Pilot Study to Enhance the Repeatability, Validity and Reliability of Traditional Observational Falls Risk Assessments by Incorporating Markerless Motion Capture Technology.

by

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Abstract

Certain individuals, especially those in the geriatric population experience falls each year. Although there are validated assessment tools, like the Berg Balance Scale (BBS), they can be very subjective and insensitive to change. These tools are also limited to face-to-face interactions between clinicians and patients. During the global COVID-19 pandemic, where face-to-face interactions have become difficult, especially for patients living in rural areas, a better way to assess the falls risk of individuals becomes pertinent.

Kinetisense is a markerless motion capture technology that has the ability to assess patients and produce objective results from these assessments.

The purpose of this pilot study was to develop a research protocol, using tasks from the BBS, to assess participants at risk of falling using markerless motion capture. The BBS assessments using markerless motion capture are referred to in this thesis as enhanced Virtual Berg Balance Scale (eV-BBS).

The long-term goal of this research is to validate markerless motion capture to objectively carry out risk assessments for falling and transform them into objective measures. Doing so would improve accessibility for patients living in rural areas, as well as establish a better way to store patient information to be accessible to clinicians over time.

This was a test-retest reliability study. It explored the hypotheses that there were no differences in the validity, reliability and repeatability of the eV-BBS tasks compared to BBS.

A convenience sample of ten participants from the healthy population and 4 participants from the long-term care (LTC) population were observed as they performed the BBS and eV-BBS tasks. The LTC population was divided into fallers and non-fallers. Following the rules of the BBS, no instructions were given to the participants on how best to perform each task outside of the time it took to complete each task which was stipulated by the researcher. While all the tasks of the BBS were used in this study, a select number of tasks were used in the eV-BBS protocol. This is because the excluded tasks were too complex for the markerless motion capture to analyse reliably at its current stage of development.

The validity (comparing the scores of the two assessment systems) of this study could not be analysed due to the small sample of individuals from the LTC population. Instead, a comparison of groups between the healthy participants and LTC participants was carried out to show the degree of variability between the healthy and LTC participants. This comparison showed a substantial difference in the values obtained between participants in their respective groups. This was attributed to the fact that each participant carried out the task differently and markerless motion capture was sensitive enough to detect the differences between participants. While the healthy population repeated each task 5 times, the LTC population only repeated each task once. As such, the test-retest reliability and repeatability analysis could only be conducted on the healthy population data but not the LTC population data.

The eV-BBS had two main subsets: Balance tasks which consists of static positions and Functional tasks which consists of dynamic positions. For the healthy population, the study showed that the balance tasks, was able to detect differences between individuals while showing good consistency within individuals (Intraclass Correlation Coefficient (ICC) ranged from 0.81 to 0.99). Using an alternative measure of repeatability (coefficient of variation), the study confirmed that the eV-BBS was repeatable (Coefficient of Variation (COV) <20%) in the healthy group. The ICC for the functional tasks indicates poor reliability with ICC values in the range between 0.1 and 0.60. Closer examination looking at the within-participant (i.e., COV), in these functional tasks/dynamic balance tests, indicates that a significant proportion of the variation is due to the fact that an individual does not perform these tasks consistently. However, we cannot definitively state that the observed variation between individuals in the functional tasks is due to technique rather than noise in the markerless motion capture data and the analysis algorithms that were used to extract features from the Markerless motion capture data may require further refinement.

In conclusion, this pilot study shows the capabilities of implementing markerless motion capture systems as part of remote falls risk assessments Improvements to the research protocol and data analysis were identified.

Preface

This thesis is the original work of Emmanuella Osuji. This thesis, including the research project conducted in order to write it received research ethics approval from the University of Alberta Research Ethics Board, Project Name "Pilot Study to Enhance the Repeatability, Validity and Reliability of Traditional Observational Falls Risk Assessments by Incorporating Markerless Motion Capture Technology", pro00105756, 11/2/2021. The ethics protocol used for the long-term care participants was a module in pro00096029.

The materials presented in this research are original work conducted at the Rehabilitation Robotics Lab of the University of Alberta and the Glenrose Rehabilitation Hospital. This research study was led by my supervisor Dr. Martin Ferguson-Pell and co-supervisor Dr. Adalberto Loyola-Sanchez. The Kinetisense system used to conduct this work was developed by Kinetisense Inc. and validated by Emmanuella Osuji with the help of Dr. Martin Ferguson-Pell, Dr. Adalberto Loyola-Sanchez, the Tele rehab team at the University of Alberta and the Kinetisense team from Kinetisense Inc. The research protocols used in the study for both participants at the University of Alberta and at the remote facilities at Hinton, Edson and Grande Cache were designed by Emmanuella Osuji with the assistance of Dr. Martin Ferguson-Pell and Dr. Adalberto Loyola-Sanchez. The data collection and analysis in chapter 5 and 6 are my original work. Mr. Khilesh Jairamdas, James Qiu and Alex Dondish assisted with writing the MATLAB code needed for part of the analysis.

Although articles on the traditional Berg Balance Scale have been published in the past by other researchers, no part of this thesis has been previously published.

Dedication

This thesis is dedicated to:

My parents (Mr. Joe Osuji & Mrs. Stella Osuji)

&

My siblings (Doris, Paul & McDonald Osuji).

Acknowledgements

I would like to acknowledge the efforts of a handful of people without which this research would not have been completed successfully.

Firstly, to the project team at Kinetisense Inc, for giving me the opportunity to carry out a pilot study on their Kinetisense software and having virtual meetings to put me through the abilities of the software thereby informing the decisions made during the course of this research study.

Additionally, I would like to thank the members of the Rehabilitation Robotics Lab for helping me accomplish my research goals.

To Khilesh Jairamdas, for his steadfast support in writing the MATLAB code needed to analyse the data that was obtained during the experimentation phase of this research. While being the mastermind behind the creation of the MATLAB code, he worked in collaboration with Alex Dondish and James Qiu to ensure the effective and timely completion of said code.

To Emily Armstrong, for her amazing support during the course of this study. She was a great help to me during the experimental phase of my research. She was also a source of strength to me and someone I could look up to and ask for help when I got stuck. She always had an answer to every problem. My research was smooth sailing because of her.

To Dr. Adalberto Loyola-Sanchez for helping me refine my research goals as well as brainstorming with me on several aspects of the study to ensure that the goals I wanted to accomplish in the course of this research study could be achieved. He helped to keep me centred and focused during this study so I didn't put a lot of work on my plate with no time to accomplish it all.

Lastly, to Dr. Martin Ferguson-Pell for his continued support during the course of this research. He is the principal investigator for this research project but he has also been my mentor during the course of my studies at the University of Alberta. Whenever I started stressing out due to the sheer amount of work that needed to be accomplished, I always asked myself, "What would Martin do?". I have been able to learn a lot from him as well as gain a new found love and interest for research. Without his insights, this research would not have been accomplished as well as it has been. He helps to push you beyond the boundaries of your knowledge as well as empower you to think outside the box. My studies at the U of A have been a very uplifting experience so far with Martin as my supervisor.

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Table of Abbreviations

BBS	Berg Balance Scale
RRL	Rehabilitation Robotics Laboratory
eV-BBS	Enhanced Virtual Berg Balance Scale
WHO	World Health Organization
DALY's	Disability-Adjusted Life Years
ED	Emergency Department
NHIS	National Health Interview Survey
TUG	Timed Up and Go
POMA	Performance Oriented Mobility Assessment
POMA-B	Performance Oriented Mobility Assessment – Balance
POMA-G	Performance Oriented Mobility Assessment – Gait
CAREN	Computer-Assisted Rehabilitation Environment
COG	Centre of Gravity
M-MOCAP	Markerless Motion Capture
IR	Intel RealSense
FPS	Frames Per Second
UI	User Interface
RMS	Root Mean Square
BMI	Body Mass Index
FORTA	Fit for the Aged
AHS	Alberta Health Services
ADL	Activities of Daily Living
KAMS	Kinetisense Advanced Movement Screen

1. Introduction

1.1 Background

Falls are the leading cause of morbidity and deaths in the elderly (Lee, Lee, & Khang, 2013). Following a severe fall resulting in a fracture, older adults experience a decrease in functional independence and long-term health complications, and ultimately a reduced quality of life (Jin, 2018).

Falls can be detrimental for patients who already suffer from neurological or orthopaedic conditions. Previous research (Homann et al., 2013) has shown that certain conditions are associated with a higher risk of falling. These include Stroke (89%), Parkinson's disease (77%), and Dementia (60%) (Homann et al., 2013). These patients are at an increased risk of repeat hospitalizations due to fall related injuries, and acquiring new musculoskeletal disorders, thereby prolonging the rehabilitation process. (Kobayashi et al., 2018).

Communities in the rural and northern regions of Canada are faced with a burden of social isolation, reduced access to health care services, and often must travel to urban communities for healthcare (Johnson, Kelly, & Rasali, 2015). Johnson et al, reported that the rates of falls in rural areas are higher amongst independent community-dwelling older adults (Johnson et al., 2015) (Johnson, Kelly, & Rasali, 2015). Therefore, it is important by falls risk assessments to be available to seniors living in rural communities so that their falling incidents can be reduced.

An option to address the accessibility issues associated with rural and remote communities is to use virtual assessments using validated objective tests for falls risk assessment. The Berg Balance Scale (BBS) is a validated assessment tool with objective measures and is used to assess an individual's falls risk. However, even with tools like the BBS, there are challenges with using validated assessment tools for virtual assessments. This includes the difficulty in performing assessments designed for face-to-face interactions with participants from a remote setting thereby making the validity of the tests questionable. Furthermore, the progress of the individual will be difficult to track when the clinician and the patient are not in the same city. Evidence is lacking for objective assessment tools that can administered remotely to predict a patient's risk of falling.

The Rehabilitation Robotics Laboratory (RRL) team has been collaborating with Kinetisense Inc (Medicine AB Canada) to create novel technologies and processes, including a markerless motion capture platform to enable neuro-muscular assessments to be performed remotely, particularly for seniors living in rural settings or continuing care facilities. Based on previous work done by the RRL, Kinetisense can produce objective measurements for a range of functional assessments. These data that can be remotely stored for each participant and later reviewed as a basis for future assessments generating efficiency and accessibility within and across clinical disciplines. The variance between assessments using these technologies is thought to be dominated by the repeatability of the task rather than the variability in the assessor's judgement. This research study applied markerless motion capture to the Berg Balance Scale (BBS) falls risk assessment, generating a hybrid assessment tool incorporating observational and markerless measurements when performing the BBS risk assessment protocol remotely as part of a virtual assessment. It is referred to as the Enhanced Virtual Berg Balance Scale (eV-BBS).

1.2 Statement of Purpose

The primary aim of this study is to determine which tasks from the BBS can be consistently measured using a markerless motion capture technology and define what kinetic parameters from this technology are most useful to define a construct for risk of falling. The specific questions are;

a). What tasks of the eV-BBS better represent static and dynamic stability?

b). What is the test-retest reliability of the kinetic measures produced by the eV-BBS selected tasks?

c). What is the repeatability of these selected tasks?

1.3 Relevance of Research

If the enhanced Virtual-Berg Balance Scale can be demonstrated to be reliable and useful to detect static and dynamic stability remotely, it would be the beginning of new possibilities in the world of tele-assessments. Other assessment tools that were developed primarily for face-to-face assessments could be modified to suit virtual assessments thereby providing better options for rehabilitation assessments that would otherwise be difficult or inconvenient to assess. This would help to provide a better quality of life for patients by assessing them on time and providing therapy, thereby giving them back their independence. This will ensure equitable access to healthcare services is available for all patients. It will also reduce cost to the healthcare system because healthcare workers would not have to travel to rural areas to provide assessments.

2. Literature Review

This section will present a review of past studies that are relevant to this study. It addresses falls in older adults and its socio-economic impact on the healthcare system. It also addresses the most common types of fall risk assessments currently being implemented into clinical practice, and the different types of technologies that have been developed to making rehabilitation services more accessible to patients.

2.1 Falls Risk in Older Adults

2.1.1 Prevalence of Falls

There is a high prevalence of falls among older adults. A statistic from the World-Health Organization (WHO) states that, 28-35% of individuals over the age of 65 and as much as 42% of individuals over the age of 70 experience falls (Gamage, Rathnayake, & Alwis, 2019). In 2010, 37% of all injuries that required medical consultations were due to a fall (Verma et al., 2016). According to the Global Burden of Disease study, the increase in U.S. disability-adjusted life years (DALYs) between 1990 and 2010 was due to increased fall rate. (Verma et al., 2016).

One in four adults above the age of 65 has reported falling, and about one in ten has reportedly sustained a fall-related injury as of 2014. Among older adults, about 60% of all visits to the emergency department (ED) were due to injuries sustained in a fall. Moreover, over 50% of injury-related deaths are attributed to falls every year (Haddad, Bergen, & Luo, 2018).

In Canada, 85% of older adults are hospitalized due injuries sustained in a fall each year (Chang & Do, 2015). About 41% of all injuries sustained by Canadians each year are the results of a fall, and this percentage is greater among the population of older adults (Handrigan et al., 2016).

A health survey carried out among Canadian seniors between the years 2005-2013 revealed an increase in fall-related injuries from 49.4% to 58.8%. This rate increase was consistently higher in women and older adults (Do, Chang, Kuran, & Thompson, 2015a). The most common type of injuries sustained from these falls were fractures to the shoulders and upper arm. These falls occur from a loss of balance while walking on a wet surface during winter (Do et al., 2015).

As per (Prevention, Institute of Medicine (US) Division of Health Promotion and Disease, Berg, & Cassells, 1992), the determinants of injuries sustained from a fall includes a decrease in the strength of muscles and bones, decrease in bone mineral density irrespective of the age of the individual, type of fall, effectiveness and reaction speed to protect the body during a fall, and the ability of the body and environmental surfaces to absorb and distribute the impact of the mechanical forces (Prevention, Institute of Medicine (US) Division of Health Promotion and Disease et al., 1992).

2.1.2 Risk Factors of Falls in Older Adults

Several risk factors contribute to falls among the elderly population. (Sharif et al., 2018) compiled a list of risk factors, which include: a history of falling, use of assistive devices, environmental hazards such as poor lighting, health conditions such as muscle weakness, gait and balance impairments, vertigo and hearing disorders, cognitive and sensory impairments, orthostatic hypotension, osteoporosis and diabetes mellitus (Sharif, Al-Harbi, Al-Shihabi, Al-Daour, & Sharif, 2018). According to these authors, several psychotropic drugs such as hypnotics, sedatives, antipsychotics and antidepressants can also increase the risk of falling because they cause sedation as well as balance and coordination impairments (Sharif et al., 2018).

Another study by (Lee et al., 2013) further investigated falls risk factors such as decreased strength, use of psychoactive medications, visual impairments, gender, urinary incontinence, and undertreated pain (Lee et al., 2013). Another study reported that the risk of falling increased with age and chronic health conditions such as cardiovascular diseases, arthritis and diabetes (Stewart Williams et al., 2015). The study also reported that nutritional deficiencies and poor sleep patterns are associated with an increased risk of falling (Stewart Williams et al., 2015).

2.1.3 Socio-economic Costs Associated with Falls

The resources required to treat patients who have been involved in falls put an overwhelming strain on the healthcare system.

A study by (Verma et al., 2016) calculated the cost of falls in the U.S. using data gathered from the National Health Interview Survey (NHIS) between 2004-2013. They estimated that the total lifetime costs of yearly unintentional fall-related injuries which resulted in a fatality, hospitalization or ED visit was $111 billion U.S., while the highest lifetime cost of unintentional fall-related injuries for middle-aged adults between the ages of 45-54 was 23 billion U.S. dollars (Verma et al., 2016).

Another study conducted in the U.S. between 2012 – 2015 calculated the direct cost of life-threatening, and non-life-threatening falls in older adults (Burns, Stevens, & Lee, 2016). This study revealed an increase in cost with the total cost for combined sexes (males and females) averaging at about $616.5 million in direct medical costs in 2012 for fatal falls, $30.3 billion for non-fatal falls, with hospitalization accounting for about 57% of that cost in 2012 (Burns, Stevens, & Lee, 2016). The total cost skyrocketed in 2015, with the total cost for fatal falls averaging $637.2 million ($282.2 million for men, $355.0 million for women), and $31.3 billion ($9.0 billion for men, $22.2 billion for women) for non-fatal falls (Burns et al., 2016).

The annual cost of fall-related injuries in 2004 (Gibson et al., 2018) was 2 billion Canadian dollars. It was also predicted that by 2031, the annual direct expenses spent on healthcare attributed to falls would be as high as 4.4 billion Canadian dollars (Gibson et al., 2018). Also, in 2004, about $4.5 billion was allocated to direct health care costs for the treatment of unintentional injuries in Canada and about half of this cost was derived from falls in the elderly population above the age of 65 (Handrigan et al., 2016).

Based on the information above, the socio-economic costs among older adults in institutionalized care or long-term care facilities is high. This is because every fall among the age group of individuals in that clinical setting almost always results in hospitalization to ensure that the individual suffered no physical or neurological damage.

2.2 Falls Risk Assessments

Falls risk assessments are multifactorial tools designed to detect the risk of falls for vulnerable individuals. These assessments are subjective in nature and mostly require visual observation from a clinician to determine the participant's fall risk.

Although the subjective falls risk assessments that have been developed and implemented in clinical settings are able to determine the risk of falls in seniors, these tools are not standardized within or across disciplines (Perell et al., 2001a). This implies that different tools are implemented in different clinical settings, and this choice lies solely on the preference of the clinician. Therefore, the history of past assessments is not considered before or during future assessments and interventions for the seniors.

Due to the subjective nature of these tools, the reliability and sensitivity to change of these measurements are questionable. If these measurements were to be repeated again by either the same clinician or different clinicians, using visual observation as the only tool for measurements of anatomical landmarks during static or dynamic postural control, it is unclear if the same results will be obtained. The variance between clinicians and within an individual significantly reduces the sensitivity of subjective falls risk assessment tools, which in turn limits the use of the tool for longitudinal monitoring of seniors and the evaluation of mitigation strategies and treatments.

A further limitation of current subjective falls assessment tools is that they do not lend themselves to remote assessment using virtual health technologies, where the assessment is guided by a specialist "hub" clinician, while the seniors are supported by a "spoke" generalist clinician.

2.2.1 Most Common Falls Risk Assessments Currently being used in Clinical Practice

Several studies that have targeted assessments of falls risk among community-dwelling older adults have repeatedly named the following assessment measures in their research papers. These measures include: Timed up and go test (TUG) (Greene et al., 2010; Palumbo, Palmerini, Bandinelli, & Chiari, 2015; Soriano, DeCherrie, & Thomas, 2007), Berg balance scale (BBS) (Greene et al., 2010; Palumbo et al., 2015; Perell et al., 2001b) and Tinetti performance-oriented mobility assessment (Palumbo et al., 2015; Perell et al., 2001).

Timed Up and Go Test (TUG):

The purpose of this test is to detect balance problems in older adults (Greene et al., 2010). During this assessment, the participant is asked to stand up from a seat, walk forward about 3 metres, turn at a pre-determined spot, and return to the seat. A stopwatch is used to measure the length of time taken for the participant to stand up from the chair and return to it (Greene et al., 2010). Current clinical assessments show that older adults with longer TUG times are more likely to fall than those with shorter times (Greene et al., 2010).

Although gait speed has been proposed as an indicator of falls risk (Palumbo et al., 2015), it is not clear how to ensure that during a clinical assessment, the patient performs the gait test in a way that is representative of their typical walking speed. Individuals vary their walking speed considerably depending upon motivation and environmental factors.

Tinetti Performance-Oriented Mobility Assessment (Tinetti-POMA):

The Tinetti-POMA has been used in clinical assessments to measure gait and balance in older individuals for so many years such that a modified version of the POMA was created like the POMA-B, which contains nine balance tasks and POMA-G, which contains seven gait tasks (Soubra, Chkeir, & Novella, 2019).

The gait component of Tinetti (POMA-G) can be used to measure initiation, symmetry, path, base of support, postural sway during gait and continuity (Canbek, Fulk, Nof, & Echternach, 2013). The content of the Tinetti-POMA, such as standing with eyes open and closed and turning 360 degrees, is sufficient to measure the fall risk of older adults. The objective measurement style of this assessment tool is also good enough such that the progress of the patient can be tracked during his/her current therapy sessions over a specific number of weeks/months.

However, a problem arises regarding the sensitivity to change that this instrument could have in terms of measuring falls risk assessments longitudinally to track patient progress. In other words, when the Tinetti-POMA is able to detect changes, it might already be too late, and the patient might already be experiencing repeated falls. Therefore, the ability of the measurement to detect changes on time in order for healthcare practitioners to be able to intervene and prevent falls is uncertain.

