensitivity Analyses

Table 5.4 summarizes the independent variables by the categorical variable FRE. P-values are calculated based on two methods and are indicated with a superscript: 1. Linear ANOVA and 2. Kruskal-Wallace. Rail is the only insignificant independent variable, while fall risk level, MFS, CCBs, Sjerk^2, and pause all significantly contribute to FRE. HFR level, higher MFS, higher CCBs, higher Sjerk^2, and pause all significantly contribute to FRE.

A sensitivity analysis was done on a simplified single-factor logistic regression model using the online software program G*Power version 3.1.9.7 (Figure 5.4). With a base rate of 0.13 (80 FREs/599 total trials), an alpha at 0.05, expecting 95% power, with a sample size of 599, we will be able to detect in the data an odds ratio of at least 1.5458 with a sufficient power of 95%.

5.6 Fall-proxy Model

Using the linear mixed model (LMM) approach, AIC values were calculated beginning with single-factor models (Table 5.5). Prior to running models, normality tests were run on all variables and conditions of normality were met, with the exception of $jerk_{CoMz}^2$. Due to the skewed distribution of $jerk_{CoMz}^2$, a logarithmic transformation was applied resulting with a normal distribution. Interactions between factors were considered; however, when included, the models were unable to converge. Therefore, no interaction factors were included in the model. As independent factors were added to the model, the AIC values continued to decrease, indicating a better fit. However, the five-factor model did not converge. Upon further investigation, collinearity was discovered between bed height and pause. There were twice as many trials with pausing at the LB (80) condition as compared to the MB (38) and HB (44). While both bed height and pausing are significantly related to FRE, because of the collinearity, both factors cannot be in the model. The decision was made to include bed height as that is influencing the biomechanics of egress, whereas the pausing is more likely a byproduct of the bed height.

This model was developed from using all trials, including trials with actual falls (Table 5.6). Considering that studies in the laboratory take safety measures to ensure elderly participants do not fall, this model needs to be able to predict an FRE without actual fall data. Therefore, in order to verify that the model is sufficiently sensitive to identify an FRE without an actual fall, all trials with a fall were removed and the model (5.7) was run comparing NONFRE to only FRE non-fall trials. Results also show significance for all four independent variables in predicting an FRE (Table 5.7).

$$\text{FRE} \sim \text{BH} + \text{Log}(S\text{jerk}^2) + \text{Fall Risk Level} + \text{CBs} + (1|\text{SUBJECT}) \qquad (5.7)$$

The odds ratios derived from the four-factor model, both all FRE data (Table 5.6) and FRE fall initiation data (Table 5.7), indicate the likelihood of experiencing an FRE when a specific factor is present or increased. Log(Sjerk^2), HFR level, LB condition, and CBs all presented as significant factors in predicting an FRE. Referring to Table 5.7, the following interpretations are made. The greatest odds ratio relates to the HFR individual who is over 416 times more likely to have an FRE than a LFR individual. An individual egressing from a LB is 12.9 times more likely to have an FRE than if they were egressing from a MB. For every increase in log(Sjerk^2), an individual is over 172 times more likely to experience an FRE. Finally, for every additional CB, an individual is 5.3 times more likely to experience an FRE. This analysis helps to put perspective on the impact of each variable listed in Table 5.7, shows variables that influences instability, and provides indicators for developing fall intervention methods.

5.7 Conclusion

This study has shown that FREs, both actual falls and fall initiations, occur most frequently during the Stand Initiation and Stand Phases of STSW. These phases involve perhaps the most challenging movement of STSW, as it is the transition from flexion to extension that occurs simultaneously with weight shifting from seat to feet with hands assisting while possibly decreasing the BoS.

With decreased lower limb and torso muscle strength, the frail elderly use compensatory strategies by employing upper extremities to aid in rising. Unlike the healthy smooth movement of STW, the frail elderly have moments of increased jerk along with increasing numbers of corrective behaviors. This study has shown that these FRE moments have correlating *S*jerk^2 and CBs. All frail depend on CBs to aid in egress; 100% of all HFR subjects employed CBs in each trial. The question becomes what kind of supporting objects would best aid in a more smooth and safe egress? Both location and type of supporting object should be investigated to optimize STSW movement for successful egress, or in other words minimize falls.

Key factors found to be significantly related to predicting an FRE are: jerk, fall-risk level, bed height, pausing, and CBs. It is important to note that although pausing prior to initiating gait was significant in predicting an FRE, pausing was identified as having collinearity with bed height and was closely related to FRE. Therefore, the four-factor model without the pause variable was selected as the fall-proxy model. The Taylor Fall-proxy Model and Taylor STSW Biomechanical Model, developed in Chapter 2, together provide a framework for researchers to study the mechanisms during STSW that lead to a fall without actually having a fall. Now, with the ability to identify when falls are more likely to occur during STSW, more appropriate interventions can be developed, decreasing patient falls.

5.8 References

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Morse Fall Scale

Variables	**Numeric Values**	**Score**
1. History of falling	No 0 Yes 25	_______
2. Secondary diagnosis	No 0 Yes 15	_______
3. Ambulatory aid None/bed rest/nurse assist Crutches/cane/walker Furniture	0 15 30	_______
4. IV or IV Access	No 0 Yes 20	_______
5. Gait Normal/bed rest/wheelchair Weak Impaired	0 10 20	_______
6. Mental status Oriented to own ability Overestimates or forgets limitations	0 15	_______

Morse Fall Scale Score = **Total** _______

Figure 5.1 Morse fall scale [15] "Development of a scale to identify the fall prone patient", Canadian Journal on Aging, vol 8, no. 4, pp. 366-377, 1989, with permission from Cambridge University Press.

Morse Fall Scale Variable Descriptions and Scoring Criteria

1. **History of falling**
   - This is scored as 25 if the patient has fallen during the present hospital admission or if there was an immediate history of physiological falls, such as from seizures or an impaired gait prior to admission. If the patient has not fallen, this is scored 0. Note: If a patient falls for the first time, then his or her score immediately increases by 25.
2. **Secondary diagnosis**
   - This is scored as 15 if more than one medical diagnosis is listed on the patient's chart; if not, score 0.
3. **Ambulatory aid**
   - This is scored as 0 if the patient walks without a walking aid (even if assisted by a nurse), uses a wheelchair, or is on bed rest and does not get out of bed at all. If the patient uses crutches, a cane, or a walker, this variable scores 15; if the patient ambulates clutching onto the furniture for support, score this variable 30.
4. **IV or IV Access**
   - This is scored as 20 if the patient has an intravenous apparatus or a saline/heparin lock inserted; if not, score 0.
5. **Gait**
   - The characteristics of the three types of gait are evident regardless of the type of physical disability or underlying cause.
     1. A <u>normal gait</u> is characterized by the patient walking with head erect, arms swinging freely at the side, and striding without hesitation. This gait scores 0.
     2. With a <u>weak gait</u> (score10), the patient is stooped but is able to lift the head while walking without losing balance. If support from furniture is required, this is with a featherweight touch almost for reassurance, rather than grabbing to remain upright. Steps are short and the patient may shuffle.
     3. With an <u>impaired gait</u> (score 20), the patient may have difficulty rising from the chair, attempting to get up by pushing on the arms of the chair and/or bouncing (i.e., by using several attempts to rise). The patient's head is down, and he or she watches the ground. Because the patient's balance is poor, the patient grasps onto the furniture, a support person, or a walking aid for support and cannot walk without this assistance. Steps are short and the patient shuffles.
     4. If the patient is in a wheelchair, the patient is scored according to the gait he or she used when transferring from the wheelchair to the bed.
6. **Mental status**
   - When using this Scale, mental status is measured by checking the patient's self-assessment of his or her own ability to ambulate. Ask the patient, "Are you able to go to the bathroom alone or do you need assistance?" If the patient's reply judging his or her own ability <u>is consistent</u> with the activity order in the patient's chart, the patient is rated as "normal" and scored 0. If the patient's response <u>is not consistent</u> with the activity order or if the patient's response is unrealistic, then the patient is considered to overestimate his or her own abilities and to be forgetful of limitations and is scored as 15.
   -

Figure 5.2 Morse fall scale descriptions and scoring instructions [15] "Development of a scale to identify the fall prone patient", vol 8, no. 4, pp. 366-377, 1989, with permission from Cambridge University Press.

Table 5.1 Demographics and subject characteristics

	MFS ≤25 n = 12		**25< MFS <55** n = 34		**MFS >55** n = 28		**Total** N=74	
Characteristic	n	%	n	%	n	%	Avg or n	%
Age (years)	Av 66.5	SD 11.8	Av 68.4	SD 10.9	Av 72.3	SD 10.7	67.9	SD 11.3
Gender								
Female	3	25.00	10	29.41	8	28.57	21	28.38
Male	9	75.00	24	70.59	20	71.43	53	71.62
Hispanic ethnicity								
Yes	0	0	2	5.88	0	0	2	2.70
No	12	100	32	94.12	28	100	72	97.30
Race								
American Indian or Alaska Native	1	8.33	1	2.94	0	0	2	2.70
Black or African American	1	8.33	0	0	1	3.57	2	2.70
Native Hawaiian or Pacific Islander	1	8.33	0	0	1	3.57	2	2.70
White	9	75.0	32	94.12	26	92.86	67	90.54
Unknown or not reported	0	0	1	2.94	0	0	1	1.35
Recruitment site								
VA Inpatient	0	0	1	2.94	2	7.14	3	4.05
VA Outpatient	6	50.00	22	64.71	16	57.14	42	56.76
Fall Clinic	0	0	4	11.76	1	3.57	5	6.76
Community	5	41.67	2	5.88	3	10.71	10	13.51
Other	1	8.33	5	14.71	6	21.43	12	16.22

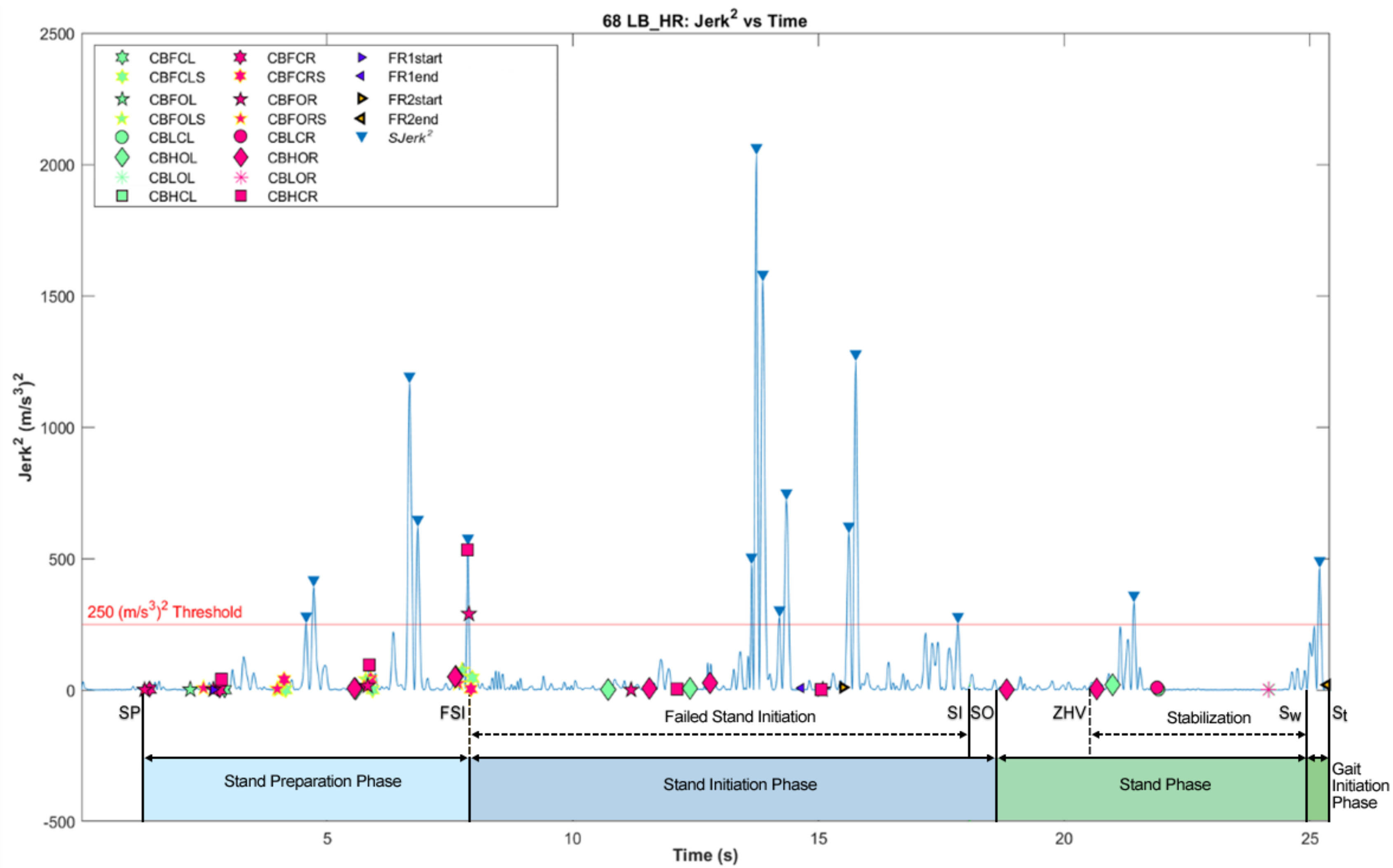

Figure 5.3 STSW for HFR subject with Sjerk2 and CCBs with designation of fall instances (FR1 and FR2).

