Use of a probabilistic model to explore the hip fracture and health economic outcomes of safety flooring implemented in an Ontario retirement home environment

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Hip fractures suffered by older adults are a serious public health concern. The direct yearly expenditure for hip fractures exceeds one billion dollars in Canada and with the older adult population expected to increase within the upcoming years, this issue will become more significant. Hip fractures therefore require consistent, structured investigations into their mechanism, and any insight which could mitigate the challenges associated with their occurrence, should be actively pursued. Hip fracture investigations frequently employ the factor of risk principle which posits that a hip fracture occurs when the loads applied to the hip exceed the strength of the bone. Appropriately designed safety flooring reduces fall-related impact forces and should theoretically reduce hip fracture risk, however, when implemented into an older adult setting the expected reduction in hip fracture risk is not observed. Yet still economic evaluations of safety flooring suggest that it is a better alternative than standard flooring, supporting its inclusion into older adult settings.

Mathematical modelling provides a cost-effective, non-invasive, investigative tool which can be used in tandem with experimental and observational approaches to consider hip fracture risk. A previous model unified experimental and observational data to simulate a population of Canadian older adults, subsequently quantifying their hip fracture risk using the factor or risk principle. However, the simulated population may not be representative of distinct subsets of the Canadian older adult population. Additionally, the model can only assess hip fracture risk in two unique conditions: when the entire population falls on safety flooring, or the entire population falls on standard flooring. These limitations reduce confidence in the model's ability to quantify hip fracture risk for arbitrary populations and reduce the model's ability to replicate situations which are objectively more feasible to recreate in the real-world.

The objectives of this thesis were to expand the capabilities of the pre-existing probabilistic model, increase its real-world utility by integrating components to simulate specific subpopulations of older adults, incorporate the probabilities of falls in different locations, and consider the economics of implementing safety flooring in specific locations within residential care facilities. The modified probabilistic model supports the notion of population-specific/population-dependent investigations. It also reaffirms the accuracy of understood model assumptions by exhibiting similar behaviours across different populations. Additionally, the model successfully integrated fall location probabilities from observational data to highlight an effect of sex and location on hip fracture risk. Finally, the model suggests that both savings and decisions to implement safety flooring may depend not only on the location of falls but sex characteristics as well.

Ultimately, this thesis demonstrates the feasibility of coupling mechanics, epidemiology, and health economics perspectives within a simulation tool to explore the effects of a safety flooring intervention on hip fracture risk in a retirement home setting on older adult hip fracture risk. The outcomes of this thesis may assist decision-makers within multiple industries (residential care facilities, flooring manufacturers, government policy makers) in developing funding policies, priorities, and design decisions.

Acknowledgements

This thesis would not have been possible without the work of several individuals at the Injury Biomechanics and Aging Lab at the University of Waterloo. I would like to acknowledge the input of Professor Andrew Laing whose considerable insight and discussion contributed to the development of this final document. Additionally, I acknowledge the seminal modelling work of Daniel Martel upon which this thesis builds. Mayank Kalra provided considerable support and feedback on the technical aspects of the model as well as assistance with generating code in MATLAB. To my thesis committee members Drs Emma Pierard, Clark Dickerson and Steven Fischer, I am also grateful for your assistance in shaping this final thesis. To the various other members of IBAL (Taylor, Steven, Thomas, Alyssa, Sukirat, Becky, Ethan, Jordan) I am grateful for you welcoming me into your midst. To anyone who may have been omitted please forgive my forgetfulness.

Dedication

Dedicated to the memory of my loving grandmother the late Theresa Clarke (Née Bernard), (1950 – 2023). Forever Loved.

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List of Abbreviations

Acronym	Meaning
BMI	Body Mass Index
SFLV	Safety Flooring Location Variable
FOR	Factor of Risk
ICER	Incremental Cost Effectiveness Ratio
iFOR	Intervened Factor of Risk
nFOR	Normalized Factor of Risk
FLV	Fall Location Variable
VI	Virtual Individual
QALY	Quality Adjusted Life Years
TSTT	Trochanteric Soft Tissue Thickness

Chapter 1: General Thesis Overview

Advances in scientific and technological knowledge and their application have facilitated an increase in the lifespan of older adults. However, these advancements have been unable to comprehensively mitigate the effects of aging such as decreases in muscular strength, decreases in central nervous system reaction time and a reduction in the rate of muscle force development. When considered together these age-related deficiencies in neuromuscular control facilitate an increase in the incidence of older adult falls, with a concomitant increase in the incidence of older adult hip fractures. Mental disorders, premature mortality and high costs borne by the provincial government are a few of the negative outcomes which are precipitated by hip fractures. These negative outcomes and their influence on society have subsequently guided inquiry into the mechanisms and possible mitigation strategies for hip fracture injuries suffered during older adult falls.

The factor of risk principle is a natural component of hip fracture investigations, it considers hip fractures to be a consequence of situations where an applied load exceeds the tolerance or strength of the bone. Since the value of the factor of risk is a ratio between the applied load and the bone strength, when it is near to or larger than one (1) an individual is at a higher risk of suffering from a hip fracture in a lateral fall onto the hip. Evidently, reductions in hip fracture risk are mediated by reductions in the loads applied to the hip during a fall which leads to a reduction in the factor of risk value. One method which has potential utility for reducing hip loading during a fall is the application of safety flooring to areas possessing large numbers of older adults e.g., retirement homes. Experimental evidence presented by Laing et al. (2006), has shown that safety flooring reduces the magnitude of forces experienced during an impact, so theoretically their implementation within a retirement home should reduce the risk of older adult fall related hip fracture. Recently, Martel (2017) employed the factor of risk principle to characterize the distribution of hip fracture risk within the Canadian older adult population using a mechanistic and probabilistic hip fracture model. The hip fracture model integrated the distributions of characteristics such as age, sex, mass, height, and BMI within the Canadian population to estimate a population hip fracture risk. In an earlier investigation, Martel (2017) also considered the influence of safety flooring on Canadian hip fracture risk, showing that safety flooring within the model reduced the population hip fracture risk. The model further indicated that the risk of hip fracture is differentially influenced by sex with older females expected to suffer from a disproportionately larger number of fractures than older males. These findings agreed with previous observations within the literature, (Kanis et al., 2002; Leslie et al., 2009; Hopkins et al., 2012; Jean et al., 2013). The hip fracture model of Martel (2017) also provided a method for estimating the number of hip fractures occurring within populations. Any individual within the population with a factor of risk exceeding the appropriate sex-specific injury criterion values are considered to fracture.