Finally, there is a lack of collaboration across disciplines such that different clinical settings depend on their own assessments for each patient. Thus, a patient's past history is not always taken into consideration during their future therapies.

Berg Balance Scale (BBS):

This test contains 14 specific tasks and can be used in clinical assessments. This test mainly targets functional positions, and each item is scored on a scale of 0-4, with a maximum total score of 56 and scores closer to the maximum indicates better performance (Soubra et al., 2019).

The BBS measures transitional movements, narrowed base of support, standing and stepping but does not measure reactive movements (Canbek et al., 2013).

The BBS is a subjective form of measurement. It could be argued that there are still limitations with this assessment tool even for face-to-face assessments, which include the fact that a patient's balance is determined by a combined total value of the assessment. This means that a patient with a good BBS value can still be at risk of falling if he/she has a low score on one of the tasks given on the assessment such as "standing unsupported", and this could be overlooked because the summation of scores is generally good.

Secondly, the BBS does not assess gait (Hayes & Johnson, 2003) which is important for falls risk. Thirdly, some of the measurements are scored based on therapist observations and not based on measurements of function, thereby making this test quite subjective and insensitive to change.

2.3 Technology-Assisted Assessment of Balance and Gait

Motion capture technologies, especially marker-based systems, have been implemented in several rehabilitation studies such that it has become the gold standard for the technical validation of technologies used to assess some aspects of falls risk, particularly those related to gait and balance. A core limitation of this technology is that it requires the use of many cameras, markers placed on anatomical landmarks and usually a controlled laboratory setting to reduce artifacts such as spurious reflections. This makes its use in everyday clinical environments impractical (Schmitz et al., 2015).

An example of a motion capture device is the "Optical Infrared Motion Capture Technology" (Skogstad, Ståle Andreas van Dorp, Jensenius, & Nymoen, 2010). This is a marker-based motion capture technology that uses at least six cameras to track the movement of individuals. Infrared light emitted from the cameras bounces off the reflective markers that have been attached to the body of the individual being observed. The system is then able to triangulate the absolute position of the individual in space and then capture that individuals' movements. The problem with this system is that it is expensive and requires a controlled lab setting to work efficiently (Skogstad, Ståle Andreas van Dorp et al., 2010).

Another motion capture technology is the "Computer-Assisted Rehabilitation Environment" (CAREN) (Isaacson, Swanson, & Pasquina, 2013a). It comes with a base that is made up of mechanical and hydraulic actuators. The base is retrofitted with a treadmill and force plate, and it has 6 degrees of freedom. It also has a harness attached to it in order to ensure the safety of patients during assessments (Isaacson et al., 2013). Although the CAREN technology has shown incredible promise in testing stress reflex and balance, there are only 2 of these systems available in Canada at the moment, limiting access to patients.

Figure 1: The computer-assisted Rehabilitation environment Technology (Isaacson, Swanson, & Pasquina, 2013b).

Aside from motion capture technologies, other smart technologies have shown real promise in the world of rehabilitation for balance and gait assessments. The use of force-plate technology has been implemented in rehabilitation studies to assess balance (Jogi, Zecevic, Overend, Spaulding, & Kramer, 2016; Mansfield & Inness, 2015; Prosperini & Pozzilli, 2013). These force-plates quantify ground reaction forces, postural sway, gait analysis, as well as static and dynamic postural control (Jogi et al., 2016; Mansfield & Inness, 2015; Prosperini & Pozzilli, 2013). However, as per (Prosperini & Pozzilli, 2013), it is not feasible to use a force plate in a clinical setting. This is because it involves a significant cost to purchase dynamic postural control equipment for gait analysis. It requires trained staff to operate efficiently as well as a dedicated space to carry out assessments (Prosperini & Pozzilli, 2013).

An example of a force-plate technology is the balance master. This computerized system is able to assess the physical ability of the patient to complete various balance tasks. It is also made up of a force plate connected to a computer software with the ability to monitor the position and movement of the center of gravity (COG) during assessments (Kenis-Coskun, Giray, Eren, Ozkok, & Karadag-Saygi, 2016). It has a harness to secure patients during assessments and it is also to change its horizon to create a perturbation. However, due to the sheer size of this technology, it also requires a designated space for operations and is expensive to purchase and assemble.

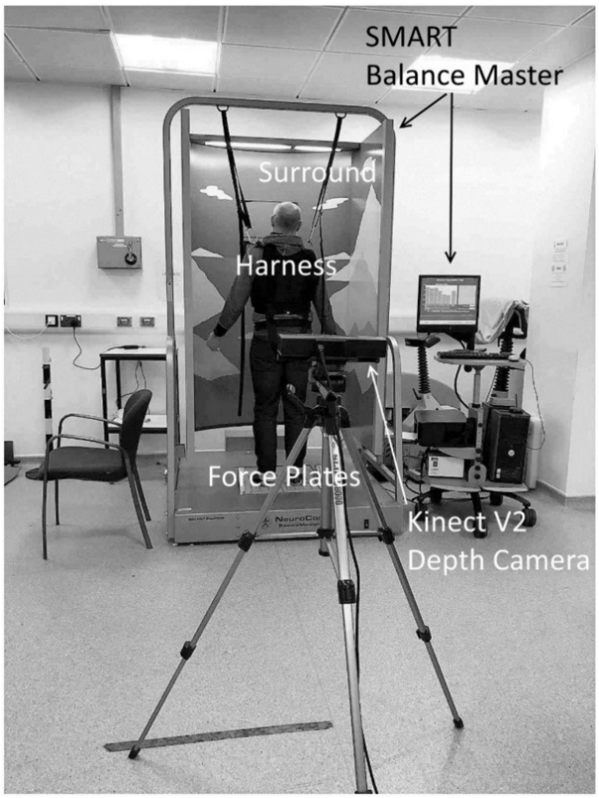

Figure 2: The Smart Balance Master Technology (Maudsley-Barton, Yap, Bukowski, Mills, & McPhee, 2020).

A family of high-end devices measures balance and gait using technologies that range from force plates for balance measurements as aforementioned; to smart-phone technologies that measure an individual's sway pattern during gait. In extreme cases, the reactive balance of individuals is assessed by tripping them on a running treadmill while ensuring their safety with the use of a harness during testing. While these technologies are undoubtedly ingenious, they either measure balance or gait, independently.

In conclusion, the existing technologies described above are not feasible to be used in a clinical or rural setting because of the following reasons:

1. They are expensive.

2. They require specialized technical knowledge to operate and complete the data analysis

3. Although they work efficiently in a lab setting, they are difficult to work within a real-world clinical setting.

4. They require a designated space.

2.4 Markerless Motion Capture System (M-MOCAP)

Markerless motion capture systems have been increasingly recognized by the biomechanical and rehabilitation industries in the last few years. In the biomechanical field, it has been used to study musculoskeletal biomechanics, skeletal models, and manual wheelchair biomechanics (Corazza et al., 2006; Nakamura et al., 2016; Rammer et al., 2018). For rehabilitation purposes, M-MOCAP has been used in the field of neurological rehabilitation, gait and postural control analysis, upper limb rehabilitation, etc. (Knippenberg et al., 2017; Metcalf et al., 2013; Schmitz, Ye, Shapiro, Yang, & Noehren, 2014).

The Kinetisense markerless motion capture system uses Intel RealSense 3D camera technology to detect anatomical landmarks in the human body without the use of physical markers. This technology has been co-developed between Kinetisense Inc (Medicine Hat AB) and the Rehabilitation Robotics Lab (RRL) at the University of Alberta for applications in virtual rehabilitation assessments. To my knowledge, no research has been done using the Kinetisense M-MOCAP device to systematically study balance and the risk of falling.

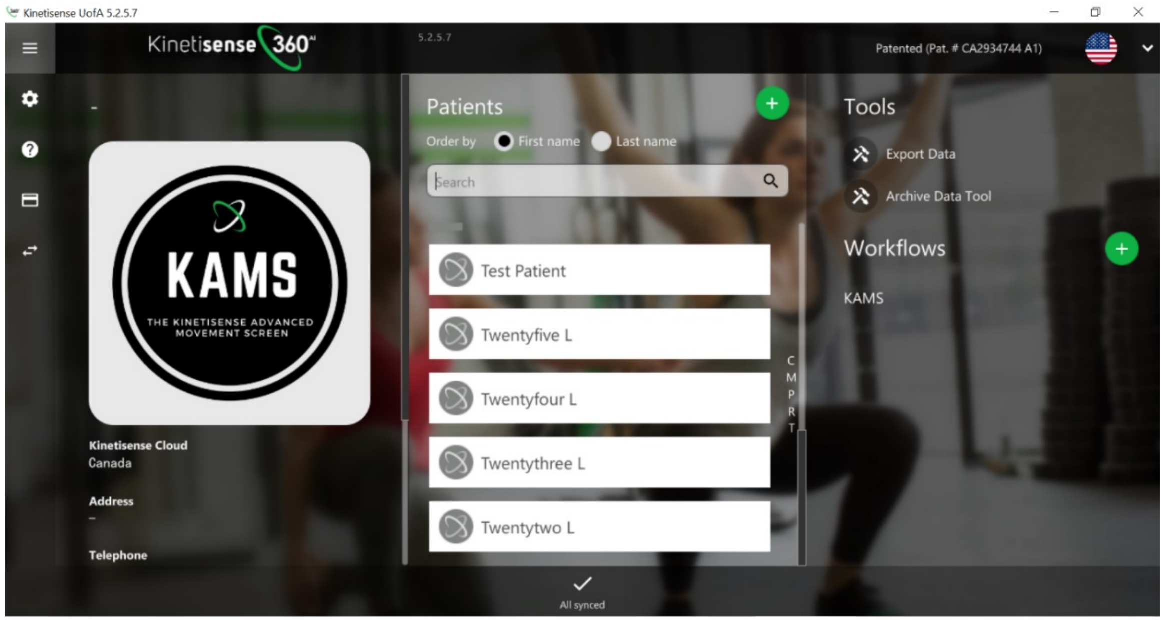

Figure 3: The Kinetisense Markerless Motion Capture System Dashboard.

Moreover, the aforementioned assessment tool has not been validated to be applied in a telehealth context when the Kinetisense technology is able to be applied for falls risk assessments in remote settings. Consequently, assessing the validity and reliability of the M-MOCAP system to assess falls risk is necessary, as this will be the first step towards implementing this technology in virtual rehabilitation settings. Ultimately, validating this technology will improve access to appropriate balance and falls risk assessment for people living in rural communities.

As for limitations of this technology, its inability to consider the patient's past history of falls is a fundamental limitation. However, this problem can be resolved using the Kinetisense technology data-storage capabilities over time, which allows different health care providers to use it at different times and build more robust falls risk assessments that consider the patients personal factors, such as past history of falling.

2.4.1 Validation of Kinetisense

A study by (Mera et al., 2013) validated kinematic data obtained from Kinetisense to analyze gait and balance responses in patients with Parkinson's disease. The study revealed that the Kinetisense system was able to provide synchronized data and was quite useful for their study. Other validations of Kinetisense have been carried out to assess other conditions such as bradykinesia and automated tremor due to Parkinson's disease (Espay et al., 2011; Giuffrida, Riley, Maddux, & Heldman, 2009; Heldman et al., 2011).The Kinetisense system has also been used to assess the posture of surgeons in a pilot study conducted by (Dwyer et al., 2020). The study revealed that Kinetisense is able to provide extremely valuable data on joint data although such data is usually not used. Although the study found Kinetisense to be efficient to use, limitations were also discovered with the camera such as the camera detecting objects in the background as well as on the participants being measured. However, this limitation was able to be modified for the purpose of the study. Other validated ergonomic assessment tools were able to support the findings of Kinetisense (Dwyer et al., 2020). This also supports the findings of the aforementioned study that Kinetisense is able to collect accurate and useful and is an efficient tool to use for assessments.

3. Study Design

This thesis reports a test-retest reliability study that required repetitions of each task for both the BBS assessments and the eV-BBS assessments using the Kinetisense technology. In order to assess the validity of the eV-BBS tasks against the subjective BBS tasks, the participants were allowed to perform each task as they saw fit adding in their own postural compensations with each task. Therefore, no learning effects should exist during this study because the study participants were not instructed on how best to perform the tasks, instead to perform them as they naturally would. There were two populations of patients involved in this study: a group of healthy subjects and a group of long-term care dwellers. The long-term care population was divided into two groups: the fallers group and the non-fallers group, based on their reported falls history in the last 12 months. The healthy group was used to determine the reliability and repeatability of the BBS tasks measured through the eV-BBS, while the long-term care group was used to provide information regarding the real-world implications of using eV-BBS in the clinical context.

3.1 Participant Recruitment

Healthy Group:

Recruitment for this study was done based on the voluntary participation of the members of the RRL at the University of Alberta. This restriction was enforced to ensure the health and safety of all participants and patients involved during the global COVID-19 health crisis. All the necessary safety measures were taken to ensure their safety during the study period as well.

Long-Term Care Group:

In an attempt to analyze the feasibility of implementing the eV-BBS protocol in the geriatric population, the project team recruited participants from supported living facilities above the ages of 65. The goal of this trial was to perform 2 repetitions of the eV-BBS on patients living in supported-living facilities.

These participants were recruited from three supported living facilities in Alberta: Parkland Lodge, Edson, Pine Valley Lodge, Hinton and Whispering Pines Lodge, Grande Cache. No age range was required for this recruitment as they were all seniors and the variations in the data produced during their balance assessments using Kinetisense in relation to their ages were considered relevant for this study.

3.1.1 Inclusion Criteria

Healthy Population:

Individuals between the ages of 18 to 60 years old were allowed to take part in this study, considering that seniors above the ages of 65 fall at least once every year (Do, Chang, Kuran, & Thompson, 2015b). Participants actually recruited for the study were between the ages of 20 – 37 years old. The participant recruitment was done by email and word of mouth.

Long-Term Care Population:

Individuals with either a history of falling or self-reported perception of high risk of falling were allowed to take part in the study. This allowed us to identify low and high risk of falling sub-groups. The Inclusion criteria required for this study was that the participant had experienced at least one fall in the last 12 months or were concerned about falling. No distinction was made in respect to the use of walking aids. Participants were allowed to perform tasks to assess their balance with the help of their mobility aids.

3.1.2 Exclusion Criteria

Healthy Population:

The following exclusion criteria were enforced for the safety of potential participants.

- Acute or life-threatening medical conditions such as cancer or end-stage Alzheimer disease
- Severe motion sickness
- Cardiovascular diseases
- Untreated visual impairments
- History of untreated neurological conditions
- History of current orthopedic injuries.

Long-Term Care Population:

Participants were only excluded if they were unable to provide consent in order to take part in the study.

3.2 Sample Size

Healthy Population:

This study intended to collect baseline data from a small convenience sample of healthy young volunteers (n=10). This small population is likely to yield the highest level of consistency in performing the BBS tasks and therefore the greatest challenge in measuring the precision of the markerless system and the repeatability of the BBS tasks.

Long-Term Population:

To assess the feasibility of applying the eV-BBS in the clinical context, a small convenience sample of long-term care indwelling participants (n=4) was considered. The sample size was divided equally between the fallers group and the non-fallers group. So, each group had a sample size of n=2.

3.3 Variables of Interest

The independent variables in this study were the categorical scores the clinician/researcher gives to each participant during the BBS task and the adjusted covariates were the demographic variables of: height (m), weight (kg), shoe size, age and gender.

For the static balance tasks of the eV-BBS, the variables of interest were the movements of the participants in the frontal plane (Z), sagittal plane (X) and transverse plane (Y) as obtained from the Kinetisense spreadsheet.

For the dynamic balance tasks of the eV-BBS, the variables of interest were the parameters taken from the Kinetisense spreadsheet and then encoded into MATLAB (see section 4.2.5).

For the test-retest and repeatability analysis, the predicted variables were the continuous measurements obtained from the eV-BBS tasks. The test-retest reliability assessment included intra class correlation coefficients (ICC) estimations through two-way mixed effects for consistency agreement, as there was only one rater of interest (i.e., Kinetisense software). The data collected from the eV-BBS assessment focused on the head, shoulders, spine, hips, knees and ankle joints. The upper limb movement was not considered during this study for the balance tasks. This was decided because the upper limb movements tend to be erratic during the execution of the included balance tasks. In addition, the purpose of the upper limb is to facilitate the bodies movement and shield the participant from harm during a fall. This movement is individualized and can therefore not be captured successfully.

3.4 Ethics

Healthy Population:

Ethics approval was received on February, 2018 for this study, (pro00105756). Included in this approval are updates to the consent form, information sheet, subjective BBS assessment sheet, etc. (*Appendix A*). It states in the approval that participants will undergo a BBS assessment, which should cause no physical, psychological, emotional or social risks or discomforts to the participants. The potential risk to the participant is minimal, similar to experiences when participants exercise. If at any point during the assessment, the participant exhibited discomfort of any kind, they are asked if they wished to rest for a few minutes. If they do not wish to continue the assessment, the researcher will stop the assessment immediately.

Participants all submitted a signed informed consent form prior to their assessment date. No identifying features of the participant, such as their names was associated with the data obtained during the assessment. After the assessment is done, the data was downloaded and saved on an RRL encrypted drive with random characters and numbers. The current anonymized code was used to identify the participant from that point onwards. All identifying features of the participant were stored separately from the data in an encrypted software. All study information will be kept in a secure RRL encrypted drive for 5 years and then destroyed or permanently deleted.

Long-Term Care Population:

This part of the research study was approved by ethics as part of a different study (pro00096029).

3.5 Hypothesis

The goals of this research were to assess the validity, repeatability and reliability of the eV-BBS, which uses a markerless motion capture tool to measure static and dynamic balance, using tasks from the BBS. The primary hypotheses were:

Ho 1: There is no correlation between the BBS and the eV-BBS tasks (validity goal).

Ho 2: The test-retest reliability of the eV-BBS tasks using intraclass correlation coefficient (ICC) shows no significance at ICC < 0.50.

Ho 3: The repeatability of each of the eV-BBS tasks will be low as demonstrated by a coefficient of variation equal to or higher than 20%. [1]

[1] https://www.researchgate.net/post/If-my-coefficient-of-variation-is-47-is-it-appropriate-to-say-47-of-the-variation-I-observe-is-due-to-heterogeneity-chance-in-my-samples

4. Materials & Methods

4.1. Explanation of Experimental Tools

The experimental tools required for this study were the Kinetisense markerless motion capture technology, the Double Telepresence Robot, the Berg Balance Scale (BBS) and the proposed enhanced Virtual Berg Balance Scale (eV-BBS).

4.1.1. Assessment using Berg Balance Scale

The BBS is usually conducted in a face-to-face assessment between the clinician and participant. The only method of evaluating the performance of the participant for any given task on the scale is, "how much time it takes the patient to complete the task" and "if the clinician is able to visually observe a change in the participants movements that contradicts the notion that the participant is not at a risk of falling". A typical BBS assessment can be found in (*Appendix B*). Some of the tasks on the scale only rely on the visual observation of the clinician to determine whether the task was completed successfully or not. In comparing different versions of the BBS, it could be argued that there is no particular method of arrangement for any of the tasks. An example of this can be found by comparing the arrangement of the tasks in (*Appendix B*) to that of (*Appendix C*).

A positive feature of the BBS is that it is made up of the activities of daily living of every individual. Each task that makes up the BBS targets a task that is performed everyday by every individual. The tasks on the scale can range from sitting unsupported to picking up an object from the floor. Therefore, the scale could be interpreted to mean that if an everyday position cannot be completed for a set amount of time, then it stands to reason that the participant is indeed at a risk of falling. However, a limitation of this clinically pragmatic approach is that is does not identify what the underlying mechanism (i.e., neurological, vision, musculoskeletal) is responsible for the heightened risk of falling. While it is quite easy to envision how most of the tasks would be challenging for the geriatric population, these tasks can be modified to suit the needs of the population in question in such a way that it would not reduce the effectiveness of performing the assessment.

4.1.2. Measurement Tools for BBS

The Stopwatch: In addition to visual observation, the stopwatch is the only measurement tool used to track the progress of the participant during an assessment. The timing for each task varies with the highest time required to complete a task being 2 minutes and the lowest time required being 4 seconds.

The BBS Assessment: The BBS assessment is used to record the progress of the participant for each completed task. Each task is scored in a range of 0 to 4 with 0 meaning the inability to perform a task independently and 4 meaning the ability to perform a task completely and independently. The requirements of scores 1-3 differs depending on the task in question.