Table 5.2 Fall risk episode (FRE) and non-FRE by subjects and trials

STSW STUDY	FRE (%)	NON-FRE (%)	TOTAL
# Subjects	30 (40.5)	44 (59.5)	74
# Trials	80 (13.4)	519 (86.6)	599

Table 5.3 Fall or type of FRE corrective method

Fall or FRE Corrective Method Type	Count (%)
Fall	18 (22.5)
Catch	26 (42.6)
Step	18 (22.5)
Touchback	18 (22.5)

Table.5.4 Summary table of independent variable contribution to FRE

FACTOR	FRE (N=80)	NON-FRE (N=519)	TOTAL (N=599)	p-value
Bed Height	# of trials	# of trials	# of trials	<0.001[1]
Low	54 (65%)7.	150 (28.9%)	204 (34.1%)	
Medium	10 (12.5%)	185 (35.6%)	195 (32.6%)	
High	16 (20.0%)	184 (35.5%)	200 (33.4%)	
Fall Risk Level	# of trials	# of trials	# of trials	<0.001[1]
Low	3 (3.8%)	89 (17.1%)	92 (15.4%)	
Moderate	31 (38.8%)	256 (49.3%)	287 (47.9%)	
High	46 (57.5%)	174 (33.5%)	220 (36.7%)	
MFS				<0.001[2]
Mean (StDev)	58.875 (17.5)	47.033 (20.1)	48.614 (20.2)	
Range	0-90	0-90	0-90	
CBs				<0.001[2]
Mean (StDev)	2.15 (1.15)	0.665 (0.98)	0.863 (1.13)	
Range	0-6	0-5	0-6	
***Sjerk*[2]**				<0.001[2]
Mean (StDev)	678.36(447.2)	228.15(221.99)	288.27(304.31)	
Range	100.8-2468.4	10.5-1391.1	10.5-2468.4	
Pause	# of trials	# of trials	# of trials	<0.001[1]
No Pause	11 (13.8%)	426 (82.1%)	437 (73.0%)	
Pause	69 (86.2%)	93 (17.9%)	162 (27.0%)	
Rail	# of trials	# of trials	# of trials	0.948[1]
HR	28 (35.0%)	173 (33.3%)	201 (33.6%)	
N	27 (33.8%)	176 (33.9%)	203 (33.9%)	
S	25 (31.2%)	170 (32.8%)	195 (32.6%)	

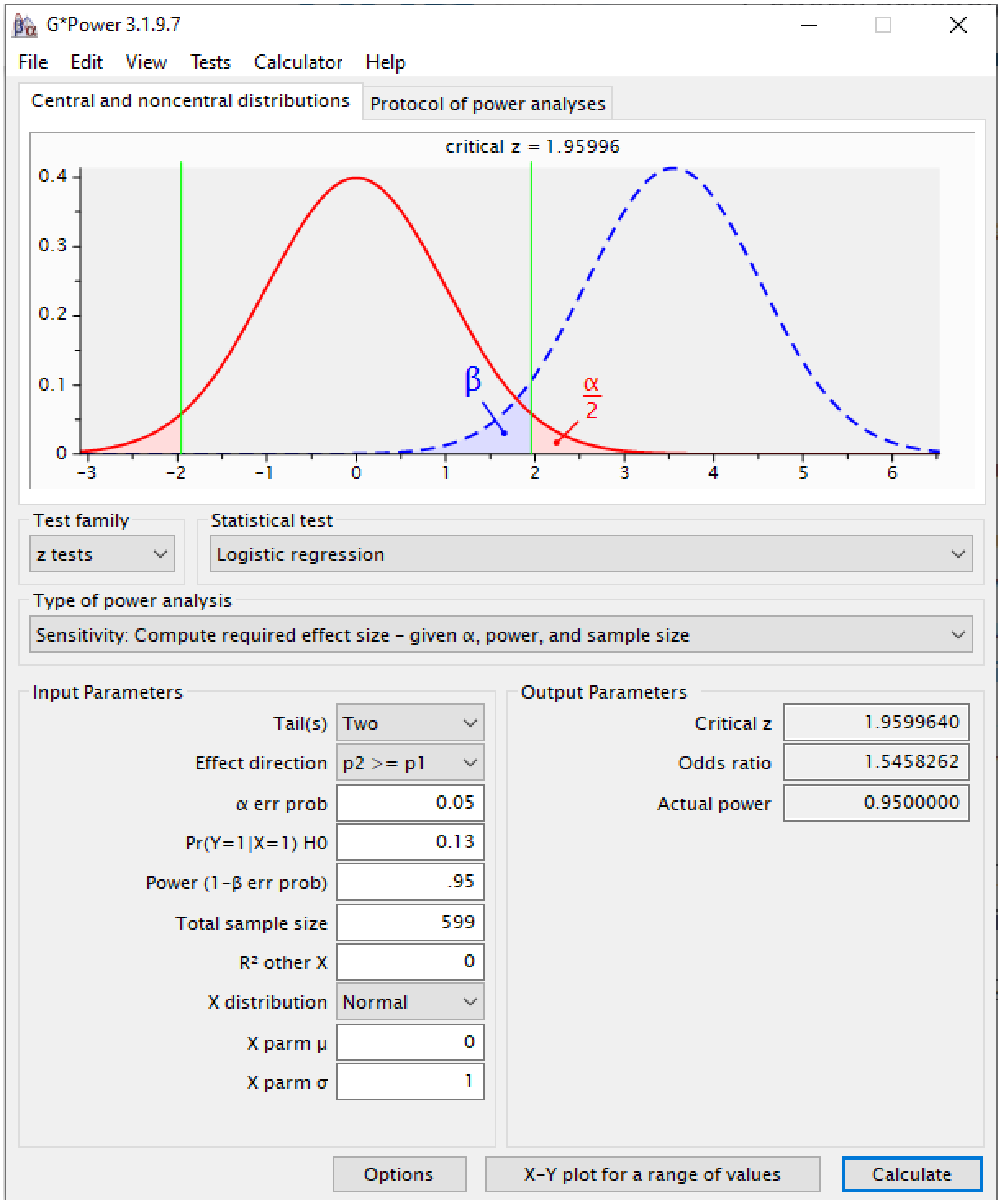

Figure 5.4 Sensitivity analysis using G*Power

Table 5.5 Generalized linear mixed models and their respective AIC.

Number of Independent Factors	Factors included in Model to predict FRE	AIC
One-factor Models	Bed Height	335.9
	Fall Risk Level	378.7
	LogSjerk^2	272.5
	CBs	285.0
	Pausing	315.0
Two-factor Models	LogSjerk^2, CBs	216.8
	LogSjerk^2, Pause	226.2
	LogSjerk^2, Bed Height	256.8
	LogSjerk^2, Fall Risk Level	263.8
	CBs, Pause	239.8
	CBs, Bed Height	251.5
	CBs, Fall Risk Level	276.5
	Pause, Bed Height	289.5
	Pause, Fall Risk Level	317.1
	Bed Height, Fall Risk Level	329.2
Three-factor Models	LogSjerk^2, CBs, Pause	187.2
	LogSjerk^2, CBs, Bed Height	207.6
	LogSjerk^2, CBs, Fall Risk Level	204.6
	LogSjerk^2, Pausing, Bed Height	218.1
	Bed Height, LogSjerk^2, Fall Risk Level	248.5
	LogSjerk^2, Pausing, Fall Risk Level	226.5
	LogSjerk^2, Bed Height, Fall Risk Level	248.5
	CBs, Pausing, Bed Height	223.9
	CBs, Pausing, Fall Risk Level	236.5
	CBs, Bed Height, Fall Risk Level	243.2
	Pausing, CBs, Bed Height	223.9
	Pausing, CBs, Fall Risk Level	236.5
Four-factor Models	LogSjerk^2, CBs, Bed Height, Pause	182.8
	LogSjerk^2, CBs, Bed Height, Fall Risk Level	196.2
	CBs, Pause, Bed Height, Fall Risk Level	219.1
	Pause, Bed Height, Fall Risk Level, LogSjerk^2	218.0

Table 5.6 Four-factor LMM (all FRE data) analysis of risk factors for FRE

VARIABLE	VARIABLE LEVELS	ODDS RATIO	STANDARD ERROR	95% CI LL	UL	p-value
Log(Sjerk^2)		330.43	1.1389	328.20	332.66	<0.0001*
Fall-risk Level	High	315.70	1.9313	311.91	319.49	<0.01*
	Moderate	17.20	1.7042	13.86	20.54	0.095
Bed Height	High	4.67	0.8734	2.96	6.38	0.078
	Low	11.91	0.8122	10.32	13.50	<0.01*
CBs		5.72	0.3670	5.00	6.44	<0.0001*

*Significance $p<0.05$. Reference for Fall Risk Level is LFR. Reference for BH is MB.

Table 5.7 Four-factor model (FRE fall initiation data) analysis of risk factors for FRE

VARIABLE	**VARIABLE LEVELS**	**ODDS RATIO**	**STANDARD ERROR**	**95% CI**		**p-value**
				LL	**UL**	
Log(*S*jerk^2)		172.16	1.1196	169.97	174.35	<0.0001*
Fall-risk	High	416.34	2.0563	412.31	420.37	<0.01*
	Moderate	24.13	1.8076	20.59	27.67	0.07821
Bed Height	High	5.15	0.9011	3.38	6.92	0.06876
	Low	12.90	0.8524	11.23	14.57	<0.01*
CBs		5.30	0.3776	4.56	6.04	<0.0001*

*Significance p<0.05. Reference for Fall Risk Level is LFR. Reference for BH is MB.

CHAPTER 6

CREATING A SAFER PATIENT ROOM ENVIRONMENT: THE CONTRIBUTION OF PATIENT BED HEIGHT

The impact of research is often measured by clinical application and, for this context, the reduction in falls of the frail. This chapter provides insights into patient care that not only helps to reduce patient falls, but also reduces caregiver injury.

This part of the dissertation research was presented at the 2021 International Symposium on Human Factors and Ergonomics in Health Care, online.

This research was primarily completed by the author, under the guidance of Dr. Andrew Merryweather, Dr. Janice Morse.

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Creating a safer patient room environment: the contribution of patient bed height

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Elderly patient falls are expensive and may cause serious harm. Studies have identified the sit-to-stand-and-walk (STSW) task as the task where the greatest number of elderly patient falls occur. There is a great need to identify the particular movement and environmental conditions that lead to these elderly patient falls. This study begins to address this gap by evaluating the elderly patient during self-selected hospital bed egress. Using an observed fall risk episode (FRE) as a fall proxy, statistically significant parameters were identified which include bed height, pausing prior to initiating gait, level of fall risk, and Stand phase. Low bed height was identified as the least safe bed height. Patient-specific bed height (PSBH) using the patient's lower leg length (LLL) is recommended. In addition, suggested guidelines are presented for clinical application in setting PSBH without measuring the patient's LLL.

INTRODUCTION

Despite the extraordinarily high fall rate and the astonishing costs in both life and dollars every year, we know little about the risk to patient safety as they egress from a hospital bed. The elderly patient fall rate in hospitals is estimated between 3.3 and 11.5 falls per 1,000 patient days and a rising trend of 3% annually with a cost of more than $50 billion each year [1-3] [https://aging.com/falls-fact-sheet/]. Patient falls often result in injuries that decrease mobility, prolong hospital stays, cause fatalities, and often lead to direct placement into a nursing home[4].

While some patient falls are unanticipated physiological events, such as a heart attack or fainting, which may not be preventable, these events account for only about 18% of patient falls[5]. The majority of elderly patient falls are preventable and are reported to occur largely in a patient room during bed egress[6]. One previous study on elderly bed egress found that low bed height was linked to a delay in rising and initiating gait which may be an indicator of potential fall conditions[7]. Numerous studies have called for further studies to determine the biomechanical cause and circumstances of real-life elderly falls[8-14].To our knowledge, no biomechanical investigation of actual patient bed egress falls has been done, likely because access to patient rooms is denied due to privacy laws.

To fill this gap in knowledge of bed egress falls, this study explores the biomechanics of fall risk episodes (FREs) which serve as a fall proxy for a fall in harnessed frail elderly participants during hospital bed egress. Specifically, the purpose of this research was to study the effect of hospital bed height on FREs associated with bed egress of the frail elderly.

METHOD

We recruited 77 participants (55 male, 22 female; 69.3 ±11.4 years old) and evaluated a total of 598 unique trials. Fall risk was assessed for each participant using the Morse Fall Scale (MFS) (13 low (controls), 37 moderate, 27 high) (Table 1). Exclusion criteria included unilateral strength amputation, medical conditions that precluded the use of the safety system, and cognitive impairments that precluded giving informed consent and/or following simple instructions to perform bed egress.

Table 1. Demographics and number of trials by fall risk level

Fall Risk Level		Low Fall Risk MFS ≤ 25		Moderate Fall Risk 25 < MFS < 55		High Fall Risk MFS ≥ 55		*Total N=77*	
Characteristic		Ave	*St Dev*	Ave	*St Dev*	Ave	*St Dev*	*Ave*	*St Dev*
Age (years)		66.3	*10.8*	67.9	*10.5*	72.2	*10.9*	*69.3*	*11.0*
		n	%	n	%	n	%	*n*	*%*
Gender	Female	3	*23.1*	11	*31.4*	8	*27.6*	*22*	*28.6*
	Male	10	*76.9*	24	*68.6*	21	*72.4*	*55*	*71.4*
# Trials		95		276		227		*598*	

With a simulated hospital room environment, each participant performed up to 9 unique bed egress trials. Controlled factors included bed height (low, medium, high) and side rail condition (large, small, no rail). Each trial began from a seated position followed by rising and walking. No conditions were placed on the participant's selected egress strategy.

The patient-specific bed height (PSBH) was defined as the deck height of the hospital bed. PSBH is determined by using a percentage of the participant's lower leg length (LLL), where the LLL is the distance between the bottom of the foot and the subject's lateral tibial plateau (Figure 1). The height of the compressed mattress (CMH) while the participant is seated on the edge of the bed with ankle and knee joints at 90° is then subtracted from the LLL to obtain the PSBH (Equation 1). Low, medium, and high bed height conditions were calculated using 95, 110, and 125% LLL, respectively.

$$PSBH = \%LLL - CMH \qquad (1)$$

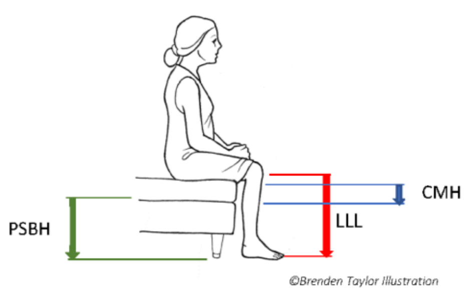

Figure 1. Patient-specific bed height (PSBH) using Lower Leg Length (LLL) and compressed mattress height (CMH)

The sit-to-stand-and-walk (STSW) task was evaluated from first movement upon verbal directive to stand and walk through gait initiation, where gait initiation is defined as the first two forward steps taken (beginning with swing foot toe-off and ending with stance foot-contact). STSW, defined by Taylor, et. al., includes Stand Preparation (SP), Stand Initiation (SI), Stand (S), and Gait (G) phases, as well as Stabilization and Gait Initiation subphases [14]. By evaluating each phase or subphase, rather than the STSW task as a whole, the unique movements of each phase can be better understood. For example, the Stand Initiation phase involves flexion, while the Stand phase moves quickly to extension, and the Gait Initiation phase requires a reduction in base of support while shifting weight to one foot. By separating these phases, difficulties in initiating a stand (i.e. achieving a successful seat-off) are differentiable from difficulties in rising (i.e. inability to reverse forward rotation or over extending and rocking back on heels) and difficulties in initiating gait (i.e. safely transferring weight to one foot to initiate walking).

The effect of bed height on stability was evaluated for each STSW phase or subphase. Because participants were protected from falling through use of a harness, a point of instability during STSW that could have resulted in a fall was visually identified as a Fall Risk Episode (FRE) to serve as a proxy for a fall.

Regression models along with chi-square analyses were used to determine relationships between factors and the model accuracy. Interactions were considered to be significant with a p-value ≤0.05.

RESULTS AND DISCUSSION

A generalized linear regression model and chi-squared analyses on the full data set showed that bed height, pause, MFS, and FRE Type (STSW Phase when FRE occurred) were significantly related to FRE, while gender was not (Table 2).

Table 2. Significant factors

Factor	Chi-squared	df	p-value
Bed height	31.438	2	<0.001
Pause	63.848	1	<0.001
MFS	11.595	2	<0.01
FRE Type	611	3	<0.001
Age	14.717	1	<0.001
Gender	1.5923	1	0.207

It is noted that 38.8% of all LBH trials had an FRE, while MBH and HBH only had 11.7 and 12% of trials with an FRE, respectively. Specifically, LBH was significantly different from MBH and HBH ($p<0.001$).

Although gender was not found to be significant, comparison of FRE and Non-FRE trials showed that FRE trials had, on average, participants with a higher age and were more likely to pause prior to initiating gait (Table 3). Significantly, as MFS increases, FRE increases.