In both versions of the scale given above in Appendices (*B*) and (*C*), the results of each task are only recorded once throughout the document. The risk of fall is only determined at the end of the assessment by adding up the total values of all the recorded numbers of the tasks completed, divided by the number of tasks completed. If all 14 tasks were completed successfully and independently, then the overall score of the BBS assessment will be 56. An interpretation table is provided below the questionnaire which places the participant in a range depending on their overall score. This tells the clinician if the participant is at a risk of falling or not because this becomes the participant's risk score. However, BBS is much less informative in guiding what measures could be taken to reduce the risk of falling. This is because information is lacking from these tests regarding the underlying cause of the increased risk.

4.1.3. Interpretation of Data from BBS

The interpretation table provided below the questionnaire is divided into 3 sections and used to determine the risk of fall of an individual. This division is as follows;

0 – 20: wheelchair bound individual

21 – 40: walking with aid

41 – 56: Independent individual

This interpretation means that participants with an overall score less than 45 may be at a greater risk of falling (Berg, Wood-Dauphinee, Williams, & Maki, 1991).

4.1.4. Synthesis of Data from BBS

Clinically, a high-risk score obtained using the Berg Balance Scale assessment can provide the rationale for the clinician to build a suitable therapy workflow to help improve the balance of the participant. However, the BBS itself does not indicate where to place the effort needed to improve balance. This can be individualized from one participant to another by taking into account the specific tasks on the assessment which the participant was either unable to perform, scored a low grade on, or was visually observed by the clinician to have struggled with or compensated on. Since the participant isn't coached on how to do these exercises, the possibility of a learning effect is minimal but because the BBS is so insensitive, it is also impossible to determine if there is a learning effect.

The assessment can also be repeated as often as needed in order to show progress or regress in the balance of the participant after a set amount of time has elapsed. This can further help the clinician decide whether to modify the treatment plan for a participant showing good progress or change the progress plan entirely for a participant showing regress or no change at all in the therapy.

4.1.5. Procedure for Performing BBS

The BBS assessment can be performed in either a standing or sitting position. Common household items such as an armchair, a chair with a backrest or a stool are required to perform most of the tasks on the scale. Traditionally, when performing the BBS assessment, the clinician is advised to demonstrate each task as well as give instructions to the participant before asking them to perform the assessment themselves. Points are deducted if the participant is unable to perform a task independently, if the time requirements on a task was not met sufficiently or if the task itself was not performed correctly to the satisfaction of the clinician. However, in demonstrating the task to the participant, the use of a fixed limb or arm is not important. That decision is left purely to the discretion of the participant. The tasks that comprise the Berg Balance Scale are as follows;

Task number	Task name	Instructions
1	Standing Unsupported	Please try to stand for 2 minutes independently. Note: This is measured using a stopwatch/timer.
2	Sit with back unsupported but feet together on floor or stool.	Please sit with folded arms for 2 minutes Note: This is measured using a stopwatch/timer.
3	Stand unsupported with eyes closed	Please stand with crossed arms for 10 seconds. Note: This is measured using a stopwatch/timer
4	Stand unsupported with feet together	Please stand independently with feet together for 1 minute. Note: This is measured using a stopwatch/timer.
5	Turn to look behind left and right shoulders with feet planted in the same spot	Please turn to look directly behind your left shoulder. Repeat this movement over your right shoulder as well. Note: This is measured using visual observation to look for a proper weight shift during each turn.
6	Stand unsupported with one foot in front of the other	Please try to stand independently by placing one foot directly in front of the other. If the former seems difficult, try stepping forward a little such that forward foot is directly in front of the backward foot. Hold this position for 30 seconds. Note: This is measured using a stopwatch/timer as well as visual observation.
7	Standing on one leg	Please stand independently on one leg for as long as you can. Note: This is measures using visual observation and a stopwatch for 10 seconds and above.
8	Reach forward with outstretched arms	Please lift both arms to 90 degrees and stretch out your fingers. Then try to lean forward as much as you can. Note: This is measured using a ruler.
9	Sit to stand	Please try to stand up independently without support. Note: This is measured using visual observation.

10	Stand to sit	Please try to sit down independently without support. Note: This is measured using visual observation.
11	Transfers	With chairs arranged in a pivot position, please try to transfer one way from a seat with armrests to a seat without armrests. Note: This is measured using visual observation
12	Pick up object from floor from a standing position	Please pick up the shoe/slipper placed in front of your feet. Note: This is measured using visual observation
13	Turn 360 degrees	Please turn around in a full circle in one direction and repeat this in the other direction. Note: This is measured using a stopwatch/timer for 4 seconds as well as visual observation.
14	Place alternate foot on stool	Try to alternately place each foot on the step/stool. Continue this movement until each foot has been placed on the step about 4 times. Note: This is measured using a stopwatch/timer as well as visual observation.

Table 1: The Berg Balance Scale tasks

4.2. Assessment using the Proposed eV-BBS

4.2.1. Measurement Tools

Kinetisense Markerless Motion Capture System: The Kinetisense technology has to be downloaded on the desktop computer running on a fast graphics card e.g. (nVIDIA RTX3060). It is made accessible to all the participants as well as the researcher in charge of this study. It is accompanied by an Intel RealSense (IR) 3D camera, model D415 or D455. The 3D camera is able to measure between 2.0 and up to 7.0 meters. Kinetisense measures a host of different modules. These modules are divided into two primary categories; Range of motion and functional assessments. However, for this study, we used the gait, balance and functional modules which can all be found under the functional assessment category. Each of these modules are able to capture the x,y,z coordinates or the frontal, sagittal and transverse coordinates of an anatomical landmark of the body and overlays a skeleton model on the image of the participant doing the task. It also presents 360-degree joint circle on each anatomical joint in order to display the range of motion of the joints in real time while tracking the participants' movements. The Kinetisense system can measure up to 90 frames per second (fps), with a default value of 30fps for most modules.

Kinetisense can also present information for overhead tracking and tracing of landmark movements. This helps to detect the movement of the body from a 3-Dimensional angle (sagittal, frontal and transverse). It is also able to distinguish the gait pattern of the participant (Trendelenburg or antalgic) during a gait assessment as well as any compensatory patterns that may arise while the participant performs either a dynamic or a static movement.

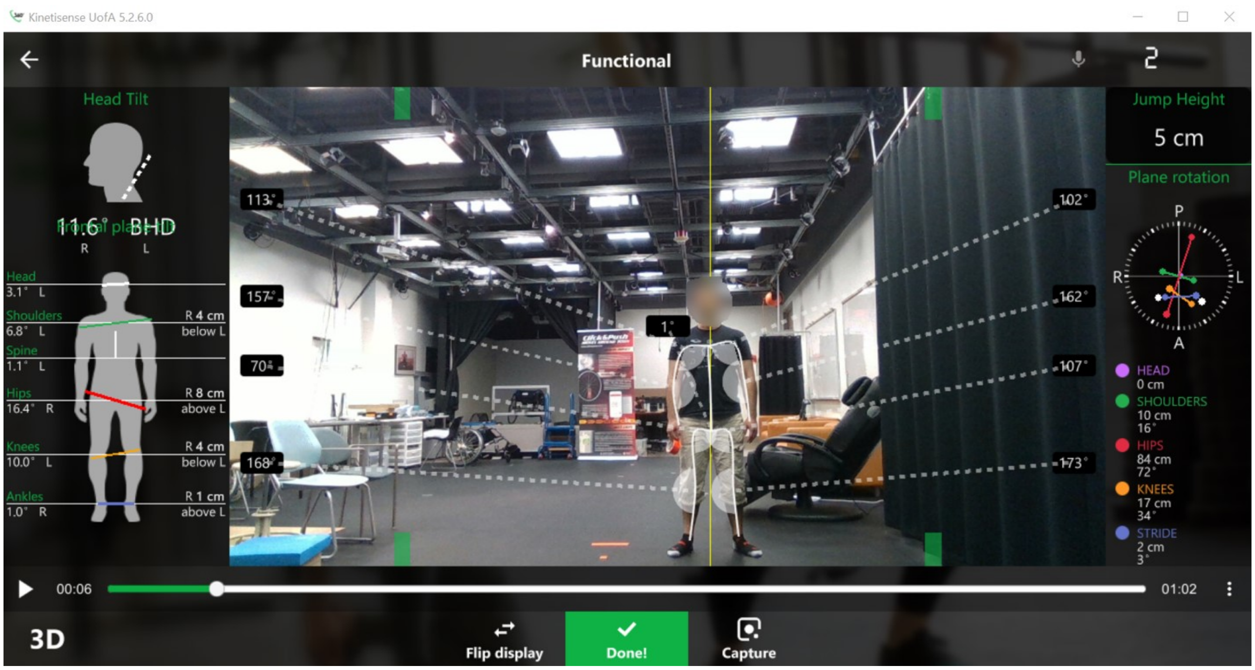

Figure 4: Kinetisense functional module with skeletal model overlay

During an assessment, Kinetisense is able to carry out background data analysis that cannot be seen in real time by the clinician but can be obtained by downloading the CSV files containing the raw data from the finished assessments. This is where the User Interface (UI) of Kinetisense becomes important. The UI synthesizes the background data that has been analyzed and presents it to the clinician in a form that is both easy to understand and useful to the clinician. It is able to present final results to the clinician immediately. This could be in the form of figures showing the range of motion, velocity or the maximal gait speed of the participant amongst a host of other useful data. It is also able to show you the coronal view of the participant moving around his/her center of mass as well as the frontal view of the participant in the form of a skeletal model. This model then further goes to show any and all compensations that were observed by the technology as well as how much compensation was observed while the participant performed a given task. In the case of a falls risk assessment, Kinetisense Inc are currently programming the UI to analyze and produce a risk score at the end of the assessment.

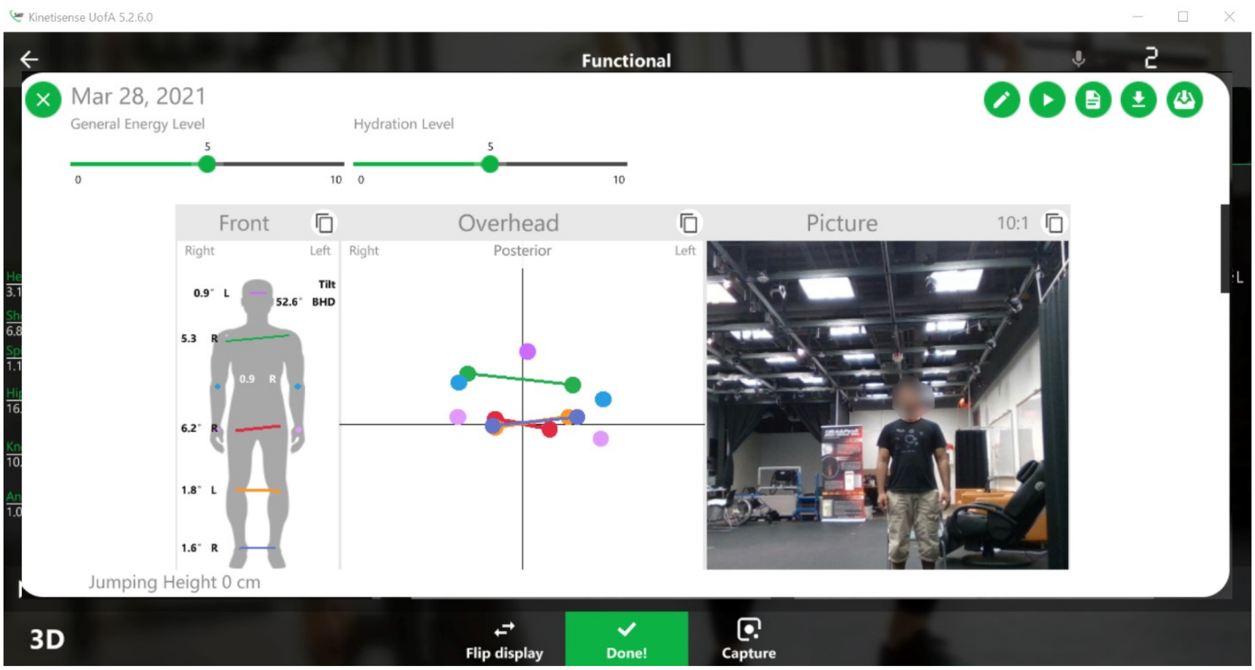

Figure 5: Kinetisense User Interface.

The Double Telepresence Robot: In this study, the Double Telepresence Robot played a supportive role to the Kinetisense. Although this tool was not used for the purposes of measuring the participant or data gathering, the Double Telepresence Robot, shown in **figure 6,** is an effective way of communicating between the specialist, generalist and the patient. It helps to create a sense of presence which improves the engagement between all of those involved in the assessment.

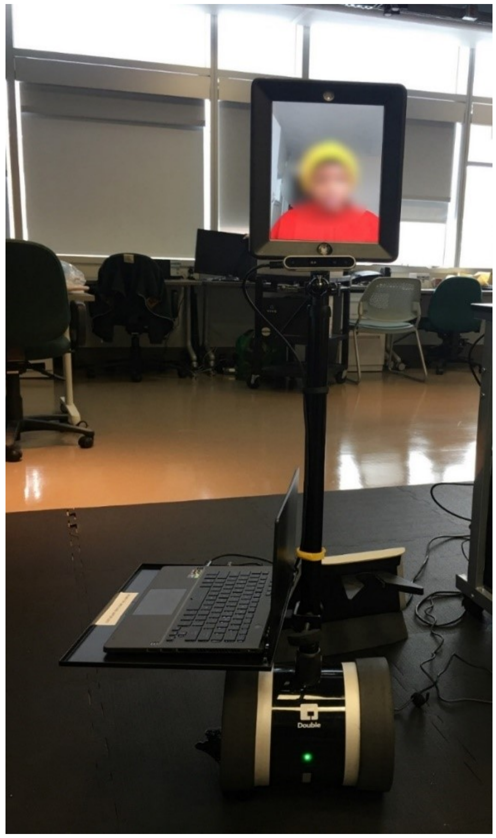

Figure 6: Double Robot set-up at the RRL.

The Proposed Enhanced Virtual-BBS (eV-BBS): The eV-BBS is made up of all the individual tasks in the subjective BBS assessment as well as two additional reactive balance exercises which were selected by the researcher. The Kinetisense recording is started after the participant has been instructed to assume the starting position. After the task has been completed, the participant is asked to remain in the final position for a few more seconds in order to give the technology time to measure any residual balance loss or sways. In most circumstances, the participant is asked to repeat a movement several times for each repetition in order to complete a task as opposed to just one movement that occurs when carrying out the subjective BBS assessment. The researcher believed that performing a task just once was not enough to invoke a possible loss of balance in a participant during an assessment unless the patient has a very low physical endurance. This is because, the circumstances that caused the participants' loss of balance may be environmental such as a slippery step as well as muscular such as loss of muscle strength. The tasks were categorized in the Kinetisense software as Balance Module (Static balance tasks) and Functional Module (Dynamic balance tasks) based on which tasks could best be measured with Kinetisense. The reason for the addition of the reactive exercises was because the researcher wanted to validate the results generated by Kinetisense when a participant experienced major instability or loss of balance. This assessment protocol was later used to assess patients in a real world setting to see if the implementation of the eV-BBS in collaboration with Kinetisense produce valuable results. The first Version of the eV-BBS protocol developed can be found in (*Appendix D*).

4.2.2. Summary of Data Acquired from eV-BBS

Visual observation of a clinician during an in-person assessment cannot be replaced by Kinetisense. However, Kinetisense provides both the visual information (including a recording) as well as quantification of the function or movements. The type of data that can be acquired from Kinetisense includes range of motion for the anatomical landmarks of the body, level of tilt and rotation either while performing a task or standing still. It can also map the sway of the body around the center of mass of the individual although this measure cannot be quantified yet. The gait speed and balance of the participant can also be measured and quantified. All quantifiable data obtained from Kinetisense are calculated by simultaneously analyzing motion in the 3 planes of the human body; sagittal, frontal and transverse planes.

Although these measures are ultimately useful, they will mean a lot more to a clinician when used in combination with visual observation. This is the principle we have used by proposing the eV-BBS. Kinetisense can provide measurements of function without losing the value of clinician observation. The combined information enables the clinician to interpret the data in terms of physical, physiological or musculoskeletal impairments before building a therapy template that is customized for every individual.

4.2.3. Synthesis of eV-BBS Data

The eV-BBS incorporating Kinetisense can be clinically useful for virtual assessments. Unlike the BBS questionnaire, the eV-BBS does not require a questionnaire to keep track of all the data produced during assessments. All patient data is saved appropriately in local or Kinetisense cloud storage. The results of the assessments are synthesized and reproduced immediately for the clinician to be used for the patient's therapy sessions.

The eV-BBS and by extension Kinetisense is able to produce a lot more useful data in comparison to the BBS. An example of this can be made using the task "standing on one leg". The BBS only considers the ability of the participant to stand on one leg independently for 10 seconds and above while the eV-BBS is able to tell you the posture of the overall body as well as the positions of specific joints such as the hip while this task was being assessed. A positive Trendelenburg sign can also be detected with the eV-BBS. It also shows you all possible compensatory movements that the participants used during this task thereby drawing the clinicians' attention to possible muscular inconsistencies that may need to be addressed during therapy sessions in order to improve their balance and additionally their muscle strength.

The clinician can also keep track of the progress or regress of the participants by having access to videos of previous assessments as well as quantitative results of past and present assessments. Basically, visual observation can be backed up by quantitative data that will not be lost overtime as opposed to past questionnaires written on paper that can be misplaced over time.

4.2.4. Procedure

Similarly, to the BBS, the eV-BBS assessment was performed in both sitting and standing positions. In the case of the eV-BBS which is performed virtually, the clinician explains the task to the participant before starting Kinetisense to record the participant perform the task. However, in order to avoid learning effects in this study, the clinician was not to demonstrate the task to the participant. Each task was repeated 5 times in order to ensures the repeatability of the assessment using Kinetisense.

Kinetisense has the unique ability of recording assessments in real time by processing/analyzing about 30-90 frames of data per second. This data is recorded and can be replayed frame by frame at any time after the assessment has been completed. This makes the technology extremely sensitive because it is able to capture really small deviations that indicate a loss of balance that cannot be seen via visual observation. As such, the timing of an assessment does not need to be as long as that of the subjective BBS. Also, right now, Kinetisense is set up to capture 30 seconds of data per task (this could be changed to longer or shorter bouts if clinically indicated). A task can be repeated as many times as possible by simply saving an already recorded video and starting a new one for a repetition if necessary. Taking this into account, the eV-BBS protocol was developed with a 30 second timing for easier tasks and 10 second intervals for harder tasks. This means that if a 30 second task were to be repeated 5 times, the overall amount of data collected will be over 150 seconds / 2.5 minutes' worth of data.

The BBS tasks that make up the eV-BBS as well as the module arrangement of the tasks and instructions given to suit Kinetisense are described in Table 2 below.

Kinetisense Module	Task Name	Instructions	Repetition
Balance Module (Static Balance Tasks)	Stand Unsupported.	Ask the patient to stand for 30 seconds without holding anything	5
	Sit with back unsupported but with feet supported on the floor or a stool.	Ask the patient to sit on a stool for 30 seconds. Make sure the stool is low enough that the patient's feet can touch the floor	5
	Stand unsupported with eyes closed.	Please ask the patient to close their eyes and stand still for 30 seconds.	5
	Stand unsupported with feet together.	Ask the patient to place both feet together and stand without holding anything for 30 seconds.	5
	Turn to look behind over left and right shoulders while standing.	Ask the patient to look directly behind their left shoulders and then over their right shoulders for 30 seconds. The examiner may pick out any object to look at directly behind the patient in order to encourage a better twist/turn.	5

	Stand unsupported, one foot in front of the other	Ask the patient to place one foot directly in front of the other. If the patient finds this difficult, the patient can step a little bit forward such that there is a little space between the forward foot and the backward foot. Hold this position for 30 seconds	5
	Stand on one leg	Ask the patient to stand on one leg for 30 seconds or as long as they can.	5
	Reach forward with outstretched arms	With the side of the patient's body facing the camera, ask the patient to lift their arms to 90 degrees, stretch out their fingers and reach forward as much as possible. Hold this position for the test.	5
Functional Module (Dynamic Balance tasks)	Sit to stand	Starting from a sitting position, please ask the patient to stand up, hold the standing position for 5 seconds.	5
	Stand to sit	Starting from a standing position, please ask the patient to sit down, hold the sitting position for 5 seconds.	5

	Transfers	Instructions: Arrange chairs for a pivot transfer. The chairs should be at 90 degrees to each other. The chair with the armrests should face the camera and the chair without armrests should be at a 90-degree position to the chair with armrests. Exercise: Ask the patient to transfer one way towards the seat without armrests and sit down, hold this position for 5 seconds and transfer back towards the sit with armrests.	5
	Pick up object from the floor from a standing position	Place an object in front of the patient's feet. Ask the patient to pick up the object from the floor, stand up and hold this position for 5 seconds.	5
	Turn 360 degrees	Ask the patient to turn around completely in a full circle, stop at the starting position for 5 seconds and turn around in a full circle in the opposite direction.	5

	Place alternate foot on step/stool while standing unsupported.	Ask the patient to place each foot alternately on a step on stool 8 times (4 steps per foot), place both feet on the floor at the end of the exercise and hold that standing position for 5 seconds.	5

Table 2: The BBS tasks arranged in the order of the Kinetisense modules used to perform the assessments.