Table 3. Comparison of factors in FRE and Non-FRE Trials

	FRE Trials		Non-FRE Trials	
	Ave	StDev	Ave	StDev
MFS	60.8	16.8	47.5	19.8
Age	75.4	10.5	68.3	10.8
Gender	Percent FRE Trials		Percent Non-FRE Trials	
Male	17.8		82.2	
Female	12.8		87.2	
Pause	73.3		13.2	

An odds ratio analysis showed that participants who paused prior to initiating gait were 15 times more likely to have an FRE than those who did not pause.

Analysis of trials with FRE showed statistical significance ($p<0.001$) between FRE and FRE Type with the majority of the FREs occurring during the Stand Phase (Figure 2).

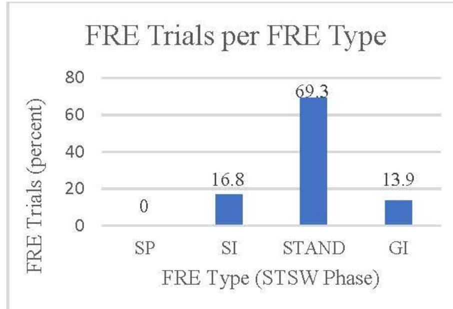

Figure 2. Percent of FRE Trials by FRE Type

Further analysis showed statistical significance ($p<0.001$) between FRE and Bed Height, with the majority of FREs occurring at the LBH condition (Table 4).

Table 4. Percent of trials with FRE by bed height

Bed Height	FRE Trials (percent)
Low	56.4
Medium	20.8
High	21.8

In addition, analysis showed a significant relationship between low bed height and FRE type for both the Stand Initiation and Stand phases (Table 5), suggesting that the LBH is the least safe position for elderly during bed egress, particularly during flexion and extension as one moves to achieve seat-off and stand. Currently, hospitals often use low bed position as standard protocol for elderly patients with the intent to reduce injury from an impact with the floor upon falling out of bed. We highly recommend that such policies be reviewed and consider establishing a PSBH policy that will enable safer transitions during STSW.

Table 5. Frequency of FRE per FRE Type and Bed Height

FRE Type	LBH (percent)	MBH (percent)	HBH (percent)
Stand Preparation	0	0	0
Stand Initiation	64.7	23.5	11.8
Stand	58.6	17.1	24.3
Gait Initiation	35.7	35.7	28.6

While it is clear from this study that LBH generated the highest number of FREs, it is not clear what the optimal height would be, though results indicate it is somewhere between MBH and HBH (i.e. somewhere between 110-125% LLL) as participants were less likely to have an FRE when the bed height was adjusted to a MBH or HBH PSBH. We suggest setting a PSBH by adjusting the bed height until the following 5 guidelines below are met: (Figure 3).

©Brenden Taylor Illustration

1. Patient is seated toward the edge of the bed.
2. Patient's thighs are slanted slightly forward.
3. Patient's knee angle is roughly 90 degrees.
4. Patient's feet are positioned back with toes underneath their knees.
5. Patient's balls of their feet are touching the floor, while heals are slightly off the floor.

Figure 3. Patient position guide for setting PSBH

The results of this study will help to inform a larger study that is evaluating the influence of other environmental aspects of the patient room on patient safety.

Key take-aways include:

1. PSBH reduces fall risk during egress.
2. PSBH is related to patient height, specifically LLL.
3. Hospitals can establish policies and protocols to include the 5 guidelines provided here for clinical application of a PSBH for safer egress.
4. Observed patient movement during bed egress, such as pausing prior to initiating gait, can inform fall risk assessments.
5. Setting appropriate bed height increases the patient bed egress success and reduces the need for nurse assistance, reducing the ergonomic risk for nurses.

CONCLUSION

We have identified, by using FRE as a fall proxy, that a fall is most likely to occur within the Stand phase during bed egress. Our data supports the importance of a patient-specific bed height in relation to safe bed egress.

By sharing this information with healthcare workers and those in the healthcare industry, a shift in the paradigm of setting bed height from the lowest position to a PSBH will lead to fewer patient falls and decrease the ergonomic strain on healthcare workers. As a result of decreased patient falls, hospital stays will be reduced, overall costs will decrease, and lives will be saved.

ACKNOWLEDGEMENT

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CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

By observing free movement of the elderly during bed egress, this research provides a framework for a more valid and arguably more reliable [1] analysis of elderly movement than the scripted protocols of healthy simulated studies. The Taylor STSW Biomechanical Model reflects real-world elderly egress movement, providing context for pursuing a better understanding of causality of falls. From the egress data and the falls that were observed, there was a large difference between the FRE subset and the overall group, indicating that the Taylor Fall-proxy Model is sensitive to detecting both fall initiation and actual fall events. This model along with the Taylor STSW Biomechanical Model provides a framework for laboratory research, or wherever corrective behaviors can be noted and position data can be obtained. By identifying $S\text{jerk}^2$ and CCBs, fall initiation points during egress can be identified and precursor movement can be analyzed for causal relationships, providing key information for determining both interventions and therapies.

In addition to filling these gaps in the field of geriatric biomechanics, this research has generated useful knowledge for clinical application, as well. A patient-specific bed height will not only decrease the likelihood of a patient fall, but it may also reduce the physical demand on the caregiver assisting the patient, decreasing the likelihood of personal injury, both acute and chronic, for the caregiver.

This research could also benefit hospital bed manufacturers. Future bed designs could include software to automatically determine and set bed height for any given person. By positioning the bed height for optimal egress, this research has shown there are likely to be fewer patient falls.

Limitations of this research include potential factors that were not considered, as well as differences between lab set-up and real-world conditions. For example, factors such as specific health condition, hunger, need to rush to the bathroom, time of day, or environmental factors such as lighting or flooring conditions may potentially influence egress performance and likelihood of a fall. Differences between a real hospital patient room and our simulated patient room may also influence egress performance. Although the laboratory set up for this study was created to resemble a hospital patient room, differences may influence egress performance. Not only was the participant wearing different from normal clothing, but they also wore retroreflective markers and many of the participants wore a harness to prevent falling, all of which could impact movement in some way. In addition, participants were being observed by others in the room. This may have influenced to some degree their performance and may not be entirely representative of actual real-world STSW. The closer one can get to obtaining data from real-world events, the more representative the data will be. Further investigation of the model and application of the model in real falls would be needed to confirm the results presented here.

Future research should include further evaluation of preparation strategies and how these strategies influence successful STSW. This would include the influence of such strategies on the Stand Initiation and Stand Phases, including the degree of pausing and ability to initiate gait. Smoothness, or the magnitude of jerk, can be used in the Stand Initiation and Stand Phases, as demonstrated in this research, and may be key in identifying fall initiation in all phases of STSW.

While this research focused on hospital bed egress without additional assistive devices or other supportive structures beyond the bed, future research should evaluate room layout and location and use of supports with respect to successful egress and other maneuvering within the patient room. Ultimately, with increased understanding of the frail elderly movement, improved interventions will be developed that will decrease the rate of falls and information that is greatly needed with the increasing elderly population.

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APPENDIX A

BIOMECHANICAL CHARACTERIZATION OF THE HAND TOUCH CORRECTIVE BEHAVIOR IN THE FRAIL ELDERLY DURING BED EGRESS

Proceedings of the 2018 International Symposium on Human Factors and Ergonomics in Health Care

BIOMECHANICAL CHARACTERIZATION OF THE HAND TOUCH CORRECTIVE BEHAVIOR IN THE FRAIL ELDERLY DURING BED EGRESS

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Falls are the leading cause of fatal and non-fatal injuries among the elderly in the United States and throughout the world. Many studies have been done over the last few decades in an attempt to better understand how to prevent falls among the elderly population. Unfortunately, most of these studies are conducted by simulating falls in a laboratory with healthy adults which has been shown to be quite different from a real world fall. This pilot study defines corrective behaviors implemented by the elderly to maintain balance and looks specifically at measures of stability when the hand touch corrective behavior is used. These measures include base of support area, proximity of center of mass to base of support perimeter, time for center of mass to contact base of support perimeter, and jerk of the center of mass of the torso. Initial findings indicate that the hand touch corrective behavior is used to both maintain and regain stability. It is anticipated that, with the evaluation of the remaining trials, a model of fall-initiation of the frail elderly will be developed to provide key biomechanical stability measures for use as a proxy for a fall in laboratory studies, as well as to provide new insights in fall interventions.

INTRODUCTION

According to the World Health Organization, falls are the second leading cause of accidental or unintentional injury deaths worldwide and occur mostly among adults older than 65 years of age [1]. In addition to fatal falls, there are 37.3 million falls that cause injury requiring medical attention every year. Falls are a major public health concern worldwide. Within the United States, falls are the leading cause of fatal and non-fatal injuries among the elderly [2].

While studies have been done to determine what factors (both intrinsic and extrinsic) may influence the likelihood that an elderly person may fall [3-5], these have often been a simulated fall in a laboratory with healthy adults which have been shown to be quite different from a real-world fall [6]. A better understanding of biomechanical factors of real-world falls, along with any balance recovery strategies could assist in predicting the conditions just prior to a fall. This knowledge would provide the ability not only to identify falls in a laboratory setting, where an actual fall of the frail elderly is perturbed, but also would provide a basis for more appropriate interventions to prevent falls of the frail elderly in their living environments. Thus, there is a critical need to understand the balance recovery strategies in frail elderly and their role in fall prevention.

There are three defined corrective behaviors (CB) for the larger study: hand/touch, foot/step, torso/jerk. This pilot study looks specifically at the Hand Touch CB during bed egress. Biomechanical measures of stability will be evaluated just prior to, during imbalance stage (IS) and immediately following when there is a hand CB. Prior research has shown that measures of stability include base of support area (BOS) and the proximity of center of mass (COM) to base of support perimeter. In addition to these measures, the COM velocity trajectory was computed, along with the time for the COM to contact the BOS perimeter (TtC).

We propose two hypotheses.

1. CBs are used by the frail elderly to assist in bed egress. Identification of biomechanical characteristics prior to and following the use of a CB will locate the imbalance leading to a potential fall.
2. The position that these CBs occur during egress will provide insights about fall risk and lead to recommendations for interventions.

METHOD

The complete data set of 88 subjects (45 frail elderly with Morse Fall Scale [MFS] score $\geq$55, and 43 control MFS < 55) contains 1442 unique trials. Subjects included 28.4% female, 71.6% male, with an average age of 69.2 years. The collected data include 3D kinematics, ground reaction forces, physiological metrics, fall history and functional assessments. Of this set, a pilot study was performed on 12 subjects (n=6 MFS score $\geq$55, n=6 MFS<55).

An 18 camera full motion capture system was used to track full-body biomechanics. Participants exited an adjustable, instrumented hospital bed with three bed rail conditions and three bed height conditions calculated as a percentage of their lower leg length. Each subject performed a sit-to-stand to walk transition from bedside.

Force plates were used both at the side rails and the floor to obtain hand force and ground reaction forces and torques at each foot. The floor force plates were covered with a linoleum surface similar to the flooring at the data collection site.

From visual inspection of each bed egress trial, the following, when present, were identified: type of CB used, point of instability, and point of recovery. Key biomechanical stability metrics calculated for each trial include BOS area, COM proximity to BOS perimeter, COM time to contact (TtC) with the BOS perimeter, and jerk (3rd derivative of position) of the upper body COM.

Figure 1 shows the progression from sit-to-stand at bedside to stand-to-sit at a chair. Position data was recorded for eight markers (three on each foot and one on each hand). Red dots represent a marker in contact (point of contact, POC) with a stabilizing surface. Yellow shaded regions indicate base of support areas according to points of contact.

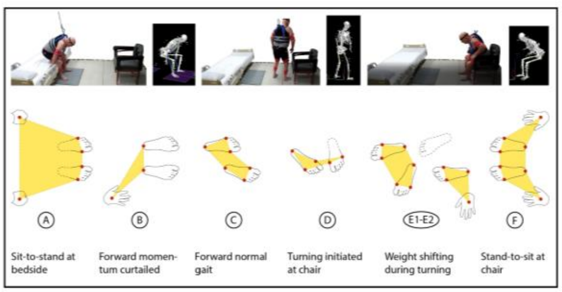

Figure 1. Base of support area (yellow) and points of contact (red dots)

RESULTS

From the 12 subjects' trials, we identified 102 instances of corrective stepping, 209 hand touch, and 15 trunk/head corrections. The subjects with the greatest number of hand CBs were selected for further study. Preliminary results indicate hand CB Points of Contact (POC) are readily identifiable when the velocity of the wrist is equal to approximately zero. The Jerk of the COM was found to be approximately zero at all key BOS transitions. However, a significant jerk occurred during IS. We anticipate that the additional biomechanical attributes we will review will also be indicators of a fall/near fall, such as a threshold value for the COM proximity to the BOS perimeter. These biomechanical attributes will then be used in establishing an automated process to review the remaining trials.

Additionally, we noted that the momentum strategies, including bouncing, of the frail elderly during sit-to-stand transitions created a forward COM velocity trajectory that must be reversed to prevent a fall. Participants reversed this trajectory by rocking back on their heels, at which time they used CBs by reaching behind to use the bed and/or bed rail as a support, or they would fall back, sitting onto the bed.

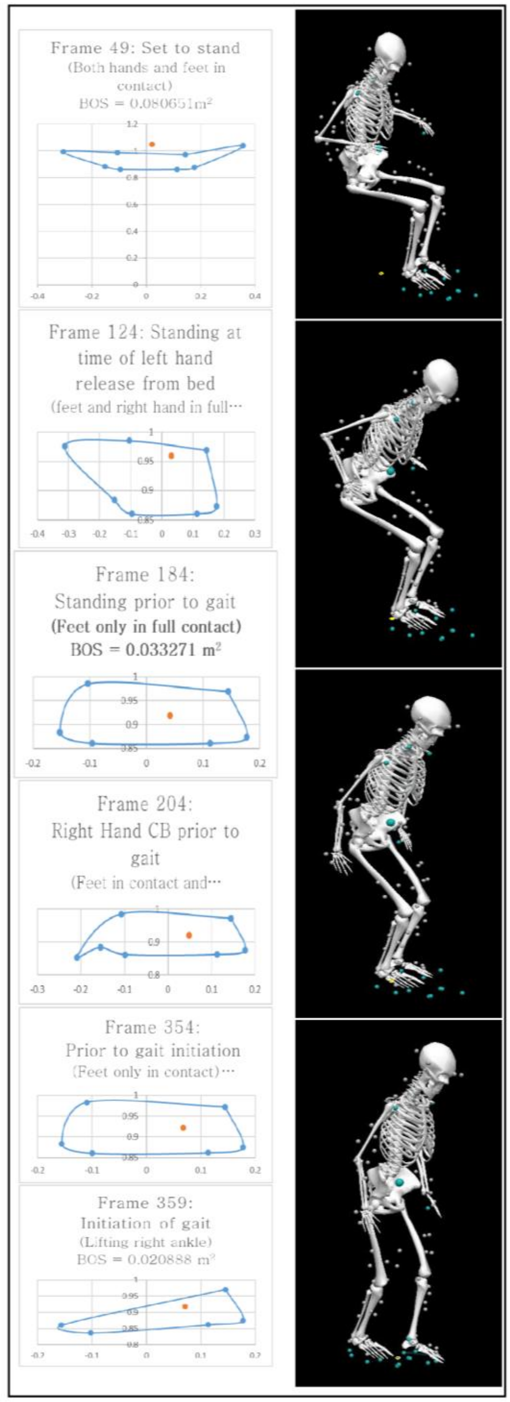

Figure 2. Progression of 3D model with COM position and BOS area

The Visual3D images in figure 2 (right) depict the transition from sit-to-stand to walk. Plots (left) display the computed BOS, along with a plot of the COM location within the BOS, at key transitions where points of contact are changed.