4.2.5. Analysis of eV-BBS Tasks

The dynamic part of the eV-BBS tasks was analyzed by creating a MATLAB code developed for this project to process the csv files exported from Kinetisense.

The MATLAB code used in the data analysis was created by a member of the Rehabilitation Robotics Laboratory in collaboration with computer scientists from York University. Regular meetings were conducted between the MATLAB team and the researcher during the creation of the code. An overview of how this code that was created is as follows;

When the participant data is exported from Kinetisense in the form of csv files, the researcher converts these csv files to excel files in order to preserve the structure of the data. The input directory from these excel files can be inputted into MATLAB. An output directory is also created and defined. This will contain the final presented data (either as a spreadsheet or in figure form). The excel files are then read into a “data Table” and the number of points in the table are counted to determine how large the data structure is.

Next, tables are defined containing UK, US and European shoe sizes. Each table is defined into different columns. The shoe size becomes important during the actual data analysis. The data obtained from Kinetisense is analyzed using the specific shoe size and height of the participant that the excel file belongs to. This means that the height and shoe sizes are inputted into the code. The MATLAB code gives the researcher the option of inputting the height of the participant that the excel file in the input directory belongs to and then the researcher also has the option to choose whether the height inserted was in centimeters or meters.

A different section of the code is written to extract the data Table into vector arrays (x,y,z). This is because the csv files produce results in these vector arrays: “X” represents data obtained in the sagittal plane, “Y” represents the transverse plane and “Z” represents the frontal plane. These vector arrays become time series for each marker on the anatomical landmarks where Kinetisense takes measurements from during the analysis (head, shoulders, hips, knees, ankles and spine), each having a column of data points. The data obtained focused on the movements of the trunk of the participant when performing both the static and dynamic balance tasks. The anatomical landmarks available from the Kinetisense system were used to estimate the location of the participant’s centre of mass. The data encoded into MATLAB was for the dynamic tasks only.

Data smoothing was performed to remove outliers that occur if the Kinetisense system momentarily loses track of a landmark. The results extracted from MATLAB at the end of the analysis contains data under the following parameters: speed of forward lean, speed of backward lean, rise speed, drop speed, duration of test, lean distance (distance of forward lean), distance of backward lean, rise height, drop height, root mean square (RMS) of forward lean, RMS of backward lean, rise RMS, drop RMS. These results are then inputted into SPSS to determine the mean, SD and Standard error of mean of the eV-BBS tasks which were used to answer hypothesis 1 and 3. STATA was used to determine the ICC of the populations for hypothesis 2. The MATLAB code can be found in (*Appendix I*). All the balance tasks were calculated from the csv files using excel.

4.3. Protocol Combining BBS and eV-BBS

This study took place at the RRL Laboratory, University of Alberta, following strict COVID-19 protocols. The participants were asked to come to the lab wearing sports clothing which includes a top of their choosing and shorts that extended below the knees for the males or leggings for the females. All participants were required to sign a consent form before their scheduled appointment date and they were sent workflow protocols for the lab via email detailing how to start the system and give access to the researcher who conducted the study. This workflow protocol can be found in (Appendix E). The researcher conducted this study either from home or from a nearby conference room using Zoom for Health. The conference room is fully enclosed and separate from the lab space. The participants were required to operate the equipment and give the researcher remote desktop access. This allowed the researcher to remote-desktop the computer in the lab while maintaining physical distancing in order to maintain safety of all present in the laboratory. Only one participant was scheduled for a study at any time but a maximum of 2 participants were scheduled per day.

All participants were asked to keep their masks on unless they were the only people in the lab space in which case taking the mask off was permitted. Of note was the fact that masks occasionally interfered with the motion capture technology, so some participants had to take the mask off to accurately collect data, but this was only done in this specific situation and only if the participant was alone in the lab space. The equipment and lab furniture were sanitized thoroughly between study participants. There has been no record of a COVID incident among the participants that participated in this study to date. Before the commencement of the eV-BBS study, the participant was required to provide their age, height, weight and shoesize to the researcher. This was later used to determine the BMI as well as create a demographic analysis of all participants involved. The researcher modified the subjective BBS to be able to measure 5 repetitions of a task. This modification can be found in (*Appendix F*). The researcher alone was in charge of this study since this study was for data collection only. Therefore, no specialist clinician was required.

For the combined BBS and eV-BBS protocol, all participants were required to repeat all tasks 5 times both for the BBS assessment and for the eV-BBS protocol. Both results of the BBS and eV-BBS were recorded by the researcher. No formal assessment was made by the researcher regarding the falls risk of the participant as this was outside of their scope of practice and all participants had been pre-selected to assume that they were very low falling risk. The only difference with combining the BBS and eV-BBS assessments was that the participants were required to finish the BBS assessment after the eV-BBS data has been recorded. This is because, while the eV-BBS tasks lasted for a maximum of 30 seconds, the BBS task could extend to about 2 minutes.

The participants were allowed to take a 5-minute break at any point during the study should they indicate that they needed one due to any reason. All participants were required to come for only one study session as there was no follow-up data collection required during this study design.

4.4 Clinical Implementation of eV-BBS in the Long-Term Care Setting.

In order to accomplish this pilot study in a geriatric population, a generalist was hired at the participating supported-living facilities listed above and a physiatrist from the Glenrose Rehabilitation Hospital in Edmonton was invited to be a part of the project team as the specialist. All the equipment required to perform this study successfully, including the Kinetisense software, was sent to the supported living facilities. The researcher was able to access the computers at the supported living facilities by using desktop sharing with the help of the generalist clinician who grants computer access to the researcher.

Before the commencement of the protocol, an intake form was filled out by interested participants living in the facilities listed above with the help of the generalist nurse who was hired to support the project in those facilities. The most important sections of the intake form, which can be found in (*Appendix G*) were the age, medical history, falls history as well as drugs which the participant was currently taking. The specialist clinician, who is an Alberta Health Services (AHS) physician, used FORTA (Fit for the Aged) to ensure that the drugs being taken by the participant did not interact with each other to cause dizziness and falling. If any interaction was found, a report was sent to the participant's family doctor in order to address this underlying risk factor that may or may not be contributing to participant's falls risk.

As the assessment commenced, the specialist clinician filled out the subjective BBS of the participant because this was what he relied upon to measure the falls risk of said participant. The reason the eV-BBS was not being used by the specialist clinician is because it had not been validated yet and as such could not be relied upon to make medical decisions. The eV-BBS was still taken by the researcher alongside the subjective BBS. However, while the eV-BBS was for data collection purposes only, the subjective BBS was relied upon to make medical decisions about the participants falls risk.

At the end of the assessment, the specialist clinician informed the participants of the results of the BBS assessment as well as future steps to be followed regarding their care. This did not involve a follow-up session but rather suggestions on exercises that were readily available at the supported living facility in which the participant could get involved with in order to better increase their balance and coordination.

5. Results

The Kinetisense software experienced some difficulty in performing some of the more complex tasks such as turn 360 degrees and pick up objects from the floor. This is because the software needs to maintain the ability to detect an anatomical landmark continuously. With the complex tasks landmarks may be hidden and the software loses track of them. In the future the simultaneous use of two or three cameras tracking continuously would overcome this limitation. Any exercises that required more than one range of movement or required the software to lose track of the anatomical landmarks of the body at any given time was considered complex and could not be properly assessed by the technology. Therefore, out of the 14 tasks carried out using Kinetisense, 8 were chosen as the basis for this analysis because they met the requirements of the Kinetisense technology at its current capabilities.

5.1. Demographics

The demographic analysis below was obtained using the unique information that was obtained during the study such as age, sex, weight and height. The BMI was calculated from this and compiled in the table below;

Demographic Analysis Results (Healthy Participant group):

AGE	GENDER	HEIGHT (cm)	WEIGHT (kg)	BMI
23	F	156	78.7	32.3
23	M	182	84	25.4
32	M	192	93	24.5
31	M	173	80.2	26.8
20	F	170	52	18
28	M	177.8	78	24.7
27	F	175	76.2	24.9
37	F	180	97	29.9
27	F	156	72.9	30

24	M	168.5	79.4	28

Table 3: Demographic analysis of the healthy participants.

Demographic Analysis Results (Long-Term Care Participant group):

GROUPS	AGE	GENDER	HEIGHT (cm)	WEIGHT (kg)	BMI
Faller	86	F	157.5	49.9	20.1
Non-faller	73	F	160	46.72	18.2
Non-faller	84	F	154.9	77.1	32.1
Faller	90	F	157.5	58.97	23.8

Table 4: Demographic analysis of the long-term care participants

5.2. Hypothesis 1: Correlation of the BBS tasks and the eV-BBS Tasks

5.2.1. Correlation of the BBS and eV-BBS Tasks between Participants in the Healthy Population

Because of the small sample size for the long-term care population, a validity analysis could not be performed in order to answer hypothesis 1. However, a comparison of the group could be reported for all the eV-BBS tasks.

The mean, standard error of the mean and standard deviation of the static balance and dynamic balance tasks respectively were calculated using SPSS, while the coefficient of variation for all the tasks was calculated using Excel.

1. The Berg Balance Scale Scores for all Groups:

Berg Balance Scale									
Participant Group	Parameters	Sit to Stand	Stand to Sit	Sit with Back Unsupported	Stand Unsupported (eyes open)	Stand Unsupported (eyes closed)	Stand Unsupported (feet together)	Stand Unsupported (one foot infront of the other)	Stand on one leg
Healthy Participants	Mean	4	4	4	4	4	3.9	3.9	3.9
	ST DEV	0	0	0	0	0	0.32	0.32	0.32
	COV (%)	0	0	0	0	0	**8.11**	**8.11**	**8.11**
Long Term Care Participants	Mean	4	3.75	4	4	4	4	3.75	2.25
	ST DEV	0	0.5	0	0	0	0	0.5	1.5
	COV (%)	0	**13.33**	0	0	0	0	**13.33**	**66.67**

Table 5: Comparison of the berg balance scale between the healthy participants and long-term care participants.

The table above shows a lack of variability between subjects in the population for both healthy participants and long-term care participants. This can be attributed to the insensitivity of the measurement tool. It may also be attributed to the tasks above being too easy for the healthy participants. The Healthy participants showed a lot more variability in tasks that involved narrowing their base of support. The LTC participants showed more variability in the same areas in addition to the Stand to Sit task. The variability in the stand to sit could be attributed to the fact that the older participants were allowed to use their walking aid to perform this task to avoid falling. The BBS does not account for a smooth transition of movements, just for the ability or inability to perform the task independently. The use of the walking aid gave the participants a lower score and had nothing to do with how they actually performed the task. Lastly, the variability between parameters in all of the results obtained during this study could also be attributed to the different ways in which the participants performed each of the tasks. This is applicable for both the functional tasks as well as the balance tasks.

2a. The Dynamic Balance Tasks of the eV-BBS (Sit to Stand)

			Sit to Stand						
			Speed of Forward Lean	Speed of Backward Lean	Rise Speed	Drop Speed	Duration of Test	Lean Distance	Distance of Backward Lean
Healthy Participants	N	Valid	50	50	50	50	46	10	10
		Missing	0	0	0	0	4	40	40
	Mean		0.043	-0.044	0.049	-0.040	9.972	0.342	0.342
	Std. Error of Mean		0.004	0.005	0.002	0.004	0.249	0.028	0.028
	Std. Deviation		0.028	0.034	0.015	0.027	1.687	0.089	0.089
	COV (%)		**64.61**	**-76.71**	**30.10**	**-67.58**	**16.92**	**25.92**	**25.92**
LTC Participants (Non-Fallers)	N	Valid	2	2	2	2	1	1	1
		Missing	0	0	0	0	1	1	1
	Mean		0.002	-0.016	0.022	-0.003		0.193	0.193
	Std. Error of Mean		0.007	0.003	0.001	0.001			
	Std. Deviation		0.010	0.004	0.001	0.001			
	COV (%)		**572.90**	**-23.19**	**3.76**	**-43.08**			
LTC Participants (Fallers)	N	Valid	1	1	1	1	0	0	0
		Missing	0	0	0	0	1	1	1
	Mean		0.002	-0.009	0.015	-0.091			

Table 6a: Comparison of the sit to stand task between the healthy participants and long-term care participants for the chosen parameters above.

The sit to stand task shows a lot of variability between the participants in the healthy and faller groups. While the high COV for the LTC non-fallers group can be associated to the low number of participants in that population, the rise speed COV of 3.76 in that group suggests that the transition from sit to stand in that group was much slower than that of the healthy population. The COV could not be estimated for the fallers group due to data incompleteness because the fallers group was unable to complete this dynamic task. The results for lean distance and distance of backward lean for both the healthy participants and the non-fallers group suggests that the distance of forward and backward lean was equal across the participants. In comparing the mean values of the LTC non-fallers group to that of the fallers group, the values obtained do not seem to differ a lot. However, for drop speed, the value of (- 0.091) for the fallers group in comparison to (-0.003) for the non-fallers group suggests that the participants in the fallers tended to just drop in their seat rather that use muscle control to perform that movement. This is to be expected because weakness in certain postural muscles as well as an overall loss of muscle strength can be the cause of an increased falls risk. Unfortunately, because only one participant in this group was able to perform this task, we are unable to evaluate the variability of the measures as this time.

			Sit to Stand					
			Rise Height	**Drop Height**	**Root Mean Square of Forward Lean**	**Root Mean Square of Backward Lean**	**Rise Root Mean Square**	**Drop Root Mean Square**
Healthy Participants	N	Valid	10	10	10	10	10	10
		Missing	40	40	40	40	40	40
	Mean		0.419	0.419	0.368	0.038	0.462	0.050
	Std. Error of Mean		0.021	0.021	0.028	0.006	0.024	0.008
	Std. Deviation		0.065	0.065	0.087	0.020	0.077	0.024
	COV (%)		**15.52**	**15.52**	**23.74**	**53.23**	**16.75**	**47.17**
LTC Participants (Non-Fallers)	N	Valid	1	1	1	1	1	1
		Missing	1	1	1	1	1	1
	Mean		0.319	0.319	0.220	0.026	0.030	0.291
	Std. Error of Mean							
	Std. Deviation							
	COV (%)							
LTC Participants (Fallers)	N	Valid	0	0	0	0	0	0
		Missing	1	1	1	1	1	1

Table 6b: Continuation of the comparison of the sit to stand task between the healthy participants and long-term care participants for the chosen parameters above.

The table above is a continuation of Table 6a. Because MATLAB was unable to produce results for the one participant in the fallers group for this section, no results could be reported at this time. However, in comparing the mean values of the healthy participants to the LTC non-fallers group, consistency in the measurements can be observed, except for the rise root mean square and drop root mean square values. The values between the two groups suggests that the healthy participants performed the exercises faster and more consistently than the LTC participants. The LTC participants only performed all their tasks once because of their lower endurance level. This is an important learning from this project that should be taken into account when designing future studies. It should also be noted that the table above reports the averages of all 5 tasks all at once by MATLAB. So, the 40 missing values are not missing at all. They are all part of the 10 valid values used in this table.

2b. The Dynamic Balance Tasks of the eV-BBS (Stand to Sit)

	Stand to Sit								
			Speed of Forward Lean	**Speed of Backward Lean**	**Rise Speed**	**Drop Speed**	**Duration of Test**	**Lean Distance**	**Distance of Backward Lean**
Healthy Participants	N	Valid	49	49	49	49	46	10	10
		Missing	0	0	0	0	3	39	39
	Mean		0.055	-0.046	0.040	-0.058	9.573	0.345	0.345
	Std. Error of Mean		0.007	0.006	0.003	0.005	0.296	0.026	0.026
	Std. Deviation		0.047	0.039	0.023	0.032	2.005	0.081	0.081
	COV (%)		**85.68**	**-84.45**	**58.23**	**-55.68**	**20.95**	**23.41**	**23.41**
LTC Participants (Non-Fallers)	N	Valid	2	2	2	2	2	2	2
		Missing	0	0	0	0	0	0	0
	Mean		0.077	-0.042	0.018	-0.049		0.314	0.314
	Std. Error of Mean		0.059	0.040	0.017	0.036		0.006	0.006
	Std. Deviation		0.083	0.056	0.025	0.051		0.009	0.009
	COV (%)		**108.70**	**-136.04**	**133.85**	**-105.00**		**2.89**	**2.89**
LTC Participants (Fallers)	N	Valid	1	1	1	1	0	0	0
		Missing	0	0	0	0	1	1	1
	Mean		0.009	-0.011	0.002	-0.008			

Table 7a: Comparison of the stand to sit task between the healthy participants and long-term care participants for the chosen parameters above.

The bigger variations in the non-fallers group in comparison to the healthy participants can be attributed to their lower participant number. This task is functionally the opposite of the sit to stand task. The participants start from a standing position and go to a sitting position. In comparing the mean values of the non-fallers group to the fallers group and the taking into consideration the fact that only one participant from the fallers group was able to perform this task, the values from the fallers group suggests that the participant is performing that task at a much slower rate that the non-fallers group. This consistency can be noticed throughout the table for all the functional tasks. The lean distance (distance of forward lean) and distance of backward leans are the same across all participants as well.

			Stand to Sit					
			Rise Height	**Drop Height**	**Root Mean Square of Forward Lean**	**Root Mean Square of Backward Lean**	**Rise Root Mean Square**	**Drop Root Mean Square**
Healthy Participants	N	Valid	10	10	10	10	10	10
		Missing	39	39	39	39	39	39
	Mean		0.407	0.407	0.110	0.262	0.483	0.077
	Std. Error of Mean		0.027	0.027	0.035	0.030	0.044	0.027
	Std. Deviation		0.084	0.084	0.109	0.094	0.138	0.085
	COV (%)		**20.67**	**20.67**	**99.22**	**35.77**	**28.50**	**110.41**
LTC Participants (Non-Fallers)	N	Valid	2	2	2	2	2	2
		Missing	0	0	0	0	0	0
	Mean		0.271	0.271	0.044	0.288	0.148	0.127
	Std. Error of Mean		0.032	0.032	0.037	0.027	0.143	0.107
	Std. Deviation		0.046	0.046	0.053	0.038	0.203	0.151
	COV (%)		**16.86**	**16.86**	**119.32**	**13.13**	**136.62**	**118.22**
LTC Participants (Fallers)	N	Valid	0	0	0	0	0	0
		Missing	1	1	1	1	1	1

Table 7b: Continuation of the comparison of the stand to sit task between the healthy participants and long-term care participants for the chosen parameters above.

The rise height and drop height across all participants for both the healthy group and non-fallers group are equal. This suggests that Kinetisense is able to measure the individual's height in their starting position as well as when the individual is at rest. The suggests that if Kinetisense is useful to assess a participant over a number of years, should this participant experience a loss of stature due to age or postural deformations, Kinetisense is able to sense that difference in height even before the patient starts showing physical changes. This also seems to be the same for lean distance and distance of backward lean.

3a. The Static Balance Tasks of the eV-BBS (Sit with Back Unsupported)

Sit with Back Unsupported										
Tasks	Parameters	Spine Shoulder X	Spine Shoulder Y	Spine Shoulder Z	Spine Mid X	Spine Mid Y	Spine Mid Z	Spine Base X	Spine Base Y	Spine Base Z
Healthy Participants	Grand RMS of task	0.657	1.929	18.241	0.580	1.116	17.989	0.561	1.768	17.776
	Associated ST DEV	0.506	1.527	2.481	0.451	1.616	2.534	0.413	1.729	2.590
	Grand COV of COV (%)	**76.89**	**79.17**	**13.60**	**77.84**	**144.83**	**14.09**	**73.58**	**97.78**	**14.57**
LTC Participants (Non-Fallers)	Average RMS	0.067	0.055	1.739	0.059	0.237	1.654	0.052	0.419	1.569
	ST DEV	0.045	0.009	0.192	0.044	0.004	0.185	0.047	0.020	0.175
	COV (%)	**67.02**	**16.70**	**11.04**	**74.14**	**1.49**	**11.17**	**90.32**	**4.74**	**11.17**
LTC Participants (Fallers)	Mean	0.115	0.183	2.108	0.098	0.341	1.992	0.080	0.500	1.876
	ST DEV	0.028	0.128	0.114	0.017	0.113	0.103	0.004	0.101	0.092
	COV (%)	**23.93**	**69.59**	**5.39**	**16.95**	**33.04**	**5.16**	**5.45**	**20.18**	**4.89**

Table 8: Comparison of the sit with back unsupported task between the healthy participants and long-term care participants.