Table 1 demonstrates one example of a subject's key biomechanical measures at points of transition during bed egress. These measures of stability were calculated for all frames of each trial. Discrete frames were tagged at each transition in the number of POCs, and thus at the change in BOS area.

	Subject 50: Hand Touch CB				
	Imminent Sit-to-stand	Standing, left hand released	Standing, right hand released	Standing, Right Hand CB	Just Prior to Gait Initiation
Frame (#)	49	124	184	204	354
Points of Contact (#)	8	7	6	7	6
BOS Area (cm^2)	806.5	439.0	332.7	439.2	339.4
COM Proximity (cm)	outside	10.4	4.94	7.46	8.83
COM TtC (s)	N/A	0.99	0.68	1.38	2.99
COM Jerk (m/s^3)	0	0.0011	0.0022	0	0.0043

Table 1. Measures of stability at discrete frames with change in POCs

CONCLUSION

The sit-to-stand to walk transition is a challenging task for the frail elderly. Momentum strategies are typically employed by the frail elderly to achieve standing, requiring the implementation of corrective behaviors to maintain and/or recover from imbalances that occur during this transition. The pilot study results suggest that the hand corrective behavior is used both to regain stability when imbalanced, as well as to maintain stability by assisting in full rising prior to normal gait. Further work includes the complete analysis of all 1442 trials, including the analysis of other corrective behaviors. From this research, a model of fall-initiation of the frail elderly will be developed to provide key biomechanical stability measures for use as a proxy for a fall in laboratory studies, as well as to provide new insights in fall interventions.

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APPENDIX B

EVALUATION OF FALL RISK EPISODES DURING SELF-SELECTED SIT-TO-STAND-AND-WALK STRATEGIES OF THE ELDERLY

Evaluation of Fall-Risk Episodes During Self-Selected Sit-to-Stand-and-Walk Strategies of the Elderly

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Introduction

Elderly patient falls cost billions of dollars each year. While there have been a variety of interventions implemented, the average fall rate continues to rise. [1, 2] Bed egress has been identified as a primary task with the majority of falls in a patient room. [3, 4] There is a need for a deeper understanding of the biomechanics of elderly movement during bed egress and, more specifically, the phase when a fall is more likely to occur. To our knowledge, this is the first study to evaluate and compare visually observed fall-risk episodes (FREs) with the self-selected hospital bed egress strategy at three different bed heights. This study shows that for self-selected bed egress a patient is more likely to fall from a low bed height. In addition, this study shows that the frequency of FREs increases with increasing fall risk and when a bouncing egress strategy is employed.

Methods

From a larger study, 15 subjects (8 male, 7 female; 67.5±9.1 years old) were randomly selected for evaluation and 122 unique trials were evaluated. Fall risk was assessed using the Morse Fall Scale (MFS) (5 low (MFS 0-25; control group), 5 moderate (MFS 30-50), and 5 high (MFS 55+)). Each participant performed up to 9 unique bed egress trials in a simulated hospital environment. Each trial began from a seated position from which the participant performed a self-selected rise to walk strategy.

Three bed heights were determined by using a percentage of the participant's lower leg length (LLL) and subtracting the height of the compressed mattress while the participant is seated on the edge of the bed. The low, medium, and high bed conditions were calculated using 95%, 110%, and 125% of LLL, respectively.

Self-selected bed egress strategies were evaluated for each trial categorized as bouncing or non-bouncing. Fall-risk episodes (FREs) served as proxy for a fall and were defined as a visually observed point of instability that could have resulted in a fall. The effect of egress strategy type on the stability of the STSW task with relationship to bed height was evaluated.

Results and Discussion

The frequency of trials with FREs increased as MFS increased. For all fall-risk groups, the low bed height had the highest percentage of trials with FREs. When stratifying by egress strategy, the majority of trials in the high fall-risk group employed a bouncing strategy that resulted in the majority of trials having an FRE. (Figure 1) This suggests that the bouncing egress strategy causes more instability more often than the non-bouncing egress strategy.

While results showed that FREs occurred in all phases of the STSW task, the majority of FREs occurred during the Stand Phase (62.9%), with the Gait Initiation Phase (14.2%), Stand Initiation Phase (14.2%), and Stand Preparation Phase (8.6%) having fewer FREs. The Stand Phase includes the critical transition from flexion to extension while experiencing a decrease in one's base of support. Analysis of the biomechanics between seat-off and gait are part of the larger study.

Significance

The results suggest that the low bed height is the least safe across the sample set, as it has the greatest number of trials with FREs. There is also evidence that bouncing is employed by a large percentage of those at high fall risk and it appears there may be a link between employment of the bouncing strategy and FREs at low and medium bed heights. Further analysis of the larger data set may provide the statistical justification for an appropriate bed height for a safer egress, as well as guidance on safe egress strategy, thus reducing the number of elderly patient falls.

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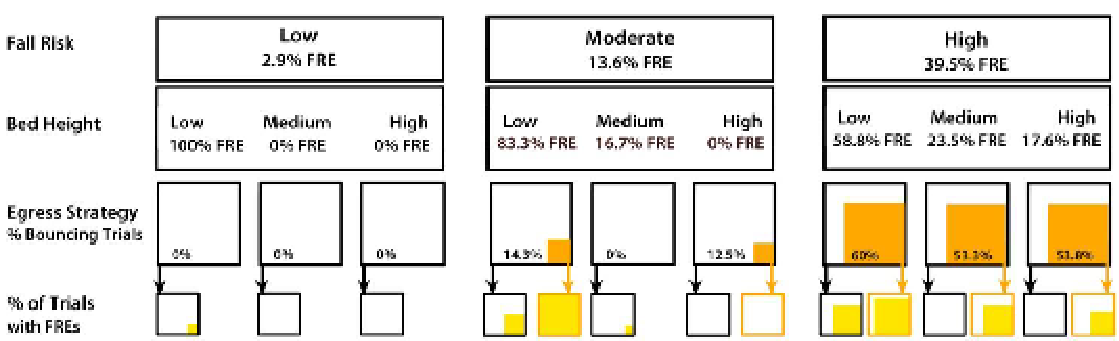


Figure 1: Distribution of FREs stratified by fall-risk groups, bed height, bed egress strategy, and unique trials with FREs. Orange blocks represent the proportion of trials using a bouncing egress strategy. Yellow blocks represent percentage of trials with FREs.

APPENDIX C

TRAINING INSTRUCTIONS FOR CODING

Training Instructions for Coding Visual and Biomechanical Events (STSW Key Events, CBs, Jerk, and FREs)

Training Instructions Part 1:

Syncing Videos with Visual3D

In order to consistently identify key events in the sit-to-walk-to-sit (SWS) movements, the following procedure is to be followed by all coders. Bed egress to chair ingress trials from the hospital bed study will be used. All needed files can be found in UBOX under the 'Hospital Bed Study Video Files' folder that has been shared with you.

STEP 1: Begin by logging into UBOX (either through CIS, or directly) and selecting the 'Hospital Bed Study' folder.

STEP 2: Select the 'Video Files' folder.

STEP 3: Select the assigned file number folder (participant number), and leave this window open.

STEP 4: Open Adobe Premiere.

STEP 5: Click on 'FILE', then 'New Project' and name this file '(two digit participant#)_VIDEO(#)_BCH'

STEP 6: With both windows open, drag the video file to the top left box in Adobe Premiere. You can also import the video by going to 'FILE' then 'IMPORT'.

STEP 7: Move blue toggle toward the right and begin video observation toward the end of the video when subject is sitting upright on the bed. Follow the instructions below to identify the start point of the bed to chair segment.

- ***Listen for the group of 3 bells.*** (The audio can be visually seen in the bottom right editing section of Premiere.) ***The third bell indicates the approximate start of the V3D recording. The starting point for the segment will need to be verified with V3D, as follows:***

STEP 8: Download the corresponding Visual3D File (see example in column 2 of Table 1 below) and open in Visual3D (V3D).

VIDEO files (.mp4) are found in UBOX under: '.../VIDEO FILES/064'	**Corresponding V3D file (.c3d) is found in UBOX under: '.../V3D files/64.cmz' and then open specific trial in V3D***	**Save Premiere *tagged* file (.prproj) in UBOX under: '../Tagged Premiere Videos/64/...'**	**Save *exported data* from Premiere under: '.../Exported Tag Data/64/...'**
VIDEO 1 S064_LB_S.mp4	S064_LB_S_003.c3d	64_VIDEO1_BCH.prproj	VIDEO 1 S064_LB_S.csv
VIDEO 2 S064_MB_S.mp4	S064_MB_S_003.c3d	64_VIDEO2_BCH.prproj	VIDEO 2 S064_MB_S.csv
VIDEO 3 S064_HB_S.mp4	S064_HB_S_003.c3d	64_VIDEO3_BCH.prproj	VIDEO 3 S064_HB_S.csv
VIDEO 4 S064_LB_HR.mp4	S064_LB_HR_003.c3d	64_VIDEO4_BCH.prproj	VIDEO 4 S064_LB_S.csv
VIDEO 5 S064_MB_HR.mp4	S064_MB_HR_003.c3d	64_VIDEO5_BCH.prproj	VIDEO 5 S064_MB_S.csv
VIDEO 6 S064_HB_HR.mp4	S064_HB_HR_003.c3d	64_VIDEO6_BCH.prproj	VIDEO 6 S064_HB_S.csv
VIDEO 7 S064_LB_N.mp4	S064_LB_N_003.c3d	64_VIDEO7_BCH.prproj	VIDEO 7 S064_LB_S.csv
VIDEO 8 S064_MB_N.mp4	S064_MB_N_003.c3d	64_VIDEO8_BCH.prproj	VIDEO 8 S064_MB_S.csv
VIDEO 9 S064_HB_N.mp4	S064_HB_N_003.c3d	64_VIDEO9_BCH.prproj	VIDEO 9 S064_HB_S.csv

Table 1. Files to be viewed and synced for each participant; participant 64 shown as an example.

***Visual3D trials to be tagged/coded that are listed in this column can be seen in Figure 1 below.

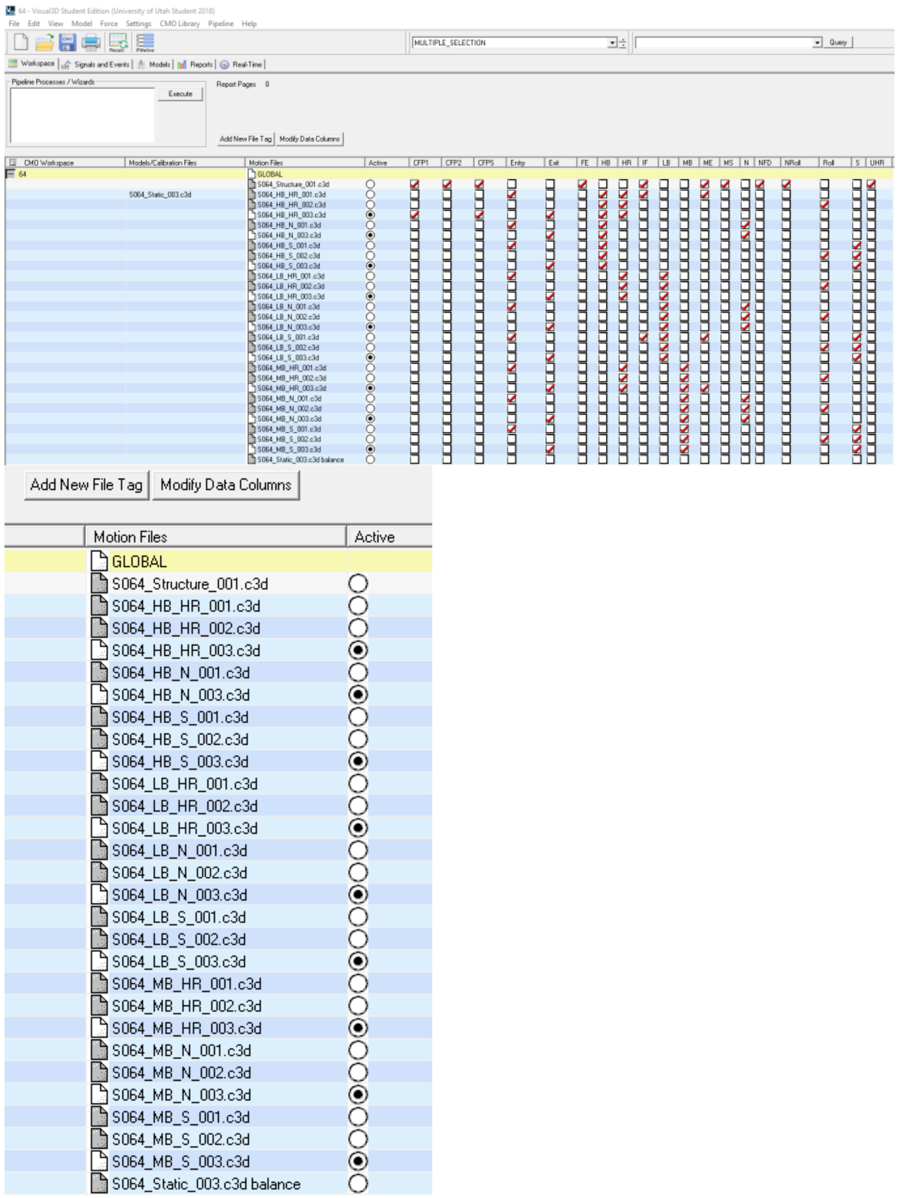


Figure 1. Nine bed to chair trials are selected in V3D file, as indicated by the darkened circles.

STEP 9: Play the V3D video with Premiere video to ensure same start.

- This can be done by having the Premiere window active, while having the cursor in the V3D window ready to click play. When ready, click the tab bar to activate the Premiere video and then immediately after, click the play button with the cursor in V3D. This should be close enough to judge if the video and V3D are starting at, or very close to, the same point in time.
- If the V3D video start cannot easily be matched to the Premiere video (ie, no identifiable movement), use the following procedure to sync the videos:
  - Step 1: Locate an identifiable event that can be matched between Premiere and V3D.

- Step 2: Note the frame number in V3D.
- Step 3: Calculate the frame number for Premiere by using the following equation:

  V3Dframe# x (30/100) = Premiereframe#

Once the Premiereframe# is calculated, check to see if that number is greater than 29.

If the Premiereframe# is greater than 29, you must subtract 30. The 30 subtracted is equal

to one second, and any remaining number is the frame number in Premiere.

For ***example***: if the frame number was 130 in V3D, I would calculate the Premiere frame number to be 130 x (30/100) = 39. This calculated Premiere frame number is greater than 29, so I subtract 30 as follows: 39 - 30 = 9. Since the remaining frame number (9) is less than 29, I have found my Premiere frame number. Thus, in Premiere, starting from the identified event, I would go back one second and 9 frames. This is the point in time where I would set the start of the segment.