For the balance parameters, the spine shoulder covers the span of the cervical spine and the upper thoracic spine as well. The spine mid covers the thoracic spine (1-12) and the center of mass which was obtained from the data in order to create a section of the MATLAB program was obtained from this parameter. Lastly, the Spine base stands for the lumbar spine. It should also be noted that in all of the balance tasks, the "X" stands for sagittal plane, "Y" stands for Transverse plane and "Z" for frontal plane. The variability for this task varies for all the parameters. Although this is a static task, this variation can be attributed to the positioning of each of the participants when performing the task. Since the subjective BBS does not account for the positioning of the participant, this study also did not position the participants. Therefore, the difference between participants could be that one participant sits with legs apart creating a wider base of support and participant 2 sits with a narrower base of support and Kinetisense detects all those variations between the participants.

3b. The Static Balance Tasks of the eV-BBS (Stand on One Leg)

Stand on One Leg										
Tasks	**Parameters**	**Spine Shoulder X**	**Spine Shoulder Y**	**Spine Shoulder Z**	**Spine Mid X**	**Spine Mid Y**	**Spine Mid Z**	**Spine Base X**	**Spine Base Y**	**Spine Base Z**
Healthy Participants	Grand RMS of task	1.241	2.268	18.262	1.172	1.249	18.120	1.132	0.752	18.060
	Associated ST DEV	1.395	0.867	1.776	1.387	0.631	1.728	1.377	1.010	1.643
	Grand COV of COV (%)	**112.39**	**38.24**	**9.73**	**118.35**	**50.48**	**9.54**	**121.66**	**134.28**	**9.10**
LTC Participants (Non-Fallers)	Average RMS	0.431	0.102	3.633	0.421	0.137	3.591	0.412	0.374	3.548
	ST DEV	0.294	0.033	0.174	0.288	0.027	0.208	0.281	0.021	0.241
	COV (%)	**68.34**	**31.94**	**4.79**	**68.33**	**19.54**	**5.78**	**68.30**	**5.75**	**6.80**
LTC Participants (Fallers)	Mean	0.638	0.124	3.510	0.624	-0.118	3.444	0.610	-0.358	3.378
	ST DEV	–	–	–	–	–	–	–	–	–
	COV (%)	–	–	–	–	–	–	–	–	–

Table 9: Comparison of the stand on one leg task between the healthy participants and long-term care participants.

In comparing the COV of tasks for the healthy participants to the COV of the non-fallers group, the results for stand on one leg show that the most sway shown across the groups were made in the "Y" (sagittal) plane for the healthy population. So, the participants in the healthy population experienced more rotational sway in comparison to swaying from front to back ("Z" plane) or side to side ("X" plane). However, the non-fallers group are shown to experience less sway than the healthy participants. Both the non-fallers group and fallers group performed the balance tasks without their walking aids. In accordance with the BBS, the Kinetisense recording was stopped when they dropped their legs. However, while the healthy participants were able to maintain their position for the during of time allocated, the long-term participant group dropped their legs before the time elapsed, Therefore, the results can either be attributed to the participant number in this group or to the lesser muscle strength and endurance of the participants in the LTC group. Only one participant was able to perform this task in the fallers group.

3c. The Static Balance Tasks of the eV-BBS (Stand Unsupported eyes open)

Stand Unsupported (eyes open)										
Tasks	Parameters	Spine Shoulder X	Spine Shoulder Y	Spine Shoulder Z	Spine Mid X	Spine Mid Y	Spine Mid Z	Spine Base X	Spine Base Y	Spine Base Z
Healthy Participants	Grand RMS of task	0.709	2.414	18.604	0.674	1.313	18.404	0.641	0.800	18.234
	Associated ST DEV	0.329	0.760	3.081	0.347	0.716	3.129	0.376	1.174	3.169
	Grand COV of COV (%)	**46.45**	**31.48**	**16.56**	**51.52**	**54.49**	**17.00**	**58.59**	**146.79**	**17.38**
LTC Participants (Non-Fallers)	Average RMS	0.162	0.137	2.660	0.159	0.099	2.617	0.158	0.333	2.574
	ST DEV	0.198	0.079	1.444	0.202	0.074	1.455	0.205	0.072	1.466
	COV (%)	**122.24**	**57.51**	**54.29**	**126.84**	**75.40**	**55.60**	**129.37**	**21.72**	**56.95**
LTC Participants (Fallers)	Average RMS	0.110	0.057	2.529	0.075	**0.172**	**2.493**	**0.057**	**0.399**	2.463
	ST DEV	0.072	0.012	1.231	0.034	0.040	1.256	0.018	0.075	1.275
	COV (%)	**65.57**	**20.64**	**48.67**	**45.23**	**23.00**	**50.39**	**31.76**	**18.80**	**51.74**

Table 10: Comparison of the task stand unsupported (eyes open) between the healthy participants and long-term care participants.

The results comparing the COV between the non-fallers group and fallers group suggests that there was more sway in the “X” plane for the non-fallers group in comparison to the fallers. On the other hand, the healthy participant group reports a higher sway in the transverse (Y) plane compared to the LTC group. This sway was not seen with the naked eye during the study so this can either be attributed to the sensitivity of the technology to detect that change or it can be attributed to the noise of the data which is created when the markerless motion capture system loses the anatomical landmark of the body and tries to recalibrate itself to find the missing landmark. This noise was seen throughout the data. Some of the noise was removed from the data either manually for the balance tasks or by using MATLAB to perform data smoothing for the functional tasks. However, not all of the noise could be extracted. This could also affect the results obtained for all of the tasks in this study.

3d. The Static Balance Tasks of the eV-BBS (Stand Unsupported eyes closed)

Stand Unsupported (eyes closed)										
Tasks	**Parameters**	**Spine Shoulder X**	**Spine Shoulder Y**	**Spine Shoulder Z**	**Spine Mid X**	**Spine Mid Y**	**Spine Mid Z**	**Spine Base X**	**Spine Base Y**	**Spine Base Z**
Healthy Participants	Grand RMS of task	0.521	2.401	17.857	0.485	1.310	17.681	0.462	0.792	17.535
	Associated ST DEV	0.429	0.761	2.630	0.443	0.715	2.567	0.457	1.173	2.503
	Grand COV of COV (%)	**82.27**	**31.69**	**14.73**	**91.27**	**54.59**	**14.52**	**99.00**	**148.13**	**14.27**
LTC Participants (Non-Fallers)	Average RMS	0.200	0.102	3.473	0.204	0.144	3.435	0.209	0.391	3.397
	ST DEV	0.113	0.025	0.329	0.108	0.018	0.339	0.104	0.008	0.350
	COV (%)	**56.67**	**24.91**	**9.46**	**53.03**	**12.67**	**9.88**	**49.82**	**1.94**	**10.29**
LTC Participants (Fallers)	Average RMS	0.195	0.066	2.093	0.107	**0.114**	**1.937**	**0.020**	**0.252**	1.819
	ST DEV	0.246	0.006	1.917	0.110	0.106	2.074	0.014	0.276	2.177
	COV (%)	**126.20**	**8.94**	**91.58**	**101.94**	**92.35**	**107.09**	**70.56**	**109.44**	**119.69**

Table 11: Comparison of the task stand unsupported (eyes closed) between the healthy participants and long-term care participants.

In comparing the result of the LTC groups to the healthy population, the fallers group shows more sway across the board in relation to the non-fallers group and the healthy participants. However, the healthy population shows more sway in the transverse plane for spine base in relation to the long-term care population. This could either be attributed to the postural differences between the groups or the sensitivity of the technology to detect these subtle rotations in the spine. It could also be attributed to the fact that the long-term care population did experience more sway while performing this task to the healthy population. Some of this sway was big enough to be observed by the researcher during the study. However, no credible conclusions can be drawn from the results of the long-term care population because of the small sample size that was used for the long-term care group.

3e. The Static Balance Tasks of the eV-BBS (Stand Unsupported Feet Together)

Stand Unsupported (feet together)										
Tasks	Parameters	Spine Shoulder X	Spine Shoulder Y	Spine Shoulder Z	Spine Mid X	Spine Mid Y	Spine Mid Z	Spine Base X	Spine Base Y	Spine Base Z
Healthy Participants	Grand RMS of task	0.507	2.347	17.561	0.464	1.247	17.389	0.435	0.727	17.234
	Associated ST DEV	0.672	0.870	2.110	0.643	0.626	2.021	0.623	0.956	1.951
	Grand COV of COV (%)	**132.48**	**37.06**	**12.01**	**138.65**	**50.24**	**11.62**	**143.08**	**131.60**	**11.32**
LTC Participants (Non-Fallers)	Average RMS	0.384	0.124	3.454	0.382	0.123	3.418	0.381	0.369	3.383
	ST DEV	0.162	0.047	0.380	0.157	0.034	0.403	0.152	0.020	0.426
	COV (%)	**42.17**	**37.64**	**11.01**	**41.01**	**28.05**	**11.79**	**39.89**	**5.36**	**12.60**
LTC Participants (Fallers)	Mean	0.266	0.068	1.991	0.163	0.126	1.810	0.064	0.266	1.682
	ST DEV	0.192	0.016	1.581	0.053	0.107	1.757	0.082	0.268	1.871
	COV (%)	**72.12**	**23.90**	**79.43**	**32.52**	**84.63**	**97.09**	**126.61**	**100.58**	**111.22**

Table 12: Comparison of the task stand unsupported (feet together) between the healthy participants and long-term care participants.

The results above show variations in the sway of the spine in the healthy group except for spine shoulder Y where the non-fallers group seems to vary more, spine Mid X where the healthy participants vary more than the other groups as well as Spine Base X and Y with the healthy population having a lot more variation in relation to the other groups. This may also be attributed to the number of individuals in the population or simply to variations in how these tasks are performed by each individual in the population.

3f. The Static Balance Tasks of the eV-BBS (Stand Unsupported One Foot in-front of the Other)

Stand Unsupported (one foot in front of the other)										
Tasks	**Parameters**	**Spine Shoulder X**	**Spine Shoulder Y**	**Spine Shoulder Z**	**Spine Mid X**	**Spine Mid Y**	**Spine Mid Z**	**Spine Base X**	**Spine Base Y**	**Spine Base Z**
Healthy Participants	Grand RMS of task	0.755	2.314	18.683	0.731	1.223	18.544	0.720	0.743	18.421
	Associated ST DEV	0.782	0.823	2.412	0.784	0.641	2.406	0.781	1.035	2.414
	Grand COV of COV (%)	**103.57**	**35.56**	**12.91**	**107.25**	**52.39**	**12.97**	**108.47**	**139.34**	**13.10**
LTC Participants (Non-Fallers)	Average RMS	0.182	0.102	3.494	0.184	0.145	3.454	0.187	0.393	3.414
	ST DEV	0.088	0.025	0.358	0.080	0.020	0.367	0.073	0.010	0.374
	COV (%)	**48.17**	**24.72**	**10.25**	**43.60**	**13.72**	**10.61**	**38.84**	**2.67**	**10.97**
LTC Participants (Fallers)	Mean	0.176	0.072	2.307	0.147	0.187	2.263	0.120	0.409	2.224
	ST DEV	0.061	0.022	1.132	0.026	0.022	1.115	0.006	0.065	1.103
	COV (%)	**34.49**	**30.01**	**49.07**	**17.79**	**11.60**	**49.29**	**4.92**	**16.01**	**49.60**

Table 13: Comparison of the task stand unsupported (one foot in front of the other) between the healthy participants and long-term care participants.

The results of the task above show that by narrowing the base of support, there seems to be more sway in the healthy population in relation to the LTC group. This may be attributed to the small sample size for the LTC participants. It can also be attributed to the fact that the long-term care participants were allowed to modify their positioning before doing this task so as to ensure their comfort and work with their endurance. Therefore, if a healthy participant was asked to place both feet together, a LTC participant was allowed to have some space in between their feet. Their base of support is not entirely closed but is narrow enough to qualify as “feet together”. The BBS does not account for this modification in the positioning but rather rates the task as 0 if the participants feet are not close together. However, considering how sensitive Kinetisense is and also the age range of the participant group, the researcher allowed this modification when necessary.

5.2.2. Hypothesis 2: The Test-retest Reliability of the eV-BBS Assessment Tasks using ICC

Because a repeated test was not carried out for the LTC population, the ICC could only be performed on the healthy population data. The ICC model used in this analysis was the two-way mixed effects model with consistency agreement.

Static Balance Tasks

Individual ICC results of the Balance Tasks									
	Spine Shoulder			Spine Mid			Spine Base		
	ICC	[95% Conf. Interval]		ICC	[95% Conf. Interval]		ICC	[95% Conf. Interval]	
Sit with Back Unsupported	0.812324	0.6178786	0.9403251	0.8254389	0.6399764	0.9449587	0.8441643	0.6725388	0.9514419
Stand on One Leg	0.9703088	0.9285353	0.9914286	0.969547	0.9267662	0.9912047	0.9471322	0.8760627	0.9845288
Stand Unsupported (eyes open)	0.9712823	0.9308009	0.9917143	0.9920484	0.980369	0.9977332	0.9933262	0.9834987	0.9980989
Stand Unsupported (eyes closed)	0.9609121	0.9069265	0.9886537	0.9524661	0.8878955	0.9861334	0.9435857	0.8682732	0.9834563
Stand Unsupported (feet together)	0.9976956	0.9942726	0.9993452	0.9970975	0.9927911	0.999175	0.9948376	0.987213	0.9985307
Stand Unsupported (one foot in front of the other)	0.9391846	0.8586923	0.982119	0.930669	0.8404183	0.9795117	0.9158682	0.8094601	0.9749163

Table 14: The test-retest reliability of the balance tasks.

The tasks above show a high degree of test-retest reliability for all of the static balance tasks performed by the healthy group.

Dynamic Balance Tasks

Individual ICC results of the Functional Tasks						
	Sit to Stand			Stand to Sit		
Parameters	**ICC**	**[95% Conf. Interval]**		**ICC**	**[95% Conf. Interval]**	
Lean Speed	0.2279385	-0.0012918	0.6070978	0.6157909	0.3279712	0.8717236
Lean Back Speed	0.2621157	0.0222741	0.6372305	0.5542203	0.2597145	0.8437659
Rise Speed	0.0889588	-0.0876321	0.4591313	-0.0976706	-0.1871246	0.1875334
Drop Speed	0.0828214	-0.0911296	0.451452	0.230787	-0.0092448	0.635089
Duration of Test	-0.0000786	-0.1537206	0.4514646	-0.1056154	-0.2022641	0.3156156

Table 15: The test-retest reliability of the functional tasks.

Some parameters could not be used to perform the ICC for the functional tasks because they were obtained from MATLAB as averages of all 5 repeated tests and not as individual values. Therefore, an ICC could not be performed. The parameters excluded were: Lean distance, distance of backward lean, rise height, drop height, RMS of forward lean, RMS of backward lean, rise RMS and drop RMS.

The results of the functional tasks show a poor reliability both for sit to stand and stand to sit. This can be attributed to the noise we obtained from the csv data extracted from Kinetisense. Further development of the algorithm is required to remove the noise from the data and perform a better data smoothing before repeating the ICC again. The duration of test is not considered during this analysis because it was the only parameter that was specified by the researcher.

5.2.3. Hypothesis 3: The Repeatability of each of the eV-BBS Tasks within Participants

1. Dynamic Balance Tasks

Repeatability of Functional Tasks (Average COV %)					
Tasks	Lean speed	Lean Back Speed	Rise Speed	Drop Speed	Duration of Test
Sit to Stand	40.85	-32.54	18.20	-55.98	36.42
Stand to Sit	24.75	-50.51	55.05	-26.17	21.72

Table 16: The repeatability of the functional tasks within participants in the healthy population.

The repeatability within participants could only be analyzed for the parameters above. The parameters excluded were obtained as averages of the 5 repetitions from MATLAB. Therefore, it was difficult to calculate the coefficient of variation for those parameters. The parameters excluded were: Lean distance, distance of backward lean, rise height, drop height, RMS of forward lean, RMS of backward lean, rise RMS and drop RMS.

Apart from the rise speed, the other parameters report a COV of above 20%, this could be attributed to the variations within the participants in how the functional tasks were performed. Because the long-term care groups could not perform a repeatability assessment, no repeatability analysis could be performed for those groups.

2. Static Balance Tasks

The repeatability (COV %) of the balance tasks was analyzed from the average root mean squares (RMS) of the healthy population. The Grand COV % represents the repeatability within the healthy population.

Grand COV (%) of the Balance Tasks									
Tasks	**Spine Shoulder X**	**Spine Shoulder Y**	**Spine Shoulder Z**	**Spine Mid X**	**Spine Mid Y**	**Spine Mid Z**	**Spine Base X**	**Spine Base Y**	**Spine Base Z**
Sit with Back Unsupported	8.28	4.73	2.82	6.57	8.58	2.79	5.31	5.87	2.73
Stand on One Leg	13.06	1.09	1.35	14.09	1.36	1.39	13.06	5.69	1.35
Stand Unsupported (eyes open)	9.46	0.21	0.35	7.97	0.61	0.23	7.31	2.35	0.20
Stand Unsupported (eyes closed)	8.65	0.23	0.34	8.18	0.43	0.33	6.66	3.90	0.34
Stand Unsupported (feet together)	5.38	0.19	0.09	3.74	0.24	0.09	3.53	1.32	0.11
Stand Unsupported (one foot in front of the other)	6.31	1.38	0.52	6.35	2.16	0.54	5.59	3.85	0.61

Table 17: The repeatability of balance tasks within participants in the healthy population.

The results of the balance tasks found in Table 16 for the healthy population, show that participants within the population are repeatable while performing the balance tasks. This result supports hypothesis 3. The values for all of the tasks are below 20% which is promising. Because the long-term care groups did not perform a repeatability assessment, hypothesis 3 could not be calculated for that population.

6. Discussion

Hypothesis 1

The results of the present study show a lot of variability between participants in the way the balance and functional tasks are performed. However, due to the insufficient sample size for the long-term care population, the validity piece of hypothesis 1 could not be answered. However, this study provides useful information to design a prospective study to predict falls using selected variables from eV-BBS. The design of such a study would undertake an eV-BBS assessment and then the patients would be followed over the period of a year. We would then determine which patients had fallen during that time. By performing a cluster analysis, it would be possible to determine if the eV-BBS parameters could be used to predict the patients in the falling group. The data collected in this pilot identify the following variables that are promising for such a study (rise speed, drop speed, lean distance, RMS of forward lean, rise RMS, drop RMS). (Sara Dolnicar, 2002) has provided guidance for estimating sample sizes for cluster analysis which is probably the most promising analytical technique for a prospective study like this. She suggests the sample size should be $5*2^k$ where k is equal to the number of variables. Therefore, a prospective study using these variables would require approximately 320 participants to be followed.

Hypothesis 2

The test-retest reliability analysis performed on hypothesis 2 revealed a good ICC of between 0.81-0.99 for the static balance tasks of the eV-BBS. However, the ICC obtained for the dynamic balance tasks was low and ranged from 0.1-0.61. The reason for this low ICC may be because of the difficulty with differentiating signal from noise in the current csv files produced by the Kinetisense software. Therefore, a better algorithm is needed to perform data smoothing and prepare the output from Kinetisense for its interpretation, therefore improving the reliability of these measurements.

Hypothesis 3

The repeatability analysis performed using coefficient of variation shows that although there is a good amount of repeatability between participants in performing the eV-BBS tasks, there is a high degree of variation within the population on how these tasks are performed. This means that individuals within the population perform the tasks in a variety of ways. This further speaks to the sensitivity of Kinetisense in picking up these unique variations.

6.1. Study Limitations

6.1.1. The BBS

The BBS is a very insensitive tool for assessing balance and gait for the following reasons;

1). Progress cannot be relied upon fully if the BBS is the only measurement tool used during a patient's assessment: Although the BBS was designed to assess a patient's balance using tasks that mimic their activities of daily living (ADL), these tasks may be too easy because compensations are allowed when performing the BBS tasks. The assessment does not allow for instructions to be given on how these tasks should be performed correctly such as postural corrections, spinal alignment, etc. Furthermore, BBS does not identify specific physiotherapy interventions to develop core stability and balance. It is a given that most patients that experience falls either have issues with their muscle strength or their postures. Therefore, they have developed postural compensations that help them perform these tasks with the least amount of pain or discomfort. The aim of the test is therefore irrelevant if these compensations are not at least challenged in some way during the assessment. An example will be having a patient with a visible discomfort in the cervical spine that causes them to look at the ground while walking. If this patient is asked to try to perform the sit to stand test while looking forward instead of the ground, A clinician might notice that the patient either becomes dizzy, their movements become shaky or signs of apprehension on their faces can be seen because of the pain in their necks. While the third sign can only be seen through visual assessment, the first two signs can be useful information's to have during a subjective assessment like the BBS.

It is therefore not presumptuous to assume that the BBS does not give a clinician all the information needed to treat a participant with balance problems outside of determining a participant's risk of falling. Again, determining that a patient is at a high risk of falling using the BBS does not tell the clinician where to focus on during the therapy (i.e., muscle strength, muscle relaxation, possible spinal misalignments, etc.) Therefore, additional assessments will be required to understand the full scope of a participant's balance impairments. Since there are not a lot of objective assessments available at the moment to make this process easier, other examples of additional subjective assessments required includes TUG to test for functional mobility, 30-second chair stand test for strength and balance in the lower extremity, Mini-cog to test for possible cognitive impairment as well as the 4-stage balance test to assess static balance (Phelan et al., 2015). A combination of tests from different sources will be required to help the diagnostic process which will further help the therapist map out an appropriate therapy session for the patient (Lusardi et al., n.d.).

2) The BBS does not allow for the assessment of both sides of the human anatomy: Because the BBS only instructs participants/patients to do a task and not how to do the task correctly, participants are given a preference on how to do certain tasks that require a repetition on the other side such as stand on one leg, stand unsupported with one foot in front of the other and pick up an object from the floor from a standing position. If a participant is asked to stand on one leg, they will most likely stand on the leg that they are most comfortable with which is their dominant leg. The same goes for pick up an object from the floor where they will use their dominant hand or stand with one foot in front of the other where the foot in front will most likely be their dominant foot. It begs the question; will the results of the assessment be different if they repeated the test with their opposite limb and the answer will most likely be yes. This is because, the human anatomy is designed in such a way that if you use one part of your body more often that the other side, you will have a higher muscle strength on the dominant side as opposed to the non-dominant side. And if this is not controlled with exercise and stretching, will cause muscle imbalance. So maybe, a simple way to improve the balance of an individual is to conduct a therapy that makes the weaker side of the body stronger and stretches the stronger part of the body to avoid muscle contracture. But you cannot know which part of the human body is stronger or weaker if you only assess one limb.

Secondly, although the BBS task “placing alternate foot on a step/stool while standing unsupported” mimics the stair climb, it only seems to focus on the stance phase of the stair climb and not the swing phase. Implementing the first section of swing phase, by asking the participant to actually stand on the step stool after placing the foot on it, might be important in giving you certain information relating to muscle imbalance and postural control.

6.1.2. The eV-BBS

During the course of this study, the reliability of the data obtained was called into question in situations where the participant was not in a frontal position thereby making it difficult for the 3D camera to map the anatomical landmarks of the body. Performing complex movements also produced unreliable data. This is because, Kinetisense is only able to reliably measure movements where the participant needed to be facing the camera at all times, complex movements such as turning 360 degrees or picking up objects from the floor tends to be a bit more complex for Kinetisense to analyze at this time. The Kinetisense team is working on ensuring that more complex movements can produce reliable data but that software development is still ongoing.

Certain movements are able to produce reliable data as long as the 3D camera is not moved from a fixed position when the assessment has begun. Moving the camera mid assessments distorts data collection process as the system would have to find the anatomical landmarks again in the new position. Also, the position of the camera in relation to the position of the participant can also affect the Kinetisense reading. This speaks to the sensitivity of the technology. The depth that the camera can cover at any given time varies as well. Therefore, the 3D camera used for stability exercises such as standing in one spot will have to be different from the 3D camera used for mobility exercises such as gait. In order to avoid changing camera's, we simply used the D410 3D camera and the participant could perform gait from 5 meters away as well as balance tasks from about 3 meters away.

On the other hand, the objective measures produced by Kinetisense can be analyzed to assess biomechanical variations in the human body. The technology is able to take multiple frames of data per second so the time limit for each assessment completion was cut in half. Also, the balance module could only record a maximum of 30 seconds of data so that was the maximum time limit that was set for each assessment. Although the time limit of the static balance module makes it difficult to perform repeatability studies at the same time, the dynamic balance module has no problem carrying out repetitions for each task because it has no time limit.

The instrument is very sensitive and is able to capture miniscule variations and frequencies of joint movement even during static positions. Its sensitivity may need to be modified to focus solely on pathological changes of movement rather than both physiological and pathological changes.

Although the over-sensitivity of the technology needs to be addressed, there is evidence present that the use of Kinetisense to assess the falls risk of individuals shows merit.

While Kinetisense is not yet sophisticated enough to fully provide objective measures for all forms of the BBS assessment, it is a stepping stone and can be built upon to be able to transform all other forms of subjective assessments into objective measurements thereby eliminating the need to rely solely on visual observations during assessments. The aesthetics of the technology, while still undergoing changes, is accessible and easy to maneuver by healthcare workers who have no prior training on how to use Kinetisense. Therefore, the vision of Kinetisense can be achieved successfully.

The scoring system in Kinetisense is part of the Kinetisense Advanced Movement screen (KAMS). While the results obtained during an assessment could be retrieved via csv files, KAMS is an additional feature of the Kinetisense technology that provides clinicians with real time visual reports at the end of any assessment. These reports are categorized via functional planar mapping into mobility movement reports and stability movement reports as well as the different planes of movements in which the assessment was carried out such as the transverse (Y), sagittal (X) and frontal (Z) planes as was reported in the results section.

During the course of the study, the research team made a lot of breakthroughs in response to the eV-BBS protocol as well as the assessment procedures for geriatric participants. The following is a description and discussion on the lessons learned regarding the eV-BBS protocol.

Gait was an important assessment that needed to be carried out with this population. The eV-BBS was therefore modified to include gait as part of the assessment however no data could be extracted from this assessment because the gait module did not have a format for extracting csv files. However, key parameters could be obtained directly from the User Interface on a frame-by-frame basis if necessary. These key parameters could include movements in the head, shoulders, hips and knees, stride and cadence could also be obtained as well as a graph showing the displacement in the center of mass of the participant during the assessment but this does not come with any sort of values. The gait module is also able to specify if the participant has a Trendelenburg gait or an antalgic gait.

The endurance of the LTC participants was very low. Therefore, the number of repetitions needed to be reduced to one per task. In order to preserve the endurance of senior participants, the eV-BBS had to be re-arranged in an order to difficulty. This was to avoid having the participant move around a lot in a short period of time thereby causing muscular fatigue before the assessment could be completed. In other words, the focus of the protocol was changed to suit the participants rather than the technology needs. The modified eV-BBS protocol can be found in (*Appendix H*).

The researcher had intended to include reactive balance exercises that could be carried out safely by both the healthy population and the long-term care population. The aim of including these tasks was to observe how Kinetisense would interpret the data if the participants were placed in a situation where a lot more instability/sway was generated. However, because the researcher was unable to find any study that targeted reactive exercises using markerless motion capture or marker-based motion capture system, that section of the research was eliminated. So, although the eV-BBS protocol has the reactive balance exercises in it, the results obtained from that was not analyzed at all.

6.2. Significance of my Work

The eV-BBS tasks assessed by the markerless motion capture system provide insights into the capabilities of the Kinetisense Markerless motion capture technology. We found that this technology is able to provide more useful information compared to the BBS and it gives clinicians the opportunity to perform more precise test-retest assessments. The technology can also aid clinician in determine targets for rehabilitation by providing detailed results on specific tasks in relation with body kinematics. The capabilities of the technology in providing information can be seen in the MATLAB results for the functional movements. MATLAB was able to extrapolate movements such as lean distance and rise speed from the csv files exported from Kinetisense. This suggests that a variety of variables could be coded into MATLAB to assess other parameters of each task. The capabilities of the markerless motion capture software also extends to its user interface as it is able to provide useful information for clinicians in real time. The software analyzes the movements from the anatomical landmarks of the body and provides information to clinicians immediately, thereby eliminating the need to export csv files with huge amounts of data for analysis.

Markerless motion capture eliminates the need for paper trails and is able to save patient information securely for as long as possible. This can help clinicians to revise their therapies and successfully create individualized therapies for patients.

The feasibility of using markerless motion capture system to assess patients in clinical settings, especially in remote areas are endless. Its benefit can shine through when assessing patients with balance problems such as patients with stroke and Parkinson's. It can also be used in sports physiotherapy to assess athletes after reconstruction surgeries like the ACL. In general, markerless motion capture systems can be beneficial in the world of clinical rehabilitation while cutting down on health costs for the government as well as financial costs for patients by promoting affordable access to services for individuals living in remote locations.

7. Conclusion

Markerless Motion Capture opens up new research opportunities because it is a technology that can be readily used in any clinical setting. Further research should be performed to assess the validity of the eV-BBS to predict falls in the long-term care population using the correct sample size as indicated in the power analysis calculated in this thesis.

Secondly, more research can be carried out using the KAMS system to assess the falls risk of participants instead of using the csv files. This can provide a more in-depth analysis on the validity of Kinetisense from a clinician's point of view. Does the report displayed on KAMS accurately represent the results of a patient's assessment?

Finally, the study of Kinetisense can also be broadened to study the behavior of the technology when assessing patients with musculoskeletal disorders as well as neurological disorders.

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Appendices

Appendix A: Ethics Approval

Approval Form

Date:	February 11, 2021
Study ID:	Pro00105756
Principal Investigator:	Martin Ferguson-Pell
Study Title:	Pilot study to remotely enhance the sensitivity and specificity of traditional observational falls risk assessments by incorporating markerless motion capture technology.
Approval Expiry Date:	Friday, February 11, 2022
Approved Consent Form:	Approval Date 2/12/2021 — Approved Document Informed consent
Sponsor/Funding Agency:	United Way COVID-19 Emergency Community Support Fund

RSO-Managed Funding:

	Project ID	Title	Grant Status	Program	Project Start Date	Project End Date	Purpose	Other Information
View	RES0053140	A process and technology innovation that can provide essential rehabilitation services to seniors and other vulnerable populations throughout the COVID-19 crisis and beyond.	Awarded		11/25/2020	3/31/2021	Grant	

Thank you for submitting the above study to the Health Research Ethics Board - Health Panel. Your application, including the following, has been reviewed and approved on behalf of the committee;

- Recruitment Email (2/11/2021)
- Information Sheet (2/11/2021)
- Research Protocol (2/11/2021)
- Dataset for BBS Data Collection (2/11/2021)
- Dataset for Collecting eV-BBS Data (2/11/2021)

https://arise.ualberta.ca/ARISE/sd/Doc/0/M7ER37K91SDKLE60UNBU0QQD19/fromString.html 1/2

4/14/2021 https://arise.ualberta.ca/ARISE/sd/Doc/0/M7ER37K91SDKLE60UNBU0QQD19/fromString.html

Any proposed changes to the study must be submitted to the REB for approval prior to implementation. A renewal report must be submitted next year prior to the expiry of this approval if your study still requires ethics approval. If you do not renew on or before the renewal expiry date, you will have to re-submit an ethics application.

Enquiries regarding Alberta Health Services approvals should be directed to (780) 407-6041. Enquiries regarding Covenant Health should be directed to (780) 735-2274.

Approval by the Research Ethics Board does not encompass authorization to recruit and/or interact with human participants at this time. Researchers still require operational approval as applicable (eg AHS, Covenant Health, ECSD etc) and where in-person interactions are proposed, institutional and operational requirements outlined in the *Resumption of Human Participant Research - June 24, 2020* ***must be met.***

Sincerely,

Anthony S. Joyce, PhD.
Chair, Health Research Ethics Board - Health Panel

Note: This correspondence includes an electronic signature (validation and approval via an online system).

Appendix B: Berg Balance Scale with Instructions

BERG BALANCE TESTS AND RATING SCALE

Patient Name ____
Date ____
Location ____
Rater ____

ITEM DESCRIPTION SCORE (0-4) Sitting to standing _____ Standing unsupported _____ Sitting unsupported _____ Standing to sitting _____ Transfers _____ Standing with eyes closed _____ Standing with feet together _____ Reaching forward with outstretched arm _____ Retrieving object from floor _____ Turning to look behind _____ Turning 360 degrees _____ Placing alternate foot on stool _____ Standing with one foot in front _____ Standing on one foot _____ TOTAL _____

GENERAL INSTRUCTIONS

Please demonstrate each task and/or give instructions as written. When scoring, please record the lowest response category that applies for each item.

In most items, the subject is asked to maintain a given position for a specific time. Progressively more points are deducted if the time or distance requirements are not met, if the subject's performance warrants supervision, or if the subject touches an external support or receives assistance from the examiner. Subjects should understand that they must maintain their balance while attempting the tasks. The choices of which leg to stand on or how far to reach are left to the subject. Poor judgment will adversely influence the performance and the scoring.

Equipment required for testing are a stopwatch or watch with a second hand, and a ruler or other indicator of 2, 5 and 10 inches (5, 12 and 25 cm). Chairs used during testing should be of reasonable height. Either a step or a stool (of average step height) may be used for item #12.

1. SITTING TO STANDING

INSTRUCTIONS: Please stand up. Try not to use your hands for support.
( ) 4 able to stand without using hands and stabilize independently
( ) 3 able to stand independently using hands
( ) 2 able to stand using hands after several tries
( ) 1 needs minimal aid to stand or to stabilize
( ) 0 needs moderate or maximal assist to stand

2. STANDING UNSUPPORTED

INSTRUCTIONS: Please stand for two minutes without holding.
( ) 4 able to stand safely 2 minutes
( ) 3 able to stand 2 minutes with supervision
( ) 2 able to stand 30 seconds unsupported
( ) 1 needs several tries to stand 30 seconds unsupported
( ) 0 unable to stand 30 seconds unassisted

If a subject is able to stand 2 minutes unsupported, score full points for sitting unsupported. Proceed to item #4.

3. SITTING WITH BACK UNSUPPORTED BUT FEET SUPPORTED ON FLOOR OR ON A STOOL
INSTRUCTIONS: Please sit with arms folded for 2 minutes.
( ) 4 able to sit safely and securely 2 minutes
( ) 3 able to sit 2 minutes under supervision
( ) 2 able to sit 30 seconds
( ) 1 able to sit 10 seconds
( ) 0 unable to sit without support 10 seconds

4. STANDING TO SITTING
INSTRUCTIONS: Please sit down.
( ) 4 sits safely with minimal use of hands
( ) 3 controls descent by using hands
( ) 2 uses back of legs against chair to control descent
( ) 1 sits independently but has uncontrolled descent
( ) 0 needs assistance to sit

5. TRANSFERS
INSTRUCTIONS: Arrange chairs(s) for a pivot transfer. Ask subject to transfer one way toward a seat with armrests and one way toward a seat without armrests. You may use two chairs (one with and one without armrests) or a bed and a chair.
( ) 4 able to transfer safely with minor use of hands
( ) 3 able to transfer safely definite need of hands
( ) 2 able to transfer with verbal cueing and/or supervision
( ) 1 needs one person to assist
( ) 0 needs two people to assist or supervise to be safe

6. STANDING UNSUPPORTED WITH EYES CLOSED
INSTRUCTIONS: Please close your eyes and stand still for 10 seconds.
( ) 4 able to stand 10 seconds safely
( ) 3 able to stand 10 seconds with supervision
( ) 2 able to stand 3 seconds
( ) 1 unable to keep eyes closed 3 seconds but stays steady
( ) 0 needs help to keep from falling

7. STANDING UNSUPPORTED WITH FEET TOGETHER
INSTRUCTIONS: Place your feet together and stand without holding.
( ) 4 able to place feet together independently and stand 1 minute safely
( ) 3 able to place feet together independently and stand for 1 minute with supervision
( ) 2 able to place feet together independently but unable to hold for 30 seconds
( ) 1 needs help to attain position but able to stand 15 seconds with feet together
( ) 0 needs help to attain position and unable to hold for 15 seconds

8. REACHING FORWARD WITH OUTSTRETCHED ARM WHILE STANDING
INSTRUCTIONS: Lift arm to 90 degrees. Stretch out your fingers and reach forward as far as you can. (Examiner places a ruler at end of fingertips when arm is at 90 degrees. Fingers should not touch the ruler while reaching forward. The recorded measure is the distance forward that the finger reaches while the subject is in the most forward lean position. When possible, ask subject to use both arms when reaching to avoid rotation of the trunk.)
( ) 4 can reach forward confidently >25 cm (10 inches)
( ) 3 can reach forward >12 cm safely (5 inches)
( ) 2 can reach forward >5 cm safely (2 inches)
( ) 1 reaches forward but needs supervision
( ) 0 loses balance while trying/requires external support

9. PICK UP OBJECT FROM THE FLOOR FROM A STANDING POSITION
INSTRUCTIONS: Pick up the shoe/slipper which is placed in front of your feet.
( ) 4 able to pick up slipper safely and easily
( ) 3 able to pick up slipper but needs supervision
( ) 2 unable to pick up but reaches 2-5cm (1-2 inches) from slipper and keeps balance independently
( ) 1 unable to pick up and needs supervision while trying
( ) 0 unable to try/needs assist to keep from losing balance or falling

10. TURNING TO LOOK BEHIND OVER LEFT AND RIGHT SHOULDERS WHILE STANDING
INSTRUCTIONS: Turn to look directly behind you over toward left shoulder. Repeat to the right. Examiner may pick an object to look at directly behind the subject to encourage a better twist turn.
( ) 4 looks behind from both sides and weight shifts well
( ) 3 looks behind one side only other side shows less weight shift
( ) 2 turns sideways only but maintains balance
( ) 1 needs supervision when turning
( ) 0 needs assist to keep from losing balance or falling

11. TURN 360 DEGREES
INSTRUCTIONS: Turn completely around in a full circle. Pause. Then turn a full circle in the other direction.
( ) 4 able to turn 360 degrees safely in 4 seconds or less
( ) 3 able to turn 360 degrees safely one side only in 4 seconds or less
( ) 2 able to turn 360 degrees safely but slowly
( ) 1 needs close supervision or verbal cueing
( ) 0 needs assistance while turning

12. PLACING ALTERNATE FOOT ON STEP OR STOOL WHILE STANDING UNSUPPORTED
INSTRUCTIONS: Place each foot alternately on the step/stool. Continue until each foot has touched the step/stool four times.
( ) 4 able to stand independently and safely and complete 8 steps in 20 seconds
( ) 3 able to stand independently and complete 8 steps in >20 seconds
( ) 2 able to complete 4 steps without aid with supervision
( ) 1 able to complete >2 steps needs minimal assist
( ) 0 needs assistance to keep from falling/unable to try

13. STANDING UNSUPPORTED ONE FOOT IN FRONT
INSTRUCTIONS: (DEMONSTRATE TO SUBJECT) Place one foot directly in front of the other. If you feel that you cannot place your foot directly in front, try to step far enough ahead that the heel of your forward foot is ahead of the toes of the other foot. (To score 3 points, the length of the step should exceed the length of the other foot and the width of the stance should approximate the subject's normal stride width)
( ) 4 able to place foot tandem independently and hold 30 seconds
( ) 3 able to place foot ahead of other independently and hold 30 seconds
( ) 2 able to take small step independently and hold 30 seconds
( ) 1 needs help to step but can hold 15 seconds
( ) 0 loses balance while stepping or standing

14. STANDING ON ONE LEG
INSTRUCTIONS: Stand on one leg as long as you can without holding.
( ) 4 able to lift leg independently and hold >10 seconds
( ) 3 able to lift leg independently and hold 5-10 seconds
( ) 2 able to lift leg independently and hold = or >3 seconds
( ) 1 tries to lift leg unable to hold 3 seconds but remains standing independently
( ) 0 unable to try or needs assist to prevent fall

TOTAL SCORE (Maximum = 56: _______

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Appendix C: Berg Balance Scale without Instructions

BERG BALANCE SCALE

Patient Name: ____________________

Rater Name: ____________________

Date: ____________________

Balance Item	**Score (0-4)**
1. Sitting unsupported	______
2. Change of position: sitting to standing	______
3. Change of position" standing to sitting	______
4. Transfers	______
5. Standing unsupported	______
6. Standing with eyes closed	______
7. Standing with feet together	______
8. Tandem standing	______
9. Standing on one leg	______
10. Turning trunk (feet fixed)	______
11. Retrieving objects from floor	______
12. Turning 360 degrees	______
13. Stool stepping	______
14. Reaching forward while standing	______

TOTAL (0–56): ______

Interpretation

0–20, wheelchair bound
21–40, walking with assistance
41–56, independent

References

Berg K, Wood-Dauphinee S, Williams JI, Maki, B: Measuring balance in the elderly: Validation of an instrument. Can. J. Pub. Health, July/August supplement 2:S7-11, 1992.