STEP 10: Using the open bracket, {, mark the start of the Premiere video segment (found in STEP 9) to be analyzed.

STEP 11: Using the close bracket, }, mark the end of the video segment at the single bell at video end.

STEP 12: Click on this video (in top left view box) and drag to bottom right view box. This will also bring the new video segment to the top right view box.

STEP 13: SAVE the cut Premiere file with the same naming protocol as found in column one, with the exception that it is a .prproj file now (not a .mp4 file).

STEP 14: UPLOAD the cut Premiere file to UBOX under 'Hospital Bed Study/CUT Premiere Videos/(Subject ##)/(VIDEO)'

Training Instructions Part 2:
Tagging PremierePro Videos with Sit-to-Stand-and-Walk-to-Sit (SWS) Key Events, Corrective Behaviors, and Rating Observed Fall Risk

STEP 1. Open the appropriate cut Premiere file.

STEP 2. Before adding any markers, **save** the Premiere project in the correct format for the

'tagged' file (see column 3 in Table 2 below).

VIDEO files (.mp4) are found in UBOX under: '.../VIDEO FILES/064'	**Corresponding V3D file (.c3d) is found in UBOX under: '.../V3D files/64.cmz' and then open specific trial in V3D***	**Save Premiere *tagged* file (.prproj) in UBOX under: '../Tagged Premiere Videos/64/...'**	**Save *exported data* from Premiere under: '.../Exported Tag Data/64/...'**
VIDEO 1 S064_LB_S.mp4	S064_LB_S_003.c3d	64_VIDEO1_BCH.prproj	VIDEO 1 S064_LB_S.csv
VIDEO 2 S064_MB_S.mp4	S064_MB_S_003.c3d	64_VIDEO2_BCH.prproj	VIDEO 2 S064_MB_S.csv
VIDEO 3 S064_HB_S.mp4	S064_HB_S_003.c3d	64_VIDEO3_BCH.prproj	VIDEO 3 S064_HB_S.csv
VIDEO 4 S064_LB_HR.mp4	S064_LB_HR_003.c3d	64_VIDEO4_BCH.prproj	VIDEO 4 S064_LB_S.csv
VIDEO 5 S064_MB_HR.mp4	S064_MB_HR_003.c3d	64_VIDEO5_BCH.prproj	VIDEO 5 S064_MB_S.csv
VIDEO 6 S064_HB_HR.mp4	S064_HB_HR_003.c3d	64_VIDEO6_BCH.prproj	VIDEO 6 S064_HB_S.csv
VIDEO 7 S064_LB_N.mp4	S064_LB_N_003.c3d	64_VIDEO7_BCH.prproj	VIDEO 7 S064_LB_S.csv
VIDEO 8 S064_MB_N.mp4	S064_MB_N_003.c3d	64_VIDEO8_BCH.prproj	VIDEO 8 S064_MB_S.csv
VIDEO 9 S064_HB_N.mp4	S064_HB_N_003.c3d	64_VIDEO9_BCH.prproj	VIDEO 9 S064_HB_S.csv

Table 2. Files to be tagged in PremierePro for each participant; participant 64 shown as an example.

STEP 3. Using this video segment (starting at time=0), visually observe the bed egress to chair ingress (***SWS***).

STEP4: Key events named below (and found in the CODING CHEAT SHEET) will be marked in Premiere using the Mark tool (first icon in the row of icons under the timeline in the top right view box). This is done by first dragging the blue marker to the correct frame in the timeline in the bottom right view box.

STEP 5: Select the white marker icon in the top right view box. A green marker will appear in the timeline.

STEP 6: Double click on the green marker, and a new box will appear.

STEP 7: Name the marker with the appropriate identifier, such as SP, SI, SO, etc.

STEP 8: Also add the rating in the comment box.

STEP 9: Finish by clicking OK, and proceed to the next event to mark.

STEP 10: Repeat steps 5-9 until all events and corrective behaviors are tagged/coded.

NOTE: Only one tag descriptor can be added per frame. If two coincide on the same frame, you will need to choose to locate one of the two on the frame before or after.

STEP 11: Save the Tagged Premiere file in the current location on your encrypted flash drive, then copy the file to UBox in '.../Tagged Premiere Videos/BCH/(two digit Participant#)/(two digit participant#)_VIDEO(#)_BCH.prproj'

STEP 12: Export Marker (tag) data from Premiere, saving as indicated in the table above, by selecting 'FILE', then 'EXPORT', then 'MARKERS'.

STEP 13: Upload this file into UBOX under '...Exported Tag Data/(two digit Participant#)' file folder.

- ***NORMAL SWS***
  1. Stand Preparation (SP) = Movements forward, shifting, etc. (NOTE: There may not be any stand preparation.)
  2. Stand Initiation (SI) = First movement indicating the intent to stand.
  3. Seat-off (SO) = Buttocks is off bed (if using bouncing strategy, SO occurs with the start of the last bounce); look for start of mattress movement.
  4. Gait Initiation Foot Off (GIFOL/R) = First step, starting at heel/foot off, after (not including) any CB Foot, indicate L or R.
  5. Foot Contact (FCL/R)* = Foot contacts floor (indicate L or R).
  6. Foot Off (FOL/R)* = Foot off of floor (indicate L or R).
  7. Turn Initiation Foot Contact (TIFCLO/CO/F/L/R)* = Foot contact of first turn step (note type of turn step: Lead Out (LO), cross over (CO) or Follow (F)=turns by making several small steps, as well as which foot: Left or Right).

8. Turn Initiation Foot Off (TIFOLO/CO/F/L/R)* = Foot off of floor for first turn step (note type of turn step: Lead Out (LO), cross over (CO) or Follow (F), as well as which foot: Left or Right).
9. Turn Foot Off (TFOL/R)* = During turning, foot comes off of floor (indicate L or R).
10. Turn Foot Contact (TFCL/R)* = During turning, foot contacts floor (indicate L or R).
11. Turn Foot Contact Cross Behind (TFCCBL/R)* = During turning, foot crosses behind other foot.
12. Turn End (TE) = Rotation of pelvis/torso has slowed or stopped, and vertical descent has started. (This may be difficult if the person is turning and sitting at the same time. If this is the case, indicate end of turn at start of vertical descent.)
13. Seat-contact (SC) = Buttocks is in contact with chair, and thigh is approximately horizontal with the floor. There will be a slight depression of the seat as the subject comes in contact with the seat.
14. Seat End (SE) = Subject is settled in chair and at rest, including back, arms and legs/feet.

*Add an ‘S’ to the end of a foot code if the foot does not completely leave the floor, ie. Slides, slips or shuffles.

- ***CORRECTIVE BEHAVIORS***

Review the video a second time to visually observe & notate any ***Corrective Behaviors***:

(Follow the same marking procedure described for key events above.)

In the future, all CBs will be analyzed to determine which CBs are, indeed, movements that correct an imbalance, or provide stability.

NOTE: Mark the frame of both contact and release of all CBs,
where CBs = irregular movements that appear to correct an imbalance, or provide stability.

The four corrective behavior types to be marked include: HAND, FOOT, TORSO, and LEG.

Hand (CBHR/L) = hand reaches and/or grasps or touches surface/object
Foot (CBFR/L) = foot takes an additional step, often small and to the side
Torso (CBT) = torso moves, usually quickly to regain or maintain balance
Leg (CBLL/R) = leg contacts surface, usually against the bed/chair

NOTE: Any foot movement/contact prior to stand initiation or once the subject is seated needs to be marked as a CBF.*

*Add an 'S' to the end of a foot code if the foot does not completely leave the floor, ie. Slides, slips or shuffles.

- ***OBSERVED FALL RISK* for Egress** (to be recorded in appropriate marker comment box in Premiere as noted below)**:**
  Rate 1-4 for each phase, where

1. **STAND PREPARATION PHASE**: SP to SI (bounce, scoot, CBs) (Put rating in SI MARKER COMMENT box)
   1 = Probably N/A (smooth motion, no use of bed and/or bedrail)
   2 = slight use of bed and/or bedrail, lightly touching
   3 = moderate use of bed and/or bedrail, light pressure applied
   4 = obvious jerky motion, bouncing, and/or obvious reliant use of bed and/or bedrail surfaces
2. **STAND INITIATION PHASE:** SI (SI = torso flexion just prior to SO) to SO (Put rating in **GIFOL/R** MARKER COMMENT box)
   1 = smooth motion, no use of bed and/or bedrail
   2 = slight use of bed and/or bedrail
   3 = moderate use of bed and/or bedrail, light pressure applied
   4 = obvious jerky motion, bouncing and/or obvious reliant use of bed and/or bedrail surfaces

3. **STAND PHASE:** SO (Seat off) to GIFOL/R (also referred to as Sw)
4. **GAIT INITIATION PHASE:** GIFOL/R (Sw) to second foot-off gait step (St)

4. **GAIT PHASE:** GIFOL/R (when GIFOL/R = first forward step taken) to **TIF...** (Put rating in **TIF...** MARKER COMMENT box)
   1 = smooth motion, regular (large) step length
   2 = slight jerky motion, regular step length
   3 = moderate jerky motion, slow and/or small step length, slight reaching or other unusual positions/motions
   4 = obvious jerky motion, very slow and/or very small step length, moderate to obvious reaching or other unusual positions/motions

5. **TURN PHASE:** TIF... to **TE** (Put rating in **TE** MARKER COMMENT box)
   1 = smooth motion
   2 = slight jerky motion, light use of chair armrest(s)
   3 = moderate jerky motion, moderate use of chair armrest(s)
   4 = obvious jerky motion, reliant use of chair armrest(s)

6. **SIT PHASE:** TE to **SC** (Put rating in **SC** MARKER COMMENT box)
1 = smooth motion
2 = slight jerky motion, light use of chair armrest(s)
3 = moderate jerky motion, moderate use of chair armrest(s), moderate plop into chair
4 = obvious jerky motion, reliant use of chair armrest(s), significant plop into chair

7. **SETTLE PHASE:** SC to **SE** (Put rating in **SE** MARKER COMMENT box)
1 = smooth motion, minimum movement after seat contact and torso relaxing back
2 = little adjustment after seat contact/torso back, such as hands/arms coming to rest or together
3 = moderate adjustment following seat contact/torso back, such as moving arms, legs, feet
4 = obvious shifting/adjusting body to settle in seat

Table 3. CODING SHEET

Code	Stands for…	Definition
SP	Stand Preparation	Movements forward, shifting, bouncing, etc.
SI	Stand Initiation	Torso flexion followed immediately by seat off and torso extension (torso flexion of last bounce when there are a series of bounces prior to torso extension that leads to a rising to a stand).
SO	Seat-off	Buttocks are off bed (if using bouncing strategy, SO occurs with the start of the last bounce); look for start of mattress movement/release of force on bed.
CBFCL/R*+	Corrective Behavior Foot Contact (L for Left *or* R for Right)	Extra step, other than normal stand or gait (indicate L or R).
CBFOL/R*+	Corrective Behavior Foot Off (L for Left *or* R for Right)	Extra step release, other than normal stand or gait (indicate L or R).
CBHCL/R*	Corrective Behavior Hand Contact (L for Left *or* R for Right)	Hand is in intentional/force applied contact with surface, other than at rest (indicate L or R).
CBHOL/R*	Corrective Behavior Hand Off (L for Left *or* R for Right)	Hand is no longer in contact with surface (indicate L or R).
CBLCL/R*	Corrective Behavior Leg Contact (L for Left *or* R for Right)	Leg is in intentional/force applied contact with surface, other than at rest (indicate L or R).
CBLOL/R*	Corrective Behavior Leg Off (L for Left *or* R for Right)	Leg is no longer in contact with surface (indicate L or R).

CBT	Corrective Behavior Torso	Torso rapidly moves to balance.
CBFACBL/R*	Corrective Behavior Fore Arm Begin Contact	While sitting down, the forearms are used to maintain downward descent/posture
CBFACEL/R*	Corrective Behavior Fore Arm End Contact	Forearms no longer in contact with the surface of the armrests
CBHRBL/R*	Corrective Behavior Hand Reach Beginning (L for Left *or* R for Right)	Hand appears to reach for correcting surface but does not contact and may hold position in-air (indicate L or R)
CBHREL/R*	Corrective Behavior Hand Reach End	Hand returns to a 'normal' position following 'contact' (indicate L or R).
IFCL/R*	Initial Foot Contact	When sitting on a medium or high bed height, often feet do not touch the floor until initiating STSW; this tag indicates when the foot makes first contact with the floor.
GIFOL/R*	Gait Initiation Foot Off (L for Left *or* R for Right)	First step, starting at heel/foot off, after (not including) any CB Foot (indicate L or R).
FCL/R*+	Foot Contact (L for Left *or* R for Right)	Foot contacts floor (indicate L or R).
FOL/R*+	Foot Off (L for Left *or* R for Right)	Foot off of floor (indicate L or R).
TIFCLO/CO/F/L/R* LO CO F L *or* R	Turn Initiation Contact - Lead Out (away from body) - Cross Over - Follow (L for Left *or* R for Right)	Foot contact of first turn step (note type of turn step: Lead Out (LO), cross over (CO) or Follow (F), as well as which foot: Left or Right). [Only use for 1st step of turn]

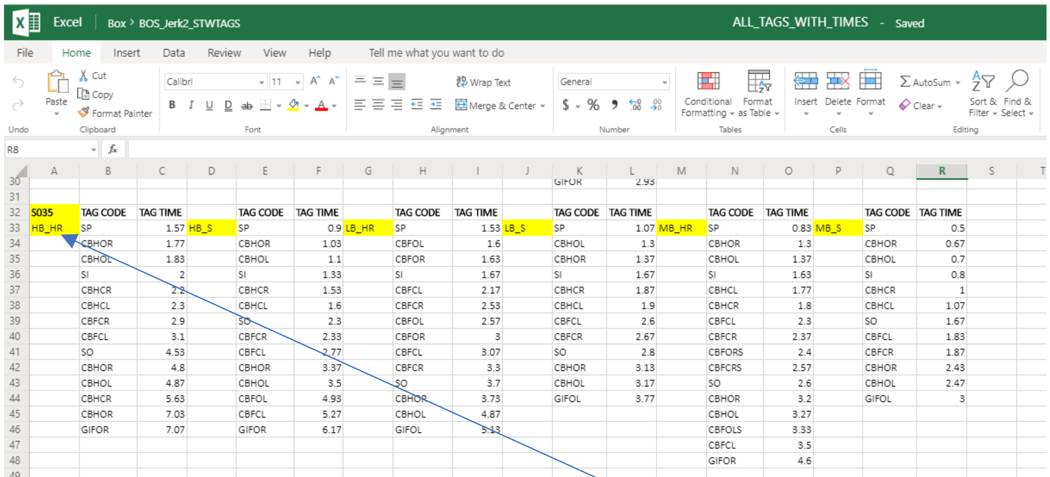
TFOL/R* L *or* R	Turn Foot Off (L for Left *or* R for Right)	During turning, foot comes off of floor (indicate L or R).
TFCL/R*	Turn Foot Contact (L for Left *or* R for Right)	During turning, foot contacts floor (indicate L or R).
TFCCBL/R*	Turn Foot Contact Cross Behind	During turning, foot crosses behind
TE	Turn End	Rotation of pelvis/torso has stopped
VD	Vertical Descent	Descent to sit begins.
SC	Seat-contact	Buttocks on chair
SE	Seat End	Subject is settled in chair and at rest

*Add an 'S' to the end of a foot code if the foot does not completely leave the floor, ie. Slides, slips or shuffles.
+Any foot movement/contact prior to stand initiation or once the subject is seated needs to be marked as a CBF.