Berg K, Wood-Dauphinee S, Williams JI, Gayton D: Measuring balance in the elderly: Preliminary development of an instrument.
Physiotherapy Canada, 41:304-311, 1989.

Appendix D: First Version of the eV-BBS

START STUDY: First eV-BBS protocol

1). BALANCE MODULE:

- **Standing unsupported**

  Instruction: Ask the patient to stand for 30 seconds without holding anything. Repeat task 5 times

- **Sitting with back unsupported but feet together on floor or stool**
  Instruction: Ask the patient to sit on a stool for 30 seconds. Make sure the stool is low enough that the patient's feet can touch the floor. Repeat task 5 times

- **Standing unsupported with eyes closed**

  Instruction: Please ask the patient to close their eyes and stand still for 30 seconds. Repeat task 5 times

- **Standing unsupported with feet together**

  Instruction: Ask the patient to place both feet together and stand without holding anything for 30 seconds. Repeat task 5 times

- **Turning to look behind both shoulders with feet planted in the same spot**

  Instruction: Ask the patient to look directly behind their left shoulders and then over their right shoulders for 30 seconds. The examiner may pick out any object to look at directly behind the patient in order to encourage a better twist/turn. Repeat task 5 times

- **Standing unsupported with one-foot in front of the other**
  Instruction: Ask the patient to place one foot directly in front of the other. If the patient finds this difficult, the patient can step a little bit forward such that there is a little space between the forward foot and the backward foot. Hold this position for 30 seconds. Repeat task 5 times

- **Standing on one leg**
  Instruction: Ask the patient to stand on one leg for 30 seconds or as long as they can.
- **Reaching forward with outstretched arms**
  Instruction: With the side of the patient's body facing the camera, ask the patient to lift their arms to 90 degrees, stretch out their fingers and reach forward as much as possible. Hold this position for the test. Repeat task 5 times

2). Reactive exercises (Balance module)

- **Standing with both legs on foam pad (eyes closed)**
  Instruction: Ask the patient to stand on foam pad and close both eyes for 30 seconds. Repeat task 5 times

- **Single leg standing balance**

  Instructions: Ask the patient to stand on the foam pad with both legs and extend one leg in 3 different directions;

  1). Anterior: Ask the patient to extend one leg forward with the other leg still on the pad and hold this position for 10 seconds. Repeat task 5 times

  2). Lateral: Ask the patient to extend one leg to the side with the other leg still on the pad and hold for 10 seconds. Repeat task 5 times

  3). Posterior: Ask the patient to extend one leg to the back and hold for 10 seconds. Repeat task 5 times

3) Functional Exercises (Functional Module)

- **Sitting to standing**
  Instruction: Starting from a sitting position, please ask the patient to stand up, hold the standing position for 5 seconds. Repeat task 5 times

- **Standing to sitting**
  Instruction: Starting from a standing position, please ask the patient to sit down, hold the sitting position for 5 seconds. Repeat task 5 times

- **Transfers**

  Instructions: Arrange chairs for a pivot transfer. The chairs should be at 90 degrees to each other. The chair with the armrests should face the camera and the chair without armrests should be at a 90-degree position to the chair with armrests. Repeat task 5 times

  Exercise: Ask the patient to transfer one way towards the seat without armrests and sit down, hold this position for 5 seconds and transfer back towards the sit with armrests. Repeat task 5 times

- **Pick up object from the floor from a standing position**

  Instruction: Place an object in front of the patient's feet. Ask the patient to pick up the object from the floor, stand up and hold this position for 5 seconds. Repeat task 5 times

- **Turning 360 degrees**

  Instruction: Ask the patient to turn around completely in a full circle, stop at the starting position for 5 seconds and turn around in a full circle in the opposite direction. Repeat task 5 times

- **Placing Alternate foot on stool**

  Instruction: Ask the patient to place each foot alternately on a step on stool 8 times (4 steps per foot), place both feet on the floor at the end of the exercise and hold that standing position for 5 seconds. Repeat task 5 times

Appendix E: Workflow Protocol for Healthy Participants

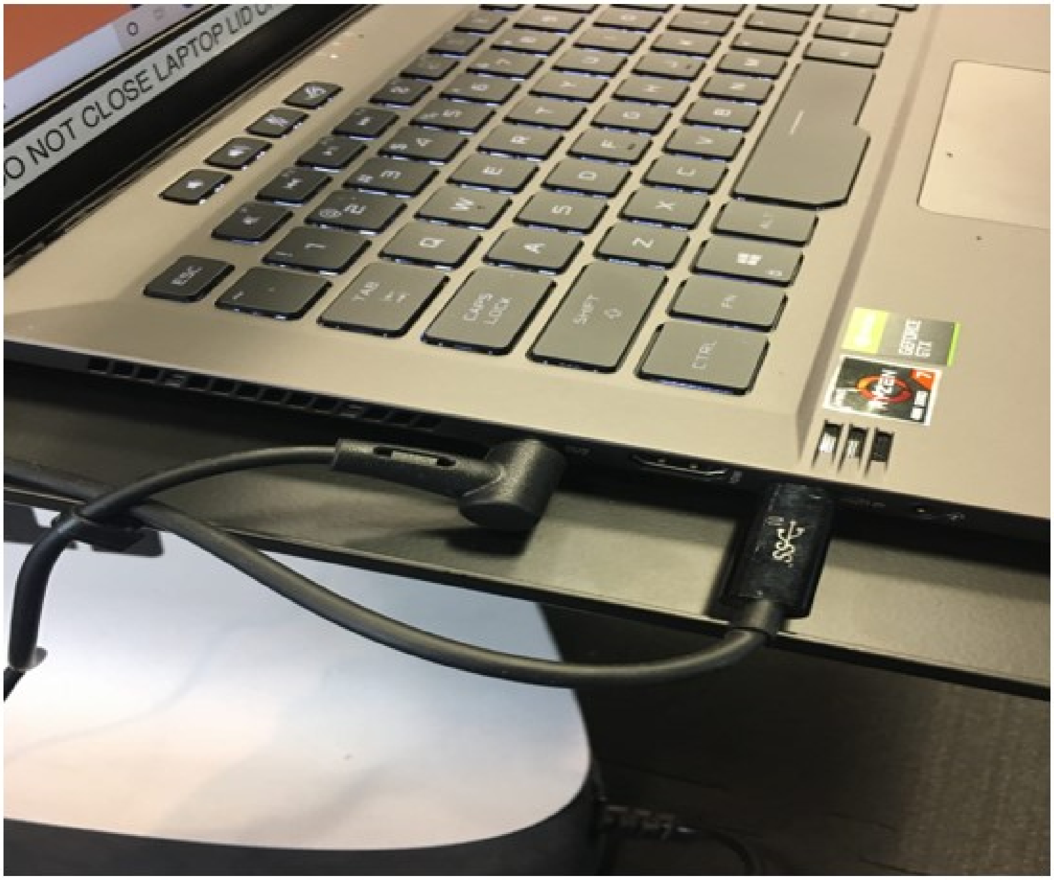
Workflow Before Research Study

- As soon as you enter the main entrance of the lab, please sanitize your hands and put on your next. Next, you will see another door to the lab itself. The access code to that door is *****.
- When you get into the lab, you will see the equipment for the study (laptop and 3D camera on a tripod stand) set-up in the middle of the lab. Please do not move the camera unless directed by the researcher.
- The laptop will be closed but booted. The password for the laptop is ***@***.
- After you input the password, the researcher will send a ZOHO link to the FRM email address which will be open on the computer or to your personal email which you can open on the laptop as well. Click on the link and hit accept to give the researcher access to the Labs computer. The labs email address is frmrobot@ualberta.ca
- I will send the zoom link to the lab email or to your personal email if you wish. Let me know what your preference is on this.
- Please do not log off the computer or close the email at the end of the study. Just close the laptop and leave it as it is.

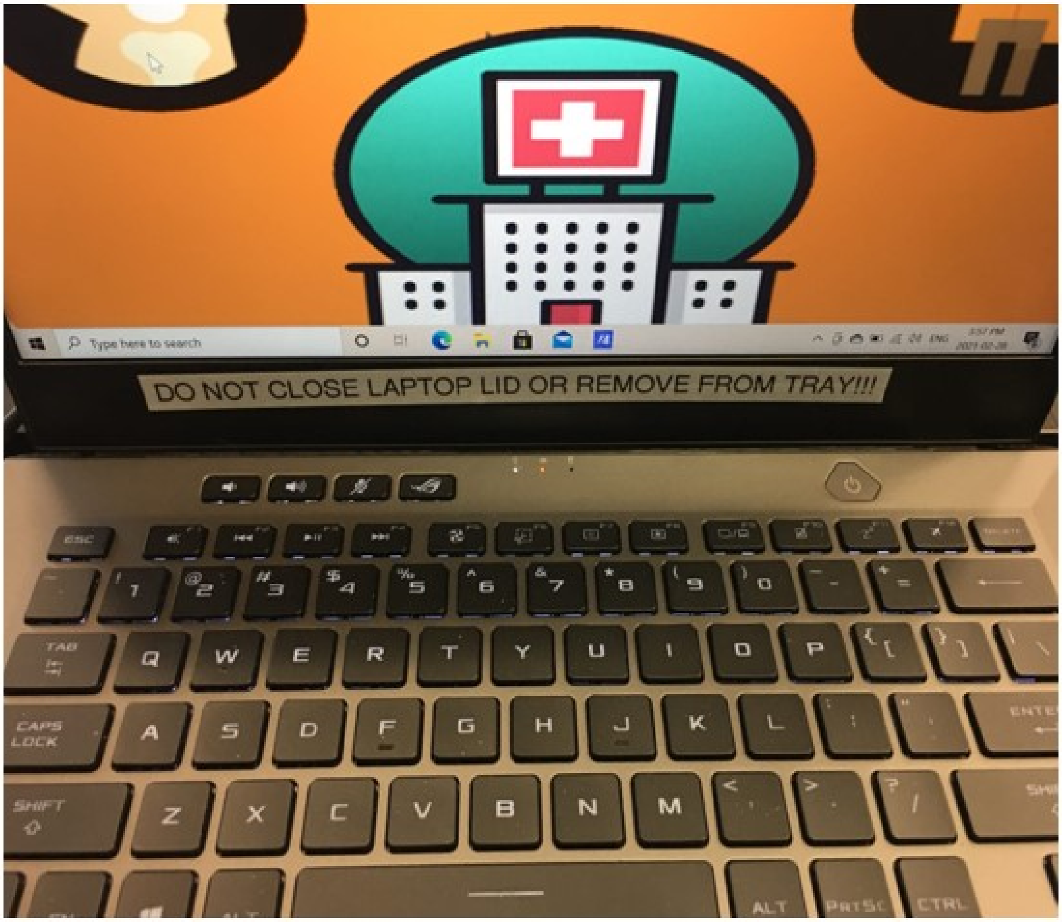
****Please scroll down to see the 3 precautions needed during this study. Thank you****

<u>PRECAUTIONS TO FOLLOW BOTH DURING AND AFTER THE ASSESSMENT</u>

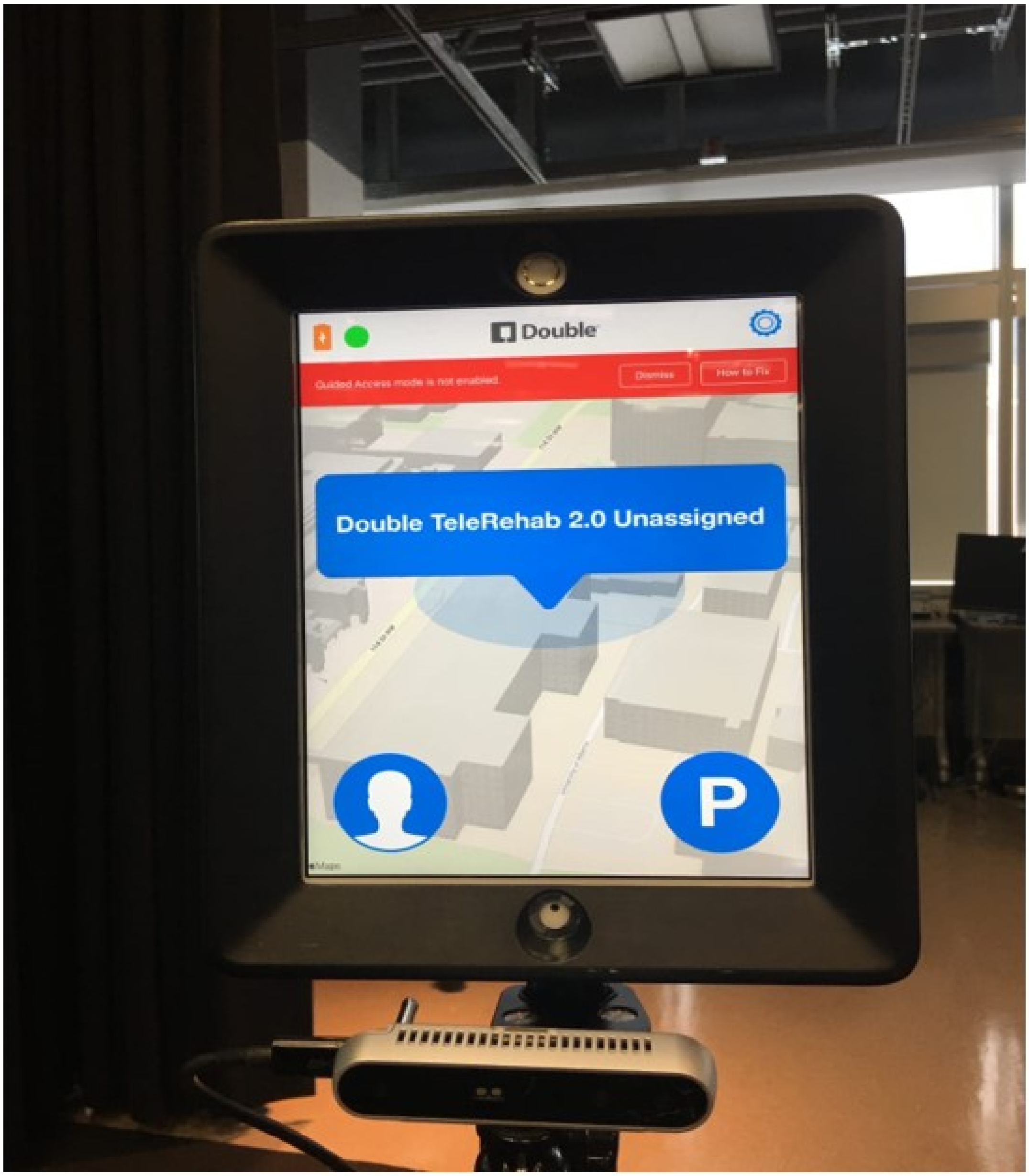
1) **Please Unplug the laptop before the assessment begins. And plug it in again at the end of the assessment as seen below;**



2). Never close the laptop lid or remove the laptop from the tray. This will break the laptop. This warning can also be seen on the laptop itself below;



3). At the end of the assessment, the researcher will log out of the double robot. Please place the Robot into its Charging station and Press "P" as seen in the picture below.



Appendix F: Modified BBS questionnaire to include 5 repetitions

BERG BALANCE TESTS AND RATING SCALE

Participant Number: ______________________ Age: ______________

Height: _________________ Weight: ____________________ BMI: _______

Balance Item	Score (0 – 4)					Average
1. Sitting to standing						
2. Standing unsupported						
3. Sitting with back unsupported but feet supported on floor or on a stool						
4. Standing to sitting						
5. Transfers						
6. Standing Unsupported with eyes closed						
7. Standing unsupported with feet together.						
8. Reaching forward with outstretched arms while standing.						
9. Pick up an object from the floor from a standing position						
10. Turning to look behind your left and right shoulders while standing.						
11. Turning 360 degrees.						

12. Placing alternate foot on step or stool while standing unsupported.						
13. Standing unsupported with one foot in front of the other,						
14. Standing on one leg.						

TOTAL (0 – 56): _______

Interpretation

0 – 20, wheelchair bound

21 – 40, walking with assistance

41 – 56, independent

Appendix G: Intake form for geriatric participants

PATIENT INTAKE FORM

Patient Information			
Last Name:		First Name:	Middle Name:
Birth Name:			Gender: M / F
City:	Province:	Postal Code:	Age:
Phone:	Mobile:		Occupation:
Email:			
Family Contact Information			
First Name:			Last Name:
Relationship to Patient:		Phone Number:	
Emergency Contact Information			
First Name:			Last Name:
Relationship to Patient:		Phone Number:	
Medical History			
Does the patient have any difficulty with their balance? ◻ Yes ◻ No			
Has the patient experienced falls in the last 12 months? ◻ Yes ◻ No			
If yes, can the patient tell us how many times they have fallen in the last 12 months?			
Can the patient tell us what happened when the patient fell? Were they falling, climbing the stairs or walking on an icy surface?			

Does the patient have any medical conditions that affects their balance and coordination? □ Yes □ No
If yes, can the patient tell us more about their medical condition?
Does the patient have a history of? □ Cancer □ End-stage Alzheimer's disease □ Severe motion sickness □ Cardiovascular diseases □ History of neurological conditions □ History of past or present orthopaedics injuries/conditions
Does the patient have any visual problems that affects their balance? □ Yes □ No
If yes, can the patient tell us more about their visual conditions?
Is the patient currently taking any medications that affects their balance?
If yes, can the patient tell us what kind of medications or the names of the medications that they are currently taking?

Appendix H: Modified eV-BBS protocols

Falls Risk Module Development

Note: The repetition for all the tasks is once because of the endurance level of the participant population.

Please collect the participants age, height (cm) and weight (kg) before proceeding with this assessment.

Kinetisense Module	Task Name	Task Description	Number of Repetitions
Gait module	Gait	Mark a distance on the floor (with a tape or some chalk) of **2 meters** away from the camera and **5 meters** from the camera. Ask the patient to walk from the 5-meter distance towards the camera and stop at the 2-meter distance, turn around and walk back to that pre-destined marked spot on the floor and stop.	1
Balance Module	Sit with back unsupported but with feet supported on the floor or a stool.	Ask the patient to sit on a stool for 30 seconds. Make sure the stool is low enough that the patient's feet can touch the floor	1
Functional Module	Sit to stand	Starting from a sitting position, please ask the patient to stand up, hold the standing position for 5 seconds.	1
Functional module	Stand to sit	Starting from a standing position, please ask the patient to sit down, hold the sitting position for 5 seconds.	1
Functional mode	Transfers	**Instructions:** Arrange chairs for a pivot transfer. The chairs should be at 90 degrees to each other. The chair with the armrests should face the camera and the chair without armrests should be at a 90-degree position to the chair with armrests. **Exercise:** Ask the patient to transfer one way towards the seat without armrests and sit down, hold this position for 5 seconds and transfer back towards the sit with armrests.	1

Balance module	Stand Unsupported	Ask the patient to stand for 30 seconds without holding anything.	1
Balance module	Stand unsupported with eyes closed.	Please ask the patient to close their eyes and stand still for 30 seconds. (If the patient is able to do this task successfully for 10 seconds, that would be enough)	1
Balance module	Stand unsupported with feet together.	Ask the patient to place both feet together and stand without holding anything for 30 seconds.	1
Balance Module	Stand unsupported, one foot in front of the other.	Ask the patient to place one foot directly in front of the other. If the patient finds this difficult, the patient can step a little bit forward such that there is a little space between the forward foot and the backward foot.	1
Balance Module	Stand on one leg	Ask the patient to stand on one leg for 30 seconds or as long as they can.	1
Balance Module	Turn to look behind over left and right shoulders while standing.	Ask the patient to look directly behind their left shoulders and then over their right shoulders for 30 seconds. The examiner may pick out any object to look at directly behind the patient in order to encourage a better twist/turn.	1
Functional Module	Turn 360 degrees	Ask the patient to turn around completely in a full circle, stop at the starting position for 5 seconds and turn around in a full circle in the opposite direction.	1
Functional Module	Place alternate foot on step/stool while standing unsupported.	Ask the patient to place each foot alternately on a step on stool 8 times (4 steps per foot), place both feet on the floor at the end of the exercise and hold that standing position for 5 seconds.	1
Balance Module	Reach forward with outstretched arms	With the side of the patient's body facing the camera, ask the patient to lift their arms to 90 degrees, stretch out their fingers and reach forward as much as possible. (the examiner may demonstrate this exercise to the patient).	1

Functional Module	Pick up object from the floor from a standing position	Place an object in front of the patient's feet. Ask the patient to pick up the object from the floor, stand up and hold this position for 5 seconds.	1
Balance Module (reactive exercise)	Stand unsupported with both legs on foam pad (eyes closed)	Ask the patient to stand on foam pad and close both eyes. Please be around the patient so you can catch them if they lose their balance. Consequently, this exercise could be carried out on the floor if the foam pad becomes too difficult.	1
Balance Module (reactive exercise)	Single leg standing balance on foam pad	Ask the patient to stand on the foam pad with both legs and extend one leg in 3 different directions; 1). Anterior: Ask the patient to extend one leg forward with the other leg still on the pad and hold this position for 10 seconds. 2). Lateral: Ask the patient to extend one leg to the side with the other leg still on the pad and hold for 10 seconds. 3). Posterior: Ask the patient to extend one leg to the back and hold for 10 seconds. (Note: The patient is allowed to change their legs before each task. Also, this task can be performed on the floor if the pad becomes too difficult).	Each exercise position is to be repeated **once** for 10 seconds each.

Appendix I: Matlab Code

```
%% comtrack.m
%% Khilesh Jairamdas August 9, 2021
%% This script loads data from a Kinetisense Excel output into arrays
%% It extracts body landmark coords into vectors
%% It performs calculations to get and plot the COM position over time

clc
clearvars

%Source and output directory
source_dir = 'C:/Users/VR-7/Documents/MATLAB/Example Patient Data';
output_dir = 'C:/Users/VR-7//Documents/MATLAB/Example Patient Output';
source_files = dir(fullfile(source_dir, '*.xlsx'));
fileIdx = 3; % Select which file to open

[~, dataSetName, ~] = fileparts(fullfile(source_dir, source_files(fileIdx).name));
mkdir(string(strcat(output_dir, {'\'}, dataSetName)));

%Read data into table from Excel
dataTable = readtable(fullfile(source_dir, source_files(fileIdx).name));

%Table size has 2 numbers: # of rows and # of columns
%We only want the # rows, so
tableSize = size(dataTable);
%size(dataArray) ========= [M, N] <---- tableSize
dataPoints = tableSize(1);

prompt = "Please enter height of your participant in m: ";
% This can be determined from their knee height from Kinetisense file
% Height of patient:
% Females:
% Height in cm = 84.88 - (0.24 X age) + (1.83 X knee height)  CONVERT RESULT to m
% Males:
% Height in cm= 64.19 - (0.04 X age) + (2.02 X knee height) CONVERT RESULT to m
% An estimate of age is sufficient
heightInput = char(inputdlg(prompt));
heightDouble = str2double(heightInput);
factor = 0;

conventions = {'male','female'};
[idx,tf] = listdlg('PromptString',{'Please select gender.'},...
   'ListString',conventions,'SelectionMode','single');

switch idx
   case 1
      factor = 0.4486;
```

```
    case 2
        factor = 0.4151;
end

% value in m
trunkLength = (heightDouble - 1.02)/1.18;
deltaCOM = factor*(trunkLength);

% if ~isnan(offsetDouble)
%     valid = 1;
% else
%     valid = 0;
% end

% while (valid == 0)
%     prompt = "That is not a valid value for mass offset. Please try again: ";
%     offsetInput = char(inputdlg(prompt));
%     offsetDouble = str2double(offsetInput);
%     if ~isnan(offsetDouble)
%         valid = 1;
%     else
%         valid = 0;
%     end
% end

%Dropdown menu for user to choose unit convention
conventions = {'m','mm','in'};
[idx,tf] = listdlg('PromptString',{'Please select unit convention.'},...
    'ListString',conventions,'SelectionMode','single');

%Depending on chosen convention and provided shoe size, calculate
%offset in m
% switch idx
%     case 1
%         offsetVal = offsetDouble / 100;
%     case 2
%         offsetVal = offsetDouble / 1000;
%     case 3
%         offsetVal = offsetDouble * 25.4 / 1000;
% end

%Extract data columns into vector arrays
leftShoulderX = dataTable.ShoulderLeftX;
leftShoulderY = dataTable.ShoulderLeftY;
leftShoulderZ = dataTable.ShoulderLeftZ;
rightShoulderX = dataTable.ShoulderRightX;
```

```
rightShoulderY = dataTable.ShoulderRightY;
rightShoulderZ = dataTable.ShoulderRightZ;
leftHipX = dataTable.HipLeftX;
leftHipY = dataTable.HipLeftY;
leftHipZ = dataTable.HipLeftZ;
rightHipX = dataTable.HipRightX;
rightHipY = dataTable.HipRightY;
rightHipZ = dataTable.HipRightZ;
leftAnkleX = dataTable.AnkleLeftX;
leftAnkleY = dataTable.AnkleLeftY;
leftAnkleZ = dataTable.AnkleLeftZ;
rightAnkleX = dataTable.AnkleRightX;
rightAnkleY = dataTable.AnkleRightY;
rightAnkleZ = dataTable.AnkleRightZ;
timeStamp = dataTable.Timestamp;

headX = dataTable.HeadX;
headY = dataTable.HeadY;
headZ = dataTable.HeadZ;

[yr, mth, day, hr, mn, s] = datevec(timeStamp);
timeAbs = 3600*hr + 60*mn + s;
time = timeAbs - timeAbs(1);

trunkCentreX = mean([leftShoulderX, rightShoulderX, leftHipX, rightHipX], 2);
% We actually need to represent the centroid of the trunk relative to the
% symphysis pubis, and so make this adjustment from the literature
trunkCentreY = mean([leftShoulderY, rightShoulderY, leftHipY, rightHipY], 2)- .0679;
trunkCentreZ = mean([leftShoulderZ, rightShoulderZ, leftHipZ, rightHipZ], 2);

midShoulderX = (leftShoulderX + rightShoulderX)/2;
midShoulderY = (leftShoulderY + rightShoulderY)/2;
midShoulderZ = (leftShoulderZ + rightShoulderZ)/2;
midHipX = (leftHipX + rightHipX)/2;
% actually plotting the symphsis pubis here
midHipY = (leftHipY + rightHipY)/2 - .0679;
midHipZ = (leftHipZ + rightHipZ)/2;
midAnkleX = (leftAnkleX + rightAnkleX)/2;
midAnkleY = (leftAnkleY + rightAnkleY)/2;
midAnkleZ = (leftAnkleZ + rightAnkleZ)/2;
% This establishes the height of the shoulders
shoulderLevelY = (leftShoulderY + rightShoulderY)/2;

crossVector = [midShoulderX - midHipX, midShoulderY - midHipY, midShoulderZ -
midHipZ];
crossVectorMag = vecnorm(crossVector, 2, 2);
```

```
crossUnitVector = crossVector ./ crossVectorMag;

% comOffsetVector = crossUnitVector * offsetVal;

comX = trunkCentreX;
% We add the distance of the sympysis pubic to the Centroid.
% We know that deltaCOM is the distance below the jugular notch which is nominally the same
as shoulderLevelY
comY = (shoulderLevelY - deltaCOM);
comZ = trunkCentreZ;

paramDX = comZ - midAnkleZ;
paramHX = comY - midAnkleY;

fullArrayX = [leftShoulderX; rightShoulderX; leftHipX; rightHipX; leftAnkleX; rightAnkleX;
headX; comX];
fullArrayY = [leftShoulderY; rightShoulderY; leftHipY; rightHipY; leftAnkleY; rightAnkleY;
headY; comY];
fullArrayZ = [leftShoulderZ; rightShoulderZ; leftHipZ; rightHipZ; leftAnkleZ; rightAnkleZ;
headY; comZ];

animplot = figure(4);

for i = 1:length(time)

  plot3(leftShoulderX(i), leftShoulderZ(i), leftShoulderY(i), 'bx', ...
    rightShoulderX(i), rightShoulderZ(i), rightShoulderY(i), 'bx', ...
    leftHipX(i), leftHipZ(i), leftHipY(i), 'bx', ...
    rightHipX(i), rightHipZ(i), rightHipY(i), 'bx', ...
    trunkCentreX(i), trunkCentreZ(i), trunkCentreY(i), 'gx', ...
    midShoulderX(i), midShoulderZ(i), midShoulderY(i), 'rx', ...
    midHipX(i), midHipZ(i), midHipY(i), 'rx', ...
    comX(i), comZ(i), comY(i), 'ro', ...
    leftAnkleX(i), leftAnkleZ(i), leftAnkleY(i), 'bx', ...
    rightAnkleX(i), rightAnkleZ(i), rightAnkleY(i), 'bx', ...
    headX(i), headZ(i), headY(i), 'bo', 'MarkerSize', 10);
  xlabel('x');
  ylabel('z');
  zlabel('y');

  xlim([min(fullArrayX), max(fullArrayX)]);
  xticks(min(fullArrayX):0.2:max(fullArrayX));
  ylim([min(fullArrayZ), max(fullArrayZ)]);
  yticks(min(fullArrayZ):0.2:max(fullArrayZ));
  zlim([min(fullArrayY), max(fullArrayY)]);
  zticks(min(fullArrayY):0.2:max(fullArrayY));
```

```
    daspect([1 1 1]);
    title(strcat({'Frame: '}, string(i)));
    %Change plot view
    %view(0, 0); % Front view (0, 0); Side View (90, 0) or (-90, 0); Comment out line for
isometric
    %GIF writer
    gifFile = string(strcat(output_dir, {'\'}, dataSetName, {'\animplot3.gif'}));
    im = frame2im(getframe(animplot));
    [A,map] = rgb2ind(im, 256);
    if i == 1
        imwrite(A,map,gifFile,'gif','LoopCount',Inf,'Delay',1/60);
    else
        imwrite(A,map,gifFile,'gif','WriteMode','append','Delay',1/60);
    end
end

%% Signal Processing - Noise Removal

% Variable declaration
t = time;
n = length(t); % Data length
Fs = 1/(mean(diff(time))); % Sampling frequency
Fn = Fs/2; % Nyquist frequency

% Remove spikes/outliers
D_threshold = 7; % Outlier filter intensity D: can be adjusted base on data sets
H_threshold = 6; % Outlier filter intensity D: can be adjusted base on data sets
D = filloutliers(paramDX,'clip','movmedian',D_threshold,'SamplePoints',t);
H = filloutliers(paramHX,'clip','movmedian',H_threshold,'SamplePoints',t);

% Fourier Transform
f = linspace(0,1,fix(n/2)+1)*Fn; % frequency vector
i = 1:length(f); % Single-sided vector length
fftD = fft(paramDX)/n; % fast Fourier transform D normalized by n
fftH = fft(paramHX)/n; % fast Fourier transform H normalized by n
D_mag = abs(fftD(i))*2; % Single-sided frequency domain of D
H_mag = abs(fftH(i))*2; % Single-sided frequency domain of H

% Low pass filter design (Convert to Hz)
fc_D = 0.5; % Cutoff frequency (Hz) for D
fc_H = 0.5; % Cutoff frequency (Hz) for H
order_D = 1; % Butterworth filter order: Intensity of filter
order_H = 1; % Butterworth filter order: Internsity of filter
[D1 D2] = butter(order_D, fc_D/(Fs/2), 'low'); %Low pass filter for D with 1st order
[H1 H2] = butter(order_H, fc_H/(Fs/2), 'low'); %Low pass filter for H with 1st order
```

```
% Filter implementation
D_filtered = filter(D1,D2,D); % Apply filter to orginal signal D
H_filtered = filter(H1,H2,H); % Apply filter to orginal signal H

% Convert Filtered signal to Frequency domain
fftDf = fft(D_filtered)/n; % fast forier transform filted D normalized by n
fftHf = fft(H_filtered)/n; % fast forier transform filted H normalized by n
Df_mag = abs(fftDf(i))*2; % Single-sided frequency domain of filtered D
Hf_mag = abs(fftHf(i))*2; % Single-sided frequency domain of filtered H

% Signal Zeroing
LM_D = islocalmin(D_filtered,'MinSeparation',2,'SamplePoints',t); % Determine the lowest part
of D
LM_H = islocalmin(H_filtered,'MinSeparation',10,'SamplePoints',t); % Determine the lowest
part of H
base_D = median(D_filtered(LM_D)); % Create a lowest baseline for signal D
base_H = median(H_filtered(LM_H)); % Create a lowest baseline for signal H
new_D = D_filtered-base_D; % Normalize the signal D to zero position
new_H = H_filtered-base_H; % Normalize the signal H to zero position

% Gradient time Response
gradient_D = gradient(new_D); % Gradient response for filtered and normalized signal D
gradient_H = gradient(new_H); % Gradient response for filtered and normalized signal H

% Gradient Peak Identification
min_sep = 7; % Minimum seperation (seconds) corresponds to stand-to-sit cycling period
P_PeakD_index = find(islocalmax(gradient_D,'MinSeparation',min_sep,'SamplePoints',t)); %
Positive Peaks D index
N_PeakD_index = find(islocalmin(gradient_D,'MinSeparation',min_sep,'SamplePoints',t)); %
Negative Peaks D index
P_PeakH_index = find(islocalmax(gradient_H,'MinSeparation',min_sep,'SamplePoints',t)); %
Positive Peaks H index
N_PeakH_index = find(islocalmin(gradient_H,'MinSeparation',min_sep,'SamplePoints',t)); %
Negative Peaks H index
P_PeakD = gradient_D(P_PeakD_index); % Positive Peaks D
N_PeakD = gradient_D(N_PeakD_index); % Negative Peaks D
P_PeakH = gradient_H(P_PeakH_index); % Positive Peaks H
N_PeakH = gradient_H(N_PeakH_index); % Negative Peaks H

% Flat Region Identification
FlatD_index = find(islocalmax(new_D,'FlatSelection','all','SamplePoints',t)); % Flat Regions
Indices for D
FlatH_index = find(islocalmax(new_H,'FlatSelection','all','SamplePoints',t)); % Flat Regions
Indices For H
FlatD = new_D(FlatD_index); % Flat Regions for Raw Signal D
```

```
FlatH = new_H(FlatH_index); % Flat Regions for Raw Signal H
P_FlatD = FlatD(FlatD>mean(FlatD)); % High Flat Regions for Raw Signal D
N_FlatD = FlatD(FlatD<mean(FlatD)); % Low Flat Regions for Raw Signal D
P_FlatH = FlatH(FlatH>mean(FlatH)); % High Flat Regions for Raw Signal H
N_FlatH = FlatH(FlatH<mean(FlatH)); % Low Flat Regions for Raw Signal H
t_P_FlatD = t(FlatD>mean(FlatD));
t_N_FlatD = t(FlatD<mean(FlatD));
t_P_FlatH = t(FlatH>mean(FlatH));
t_N_FlatH = t(FlatH<mean(FlatH));

%% Signal Processing - Output Parameters

% An estimate of the lean speeds(Gradient of +D)
Lean_Speed = P_PeakD;
t_Lean_Speed = t(P_PeakD_index);
% An estimate of the lean back speeds (Gradient of -D)
Lean_Back_Speed = N_PeakD;
t_Lean_Back_Speed = t(N_PeakD_index);
% An estimate of the rise speed (Gradient of +H)
Rise_Speed = P_PeakH;
t_Rise_Speed = t(P_PeakH_index);
% An estimate of the sit speed (Gradient of -H)
Sit_Speed = N_PeakH;
t_Sit_Speed = t(N_PeakH_index);
% Lean-in to Lean-back (+D) Step Height
P_delta_D = abs(mean(P_FlatD)-mean(N_FlatD));
% Lean-back to Lean-in (-D) Step Height
N_delta_D = abs(mean(N_FlatD)-mean(P_FlatD));
% Sit to Stand (+H) Step Height
P_delta_H = abs(mean(P_FlatH)-mean(N_FlatH));
% Stand to Sit (-H) Step Height
N_delta_H = abs(mean(N_FlatH)-mean(P_FlatH));
% Leaning Variation (+D rms)
Leaning_rms = rms(P_FlatD);
% Leaning-back Variation (-D rms)
Leaning_back_rms = rms(N_FlatD);
% Standing Variation (+H rms)
Standing_rms = rms(P_FlatH);
% Siting Variation (-H)
Sitting_rms = rms(N_FlatH);

% Cycling Period
index = islocalmax(gradient_H,'MinSeparation',6,'SamplePoints',t);
Ts = diff(t(index));

%% Plot Results
```

```
% Display original and filtered signal in time domain
figure(1)
subplot(2,1,1)
hold on
plot(t,paramDX,t,new_D,t_Lean_Speed,new_D(P_PeakD_index),'*r',t_Lean_Back_Speed,new_
D(N_PeakD_index),'ob')
plot(t(FlatD_index),FlatD,'.g')
yline(base_D,'--k','Baseline');
hold off
ylim([-1 1]);
title('D Response - Time Domain')
xlabel('Time(s)')
ylabel('D Position(m)')
legend({'Original','Filtered'},'Location','southeast')
subplot(2,1,2)
hold on
plot(t,paramHX,t,new_H,t_Rise_Speed,new_H(P_PeakH_index),'*r',t_Sit_Speed,new_H(N_Pea
kH_index),'ob')
plot(t(FlatH_index),FlatH,'.g')
yline(base_H,'--k','Baseline');
hold off
ylim([-0.5 1.5]);
title('H Response - Time Domain')
xlabel('Time(s)')
ylabel('H Position(m)')
legend({'Original','Filtered'},'Location','southeast')

% Display original and filtered signal in frequency domain
figure(2)
subplot(2,1,1)
hold on
plot(f,D_mag,f,Df_mag)
xline(fc_D,'--k','Cut-off Frequency')
hold off
title('D Response - Single Sided Frequency')
xlabel('Frequency(Hz)')
ylabel('D Magnitude(dB)')
legend({'Original','Filtered'},'Location','northeast')
subplot(2,1,2)
hold on
plot(f,H_mag,f,Hf_mag)
xline(fc_H,'--k','Cut-off Frequency')
hold off
title('H Response - Single Sided Frequency')
xlabel('Frequency(Hz)')
```

```
ylabel('H Magnitude(dB)')
legend({'Original','Filtered'},'Location','northeast')

% Plot Gradient Response in time domain
figure(3)
subplot(2,1,1)
plot(t,gradient_D,t_Lean_Speed,Lean_Speed,'*r',t_Lean_Back_Speed,Lean_Back_Speed,'ob')
ylim([-0.1 0.1]);
title('D gradient Response - Time Domain')
xlabel('Time(s)')
ylabel('Gradient D(m/s)')
subplot(2,1,2)
plot(t,gradient_H,t_Rise_Speed,Rise_Speed,'*r',t_Sit_Speed,Sit_Speed,'ob')
ylim([-0.1 0.1]);
title('H gradient Response - Time Domain')
xlabel('Time(s)')
ylabel('Gradient H(m/s)')

%% Export Outputs

outputWrite = string(strcat(output_dir, {'\'}, dataSetName, '\Results.xlsx'));

xlsTitles1 = ["leanSpeed", "leanSpeedTimestamp", "leanBackSpeed",
"leanBackSpeedTimestamp", ...
    "riseSpeed", "riseSpeedTimestamp", "dropSpeed", "dropSpeedTimestamp", "cyclePeriod"];

xlsTitles2 = ["leanDistance", "leanBackDistance", "riseHeight", "dropHeight", ...
    "leanRMS", "leanBackRMS", "riseRMS", "dropRMS"];

xlswrite(outputWrite, xlsTitles1, 1, 'A1');
xlswrite(outputWrite, xlsTitles2, 2, 'A1');

xlswrite(outputWrite, Lean_Speed, 1, 'A2');
xlswrite(outputWrite, t_Lean_Speed, 1, 'B2');
xlswrite(outputWrite, Lean_Back_Speed, 1, 'C2');
xlswrite(outputWrite, t_Lean_Back_Speed, 1, 'D2');
xlswrite(outputWrite, Rise_Speed, 1, 'E2');
xlswrite(outputWrite, t_Rise_Speed, 1, 'F2');
xlswrite(outputWrite, Sit_Speed, 1, 'G2');
xlswrite(outputWrite, t_Sit_Speed, 1, 'H2');
xlswrite(outputWrite, Ts, 1, 'I2');

xlswrite(outputWrite, P_delta_D, 2, 'A2');
xlswrite(outputWrite, N_delta_D, 2, 'B2');
xlswrite(outputWrite, P_delta_H, 2, 'C2');
xlswrite(outputWrite, N_delta_H, 2, 'D2');
```

```
xlswrite(outputWrite, Leaning_rms, 2, 'E2');
xlswrite(outputWrite, Leaning_back_rms, 2, 'F2');
xlswrite(outputWrite, Standing_rms, 2, 'G2');
xlswrite(outputWrite, Sitting_rms, 2, 'H2');

saveas(figure(1), string(strcat(output_dir, {'\'}, dataSetName, '\figure1.png')));
saveas(figure(2), string(strcat(output_dir, {'\'}, dataSetName, '\figure2.png')));
saveas(figure(3), string(strcat(output_dir, {'\'}, dataSetName, '\figure3.png')));
```