TRAINING INSTRUCTIONS Part 3:

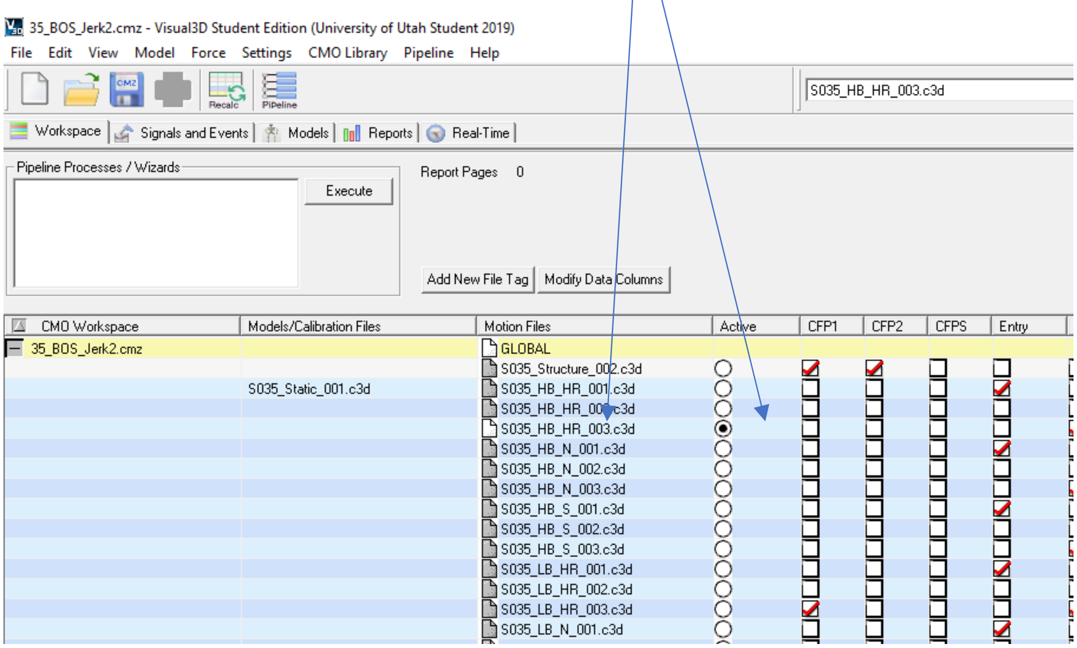
Adding Premiere Tags in Visual 3D

1. Open Ubox; select the ‘Hospital Bed Study’ folder; then select the ‘BOS_Jerk2’ folder
2. From this folder, select the specific subject’s .cmz file (‘##_BOS_Jerk2.cmz’), download and then open it on your laptop.
3. Back in ‘Ubox/Hospital Bed Study’, open the ‘BOS_Jerk2_STWTAGS’ folder.
4. From this folder, open the ‘ALL TAGS WITH TIMES.xlsx’ file (shown below) and keep open for reference for all subject .cmz files.

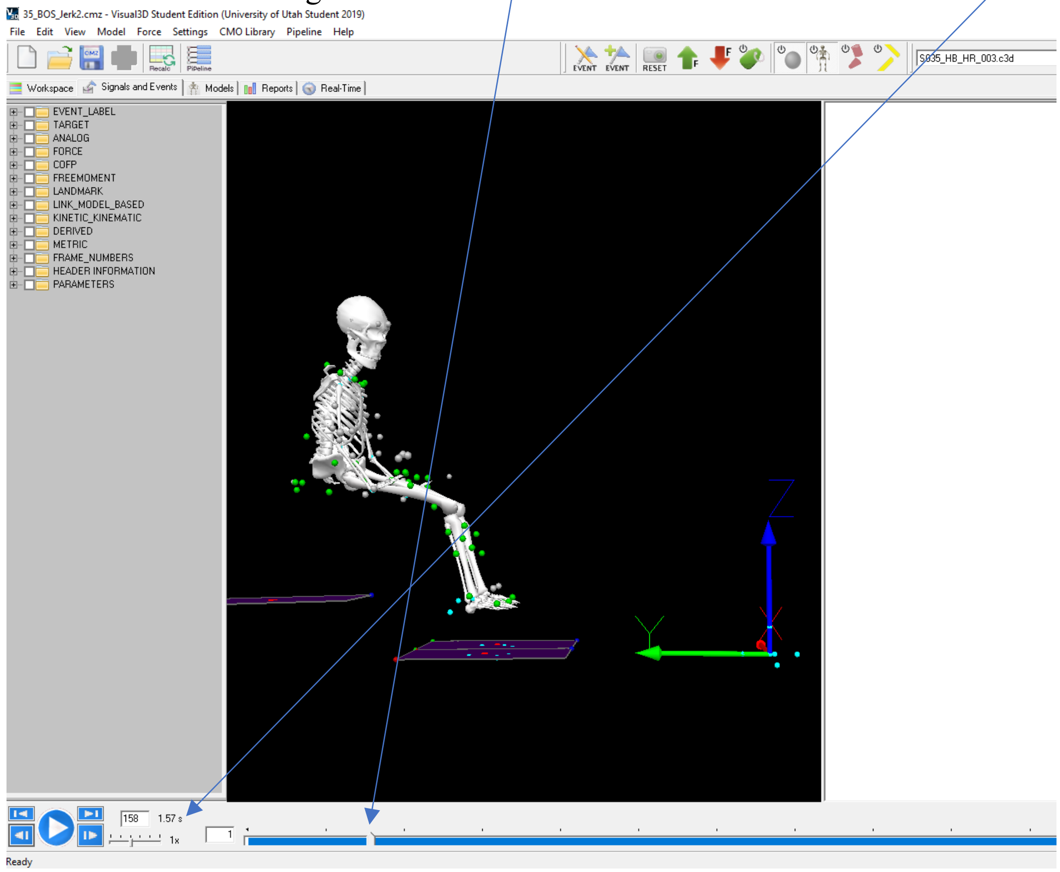


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
30											GIFOR	2.93						
31																		
32	S035	TAG CODE	TAG TIME		TAG CODE	TAG TIME		TAG CODE	TAG TIME		TAG CODE	TAG TIME		TAG CODE	TAG TIME		TAG CODE	TAG TIME
33	HB_HR	SP	1.57	HB_S	SP	0.9	LB_HR	SP	1.53	LB_S	SP	1.07	MB_HR	SP	0.83	MB_S	SP	0.5
34		CBHOR	1.77		CBHOR	1.03		CBFOL	1.6		CBHOL	1.3		CBHOR	1.3		CBHOR	0.67
35		CBHOL	1.83		CBHOL	1.1		CBFOR	1.63		CBHOR	1.37		CBHOL	1.37		CBHOL	0.7
36		SI	2		SI	1.33		SI	1.67		SI	1.67		SI	1.63		SI	0.8
37		CBHCR	2.2		CBHCR	1.53		CBFCL	2.17		CBHCR	1.87		CBHCL	1.77		CBHCR	1
38		CBHCL	2.3		CBHCL	1.6		CBFCR	2.53		CBHCL	1.9		CBHCR	1.8		CBHCL	1.07
39		CBFCR	2.9		SO	2.3		CBFOL	2.57		CBFCL	2.6		CBFCL	2.3		SO	1.67
40		CBFCL	3.1		CBFCR	2.33		CBFOR	3		CBFCR	2.67		CBFCR	2.37		CBFCL	1.83
41		SO	4.53		CBFCL	2.77		CBFCL	3.07		SO	2.8		CBFORS	2.4		CBFCR	1.87
42		CBHOR	4.8		CBHOR	3.37		CBFCR	3.3		CBHOR	3.13		CBFCRS	2.57		CBHOR	2.43
43		CBHOL	4.87		CBHOL	3.5		SO	3.7		CBHOL	3.17		SO	2.6		CBHOL	2.47
44		CBHCR	5.63		CBFOL	4.93		CBHOR	3.73		GIFOL	3.77		CBHOR	3.2		GIFOL	3
45		CBHOR	7.03		CBFCL	5.27		CBHOL	4.87					CBHOL	3.27			
46		GIFOR	7.07		GIFOR	6.17		GIFOL	5.13					CBFOLS	3.33			
47														CBFCL	3.5			
48														GIFOR	4.6			
49																		

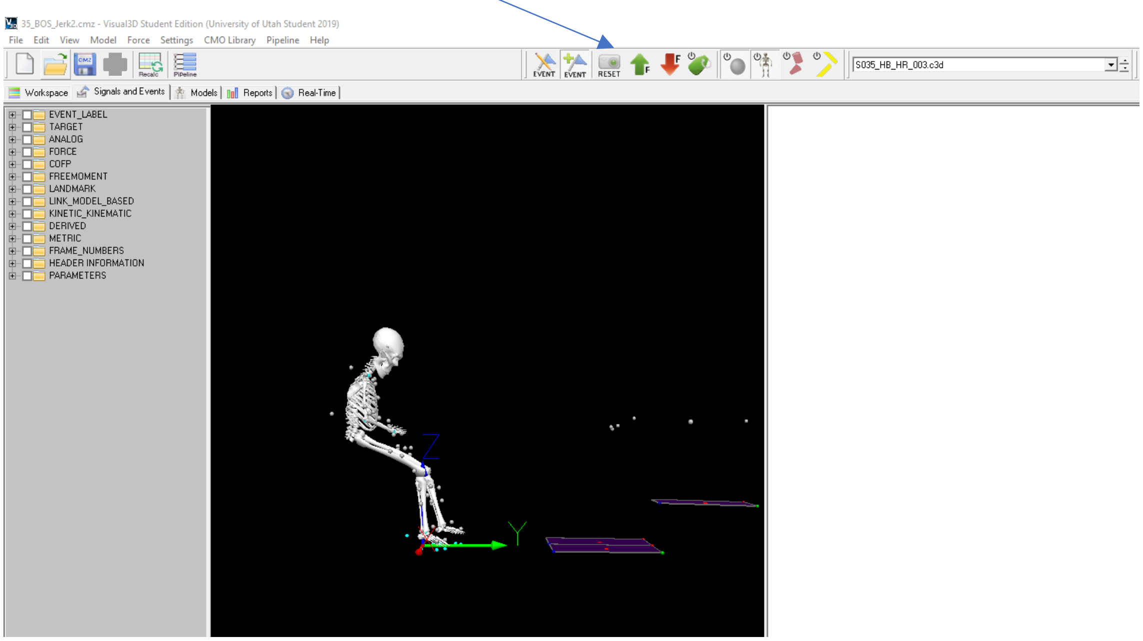
5. Look on the .xlsx file ‘ALL TAGS WITH TIMES” to see the first egress trial listed for the given subject number. Double click on the corresponding trial (usually _003, sometimes .004 to indicate egress trial) in the Visual 3D Workspace tab. This opens the ‘Signals and Events’ tab in Visual 3D.



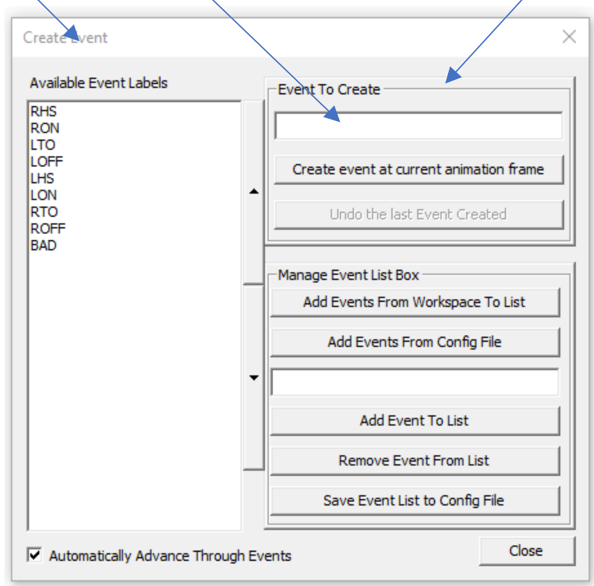
6. By clicking on and dragging the white indicator tab, position it at the appropriate event time where the tag is to be added.



7. Next, select the '+ EVENT' button to add a tag.



8. A small window will open where the tag can be added (shown below). Select from the ‘Available Event Labels’ (which automatically places the tag in the Event To Create box. Or, if the tag has not been created yet, type the new tag name in the ‘Event to Create’ box and click ‘Create event at current animation frame’. The tag has now been added.



9. Repeat steps 6-8 for all tags in the current trial.
10. Repeat steps 5-9 for each trial (for a given subject).
11. SAVE the .cmz file as ‘subject#_BOS_Jerk2_STWTAGS’ in the ‘BOS_Jerk2_STWTAGS’ folder.
12. Repeat steps 1-2 and 5-11 for each subject.

TRAINING INSTRUCTIONS Part 4:

Coding Fall Risk Episodes (FRE) in Visual3D

1. Open video into Adobe Premiere Pro and save as new project.
   (VIDEO # SOSUBJECT#_BedCondition_whoops_INITIALS)
2. Watch video to identify any FRE (cause concern, make you nervous, look unstable/potential fall).
3. Tag start and end of FRE
   a. FALL RISK EPISODE START LABEL: FR1start, FR2start,….
   b. FALL RISK EPISODE END LABEL: FR1end, FR2end,….
   c. Add a comment at end marker on what the motion of concern is, for example stumble step, reaching, etc.
4. Save Premiere Project (with tags completed*).
5. Export markers to .csv file
   (VIDEO #
   SOSUBJECT#_BedCondition_RailCondition_whoops_tags_INITIALS
6. Upload to Ubox.
   a. Premiere project file at 'Hospital Bed Study/Visual Identification of 'whoops' moments'
   b. .csv file at 'Hospital Bed Study/Visual Identification of 'whoops' moments/Exported visual tags csv files'
7. Delete files from computer
8. Repeat for all trials for each subject.

NOTE: If there are no FREs in a video trial, the following action should be taken:

- At the start of the video segment, after the three bells, insert one tag with the label "NA"
- In the marker comment field, enter "No whoops identified"
- Export Premiere project file and .csv file as outlined above

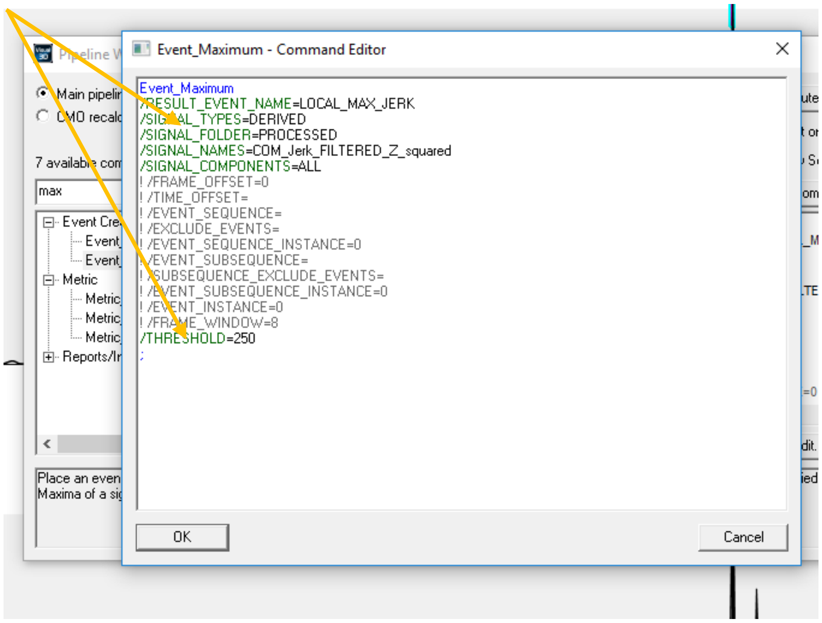
TRAINING INSTRUCTIONS Part 5:

Executing Jerk^2 pipeline

1. Open your first subject's .cmz file from the appropriate "Base of Support/BOS-(name)/(subject number)/(subject number) Edited" folder in Ubox. *[Ryan, I noticed your processed .cmz files are not labeled this way. So as to not cause any confusion with the original .cmz file, the edited files that you ran the BOS pipeline on need to be saved with the file name: "(subject number) Edited.cmz"]*
2. Within Visual 3D, select all "exit" files, so that all exit files can be run with the pipeline at the same time.
3. Open the pipeline "Jerk_squared_local_maximums" (found in the "BOS_Jerk2" folder on Ubox).
4. Execute the pipeline; a new screen will open.
5. Check for errors by scrolling through the screen.
6. If any errors are present, note in the "Jerk2" spreadsheet (found in the "BOS_Jerk2" folder on Ubox).
7. Save the updated .cmz file as "subject#_BOS_Jerk2" in the "BOS_Jerk2" Ubox folder.
8. Note on "Jerk2" spreadsheet that the specific subject file has been:
    a. run with the Jerk2 pipeline
    b. uploaded to Ubox
9. Close .cmz file.*
10. Open next .cmz file and repeat until all files are run with the Jerk2 pipeline.
    *NOTE: Once the new file has been saved, steps 9 and 10 can be done at the same time by selecting "File" then "Open/Add" and "Close all open files…", and then selecting the new file you want to open.

INSTRUCTIONS: *Jerk* identification

1. To identify significant Jerk, open the 'Event_Maximum' pipeline (found in Visual 3D Pipelines), and edit the pipeline as outlined in the image below (indicated by green):



*NOTE: This pipeline has been created and can be found in the 'BOS_Jerk2' folder as 'Jerk_squared_local_maximums.v3s'.

2. Execute pipeline, and verify that 'COM_Jerk_FILTERED_Z_squared' has been created without any 'WARNINGS'.

APPENDIX D

JERK^2 TRAJECTORY OF A-HIGH FALL-RISK INDIVIDUAL PERFORMING STSW AT LOW BED HEIGHT

The following images represent one trial of a high fall-risk level participant performing STSW from a hospital bed at the low bed height (LB) setting. The two shaded regions indicate the duration of two fall-risk episodes (FREs). The red horizontal line indicates the 250 $(m/s^3)^2$ threshold for *S*jerk^2. Any jerk^2 peak value above the threshold is marked as *S*jerk^2 with a blue triangle (see legend). STSW phases are designated, as well as STSW subphases. Additional text is added which indicates what movement was occurring during the peak jerk^2, along with the jerk^2 value. All corrective behaviors (CBs) are also noted on the graph (see legend). This specific trial includes multiple CBs, scooting, bouncing, falls, and rocking back on heels. All falls were readily identified by *S*jerk^2 in the Stand Initiation and Stand Phases. It should be noted that the *S*jerk^2 during the Stand Phase was representative of a fall being prevented. This indicates that when a harness is used to prevent a fall, there is still *S*jerk^2, although definitely lower than the actual fall that occurred earlier in the Stand Initiation Phase of this trial. Additional *S*Jerk^2 values in the Stand Preparation phase identified difficulty in rising, as well as in the Gait Initiation Phase during the transfer of weight at the end of the first step taken. While the Taylor Fall-proxy Model has been demonstrated to identify fall initiation in the Stand Initiation and Stand Phases, additional research would need to be done to identify an appropriate *S*jerk^2 threshold for other STSW phases.

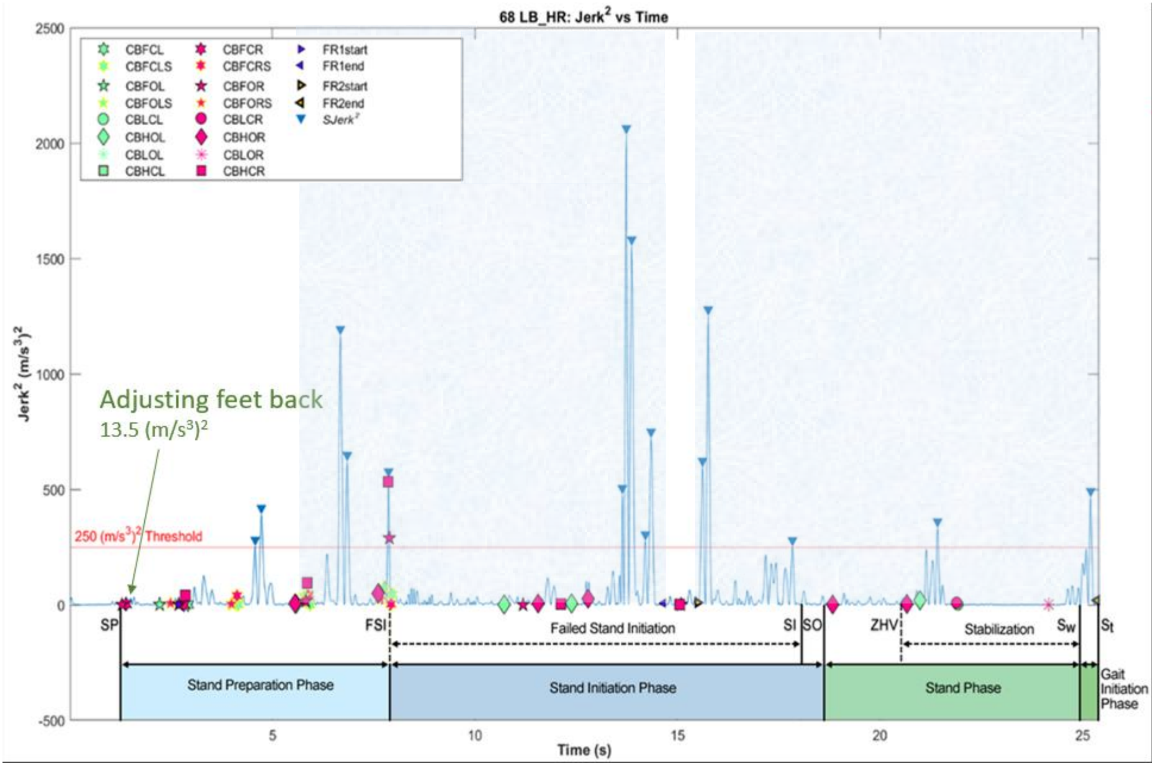


Figure D.1. Adjusting feet back

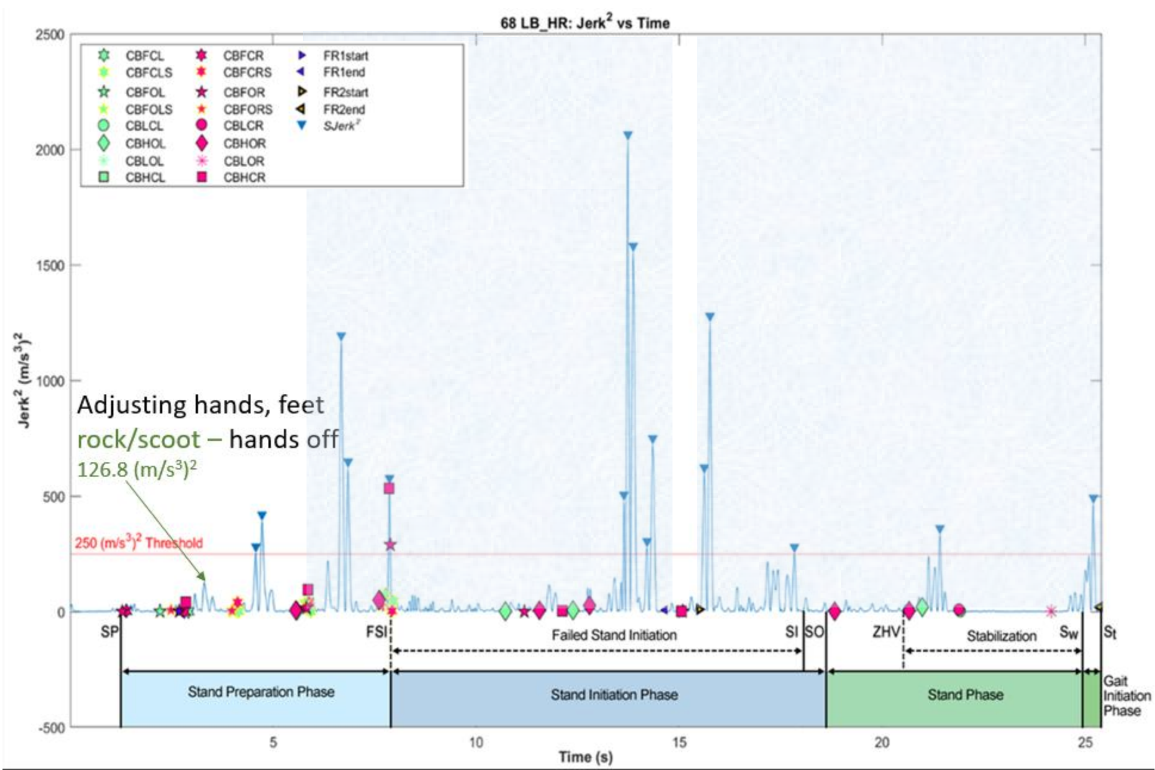


Figure D.2. Scooting

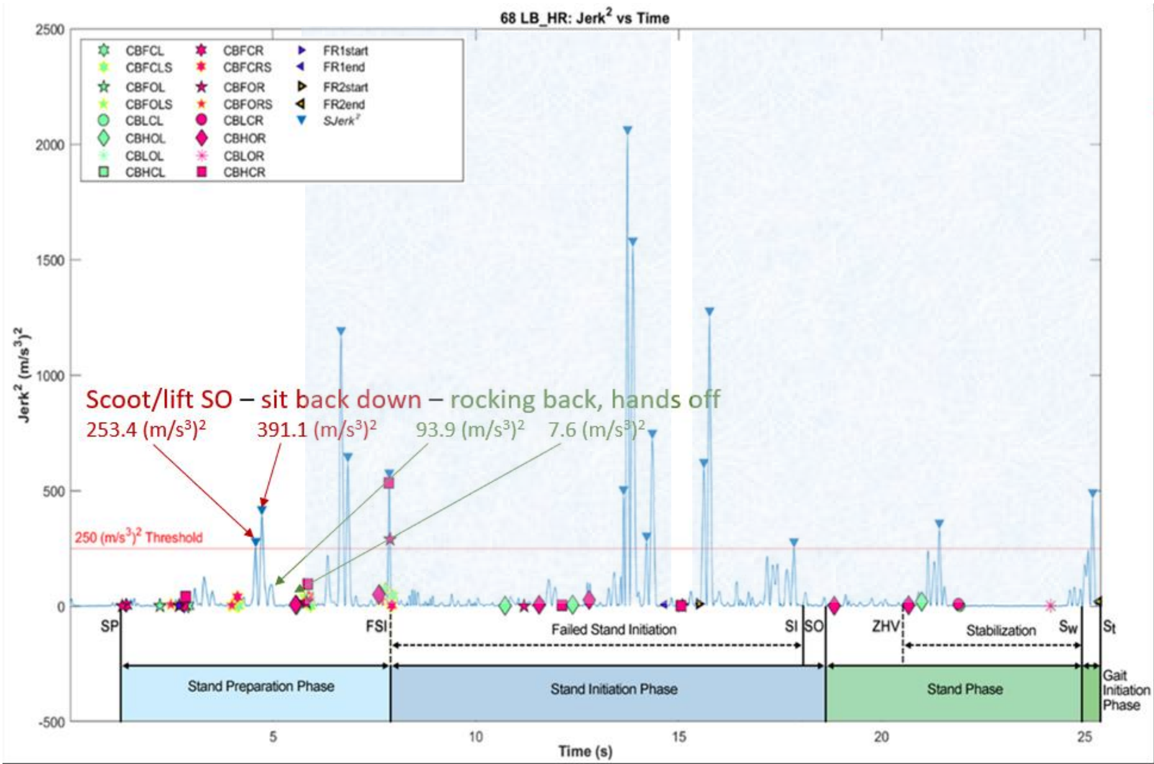


Figure D.3. Lift and sit back down

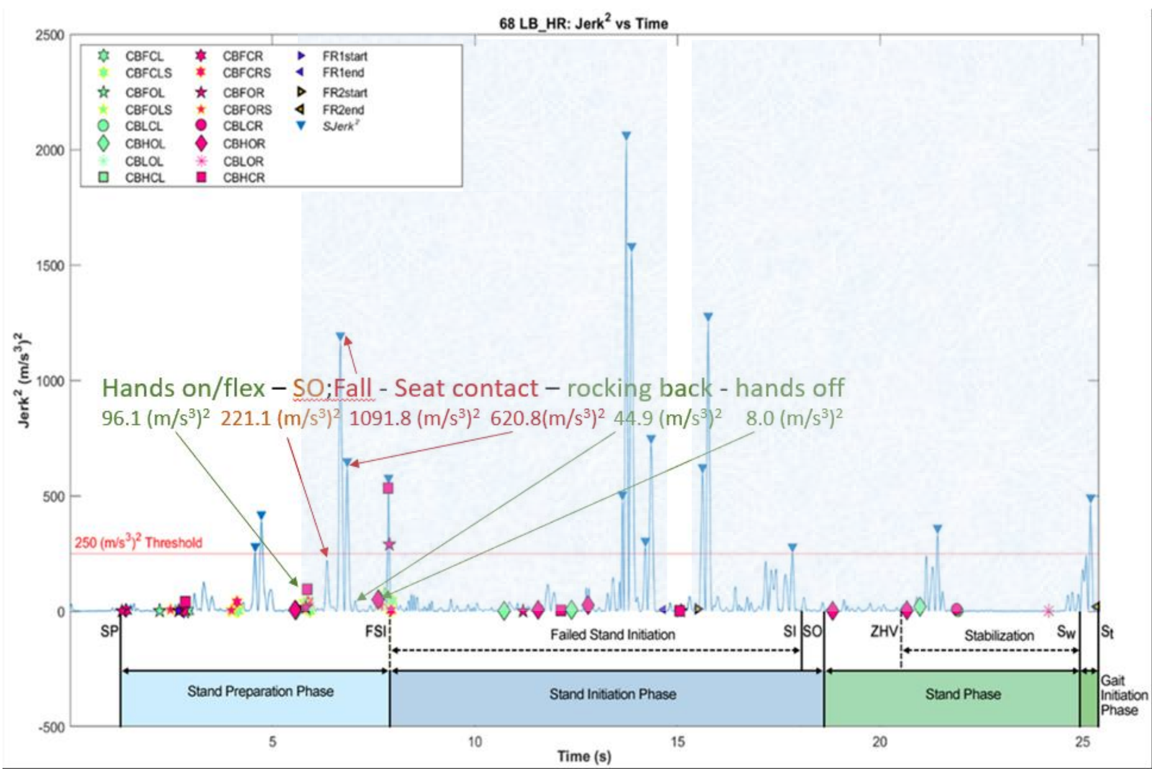


Figure D.4. Fall Initiation

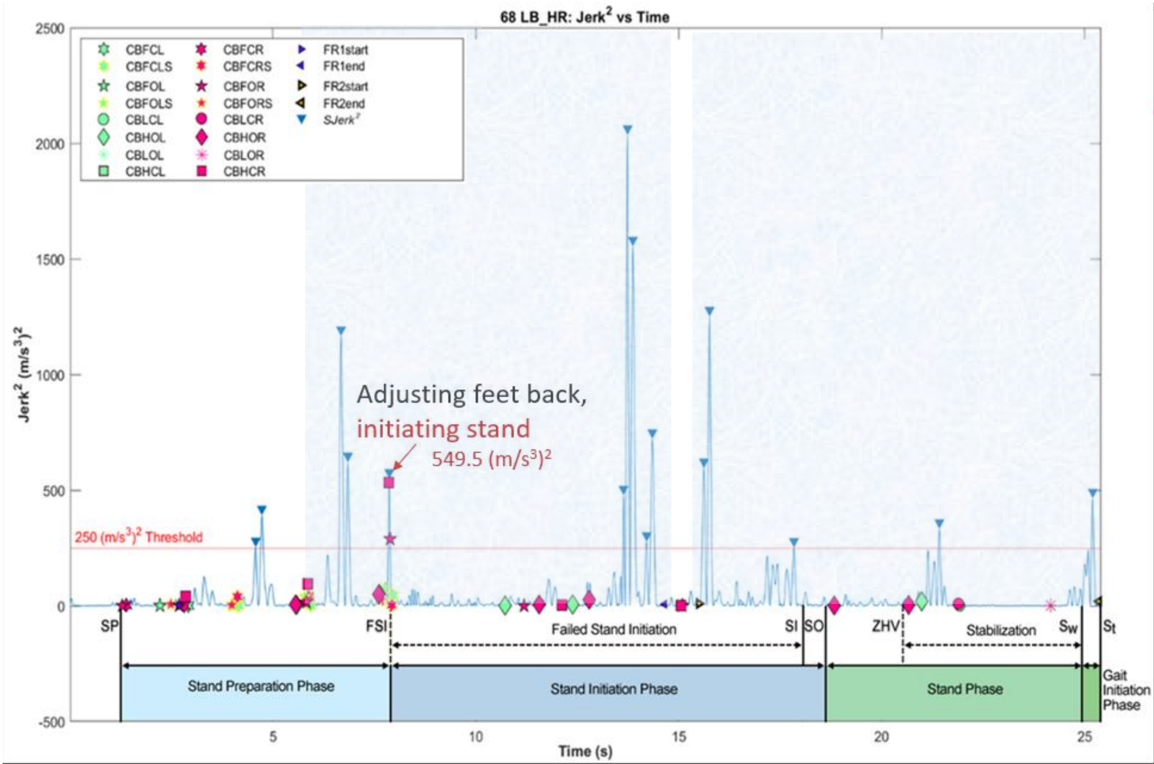


Figure D.5. Initiating a stand

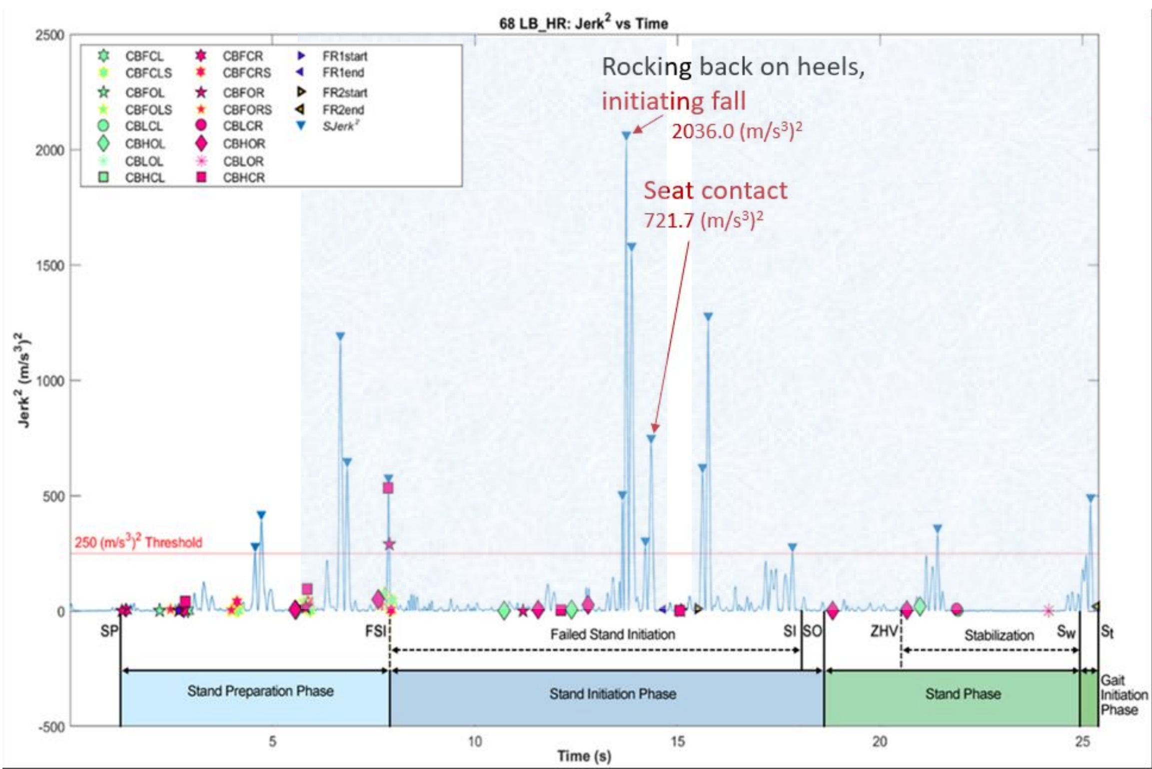


Figure D.6. Second fall initiation

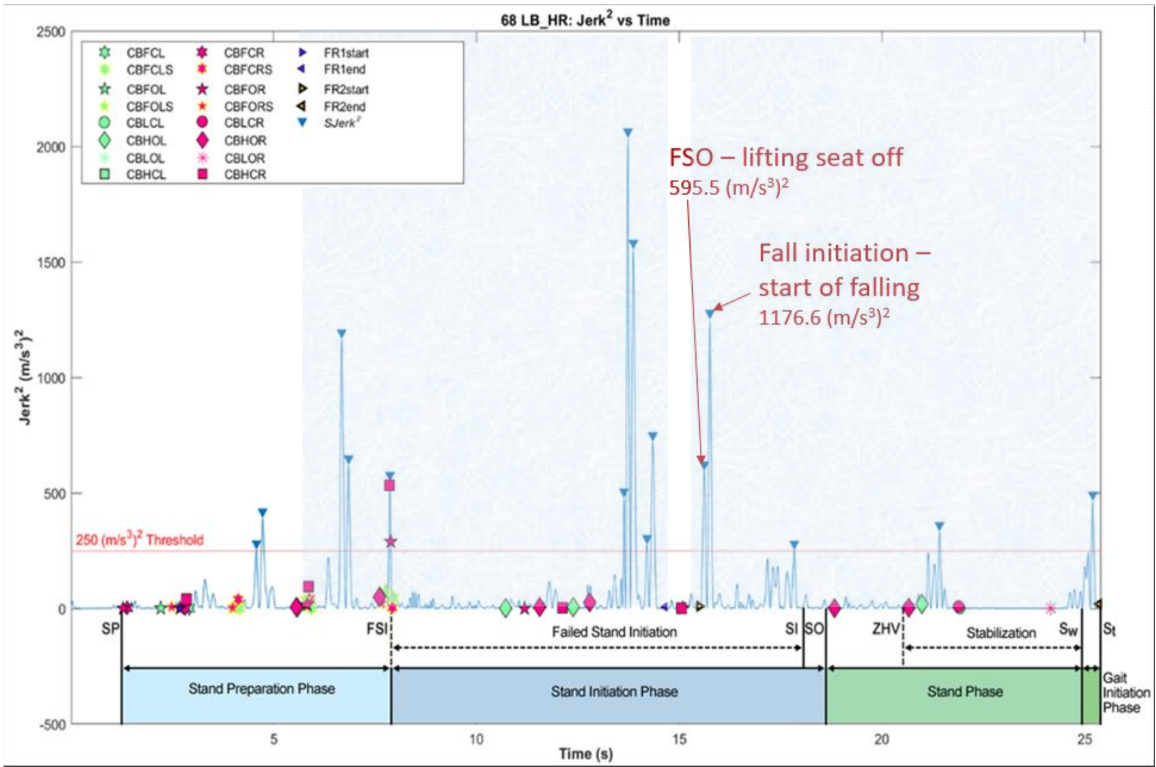


Figure D.7. Third fall initiation

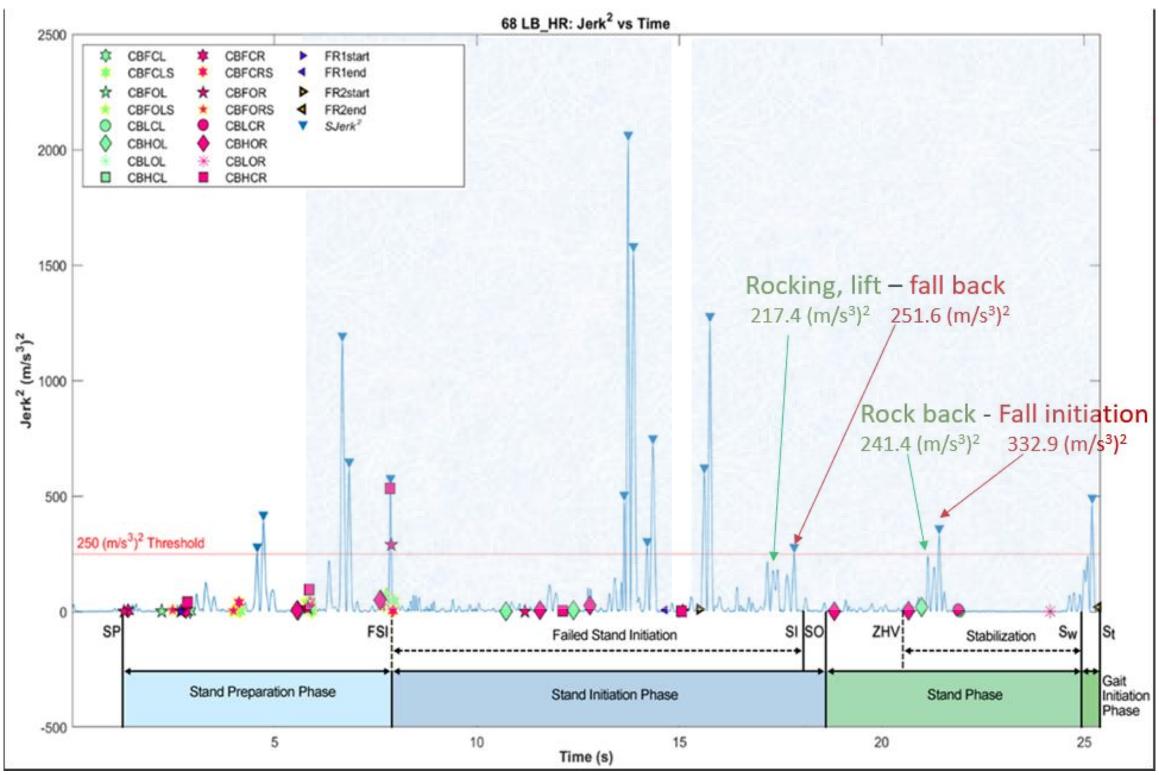


Figure D.8. Fourth fall initiation

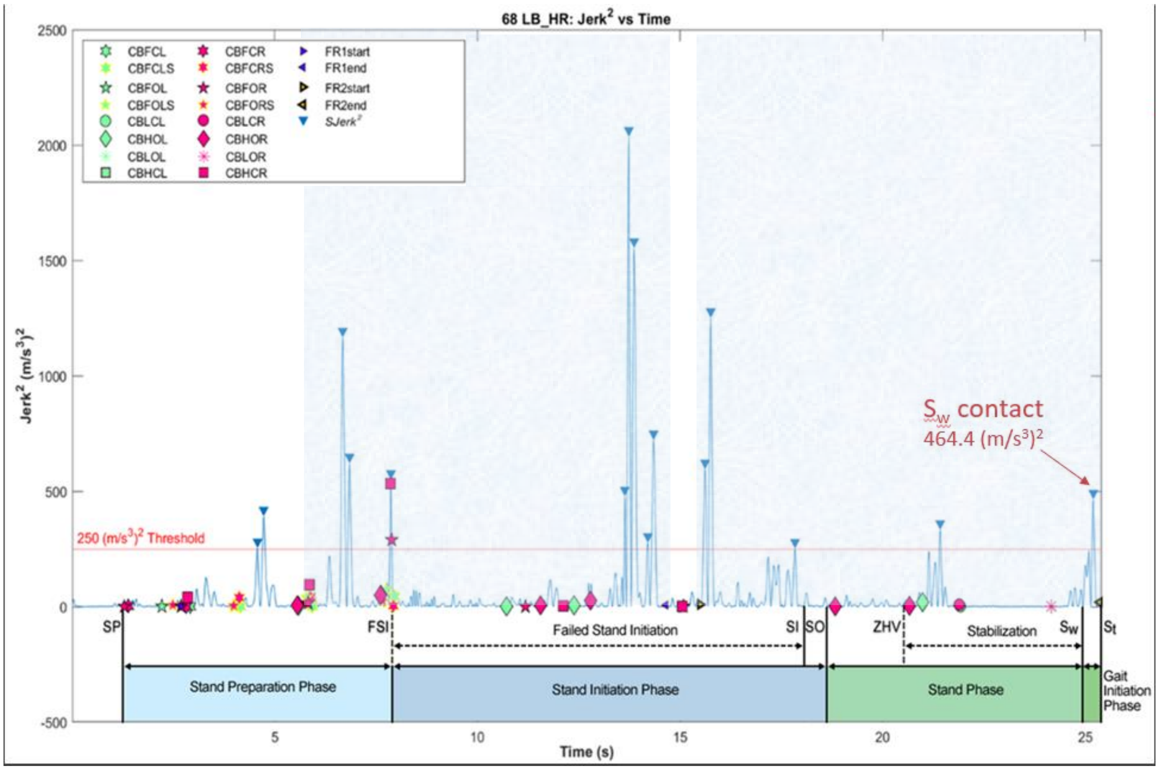


Figure D.9. Initiation of gait