More recently, Cleworth et al. (2021) characterized the spatial distribution of falls obtained from a retirement home, the data pertaining to percentage of falls observed in selected rooms was as follows: Bedroom 62.8%, Bathroom 13.5%, Other 8.2%, Walkway 6.3%, Lounge 5.8%, Dining Room 3.0%, Activity Room 0.4%. This suggested that considerable differences exist between fall locations in retirement homes and that judicious choices for the placement of safety flooring could reduce the incidence of older adult hip fracture relative to other choices. Attempts had been made to estimate the annual cost of older adult hip fractures within Canada (Nikitovic, 2013; Leslie et al., 2011), these assessments generally conclude that hip fractures impose a considerable financial demand on those responsible for bearing the costs. Furthermore, Nikitovic (2013) observed differential post-fracture costs between sexes with older males incurring greater post fracture expenses per individual than older females. Finally, economic evaluations have been conducted to determine the effectiveness of safety flooring in older adult settings, these have determined that safety flooring is or could be cost effective when compared to the typical alternative of standard flooring (Latimer et al., 2013, Ryen & Svensson, 2015, Zacker & Shea, 1998).

Recognizing the high levels of agreement between the outputs of the Martel (2017) and Martel et al. (2020) hip fracture model and observed hip fracture trends within the literature, as well as the benefit of applying models to situations which are challenging to recreate experimentally, this thesis will attempt to extend the model's current capability. By extending its current capability, this thesis will attempt to transform a general model which quantifies hip fracture risk in a simulated population into a model which is capable of estimating hip fracture risk in a simulated Ontario retirement home where safety flooring is being trialled at various locations. Subsequently, the spatial distribution of falls within Ontario retirement homes provided by Cleworth et al. (2021), will be integrated into the model to impose a spatial dimension upon the generated virtual individuals. By imposing a spatial dimension, the virtual individuals will be assigned to fall within locations as observed within a group of Ontario older adult care facilities.

Martel et al. (2020) previously showed that implementing safety flooring would reduce the population level risk of hip fracture, however, this was done under a general application of the probabilistic mechanistic model to situations where the virtual individuals were subjected to fall on a surface which was either only standard flooring or only safety flooring. The proposed extension to the program's capabilities would lead to consideration of a similar situation, when safety flooring is everywhere or nowhere within the simulated Ontario retirement home. However, this thesis will further attempt to perform comparisons between no safety flooring conditions and variable safety floor conditions. Alternatively stated, a selected subset of the total permutations of safety flooring locations would be simulated within the extended hip fracture model to estimate changes in hip fracture risk within the simulated Ontario retirement home. This part of the proposed inquiry will determine if increasing the coverage of safety flooring within the simulated Ontario retirement home would lead to a reduction in the number of older adult hip fractures.

Martel (2017) and Martel et al. (2020) also showed previously that a differential effect of safety flooring on the reduction of hip fractures partitioned according to sex existed when using the hip fracture model. During the simulation a larger number of older adult males were reclassified from the fracture group to the non-fracture group when the distribution of their factor of risk values were decreased by the presence of safety flooring Martel (2017) and Martel et al. (2020). Though older adult females were similarly reclassified from the fracture group to the non-fracture group the number of reclassifications were much smaller Martel (2017) and Martel et al. (2020). The proposed extension to the program's capabilities would lead to consideration of a similar situation, by considering the effect of safety flooring on the reclassification of virtual individuals from the fracture group to the non-fracture group when compared to standard flooring. However, this thesis will further attempt to determine whether a similar trend occurs when a subset of the total permutations of safety flooring locations is simulated. This part of the proposed inquiry will determine if sex-specific reductions in hip fracture risk would occur as the coverage of safety flooring increases within the simulated Ontario retirement home.

Finally, this thesis will perform a rudimentary economic assessment to determine the efficiency of safety flooring when compared to the baseline standard flooring. This portion of the thesis would be used to determine if sex-specific differences in savings occur when safety flooring is placed within an Ontario retirement home. Additionally, they would be used to estimate the potential effectiveness of safety flooring implemented within a Canadian retirement home. Though safety flooring should theoretically reduce the number of hip fracture events it is expensive and subsequently the practicality of its implementation follows from its effectiveness in reducing hip fracture injuries and the cost to lay it. This part of the proposed inquiry will determine if safety flooring is an acceptable intervention for the prevention of hip fractures.

It should be noted that there is no current insight into the differential effectiveness which may exist relative to the spatial distribution of safety flooring within retirement homes. Additionally, there is little and sometimes conflicting insight into the effectiveness of safety flooring in the context of Canadian retirement homes when compared to the baseline of standard flooring. The work of this thesis should contribute to a body of knowledge on older adult hip fractures and assist in generating insight into the potential utility of safety flooring in older adult settings.

1.1 Research Questions

The information obtained from this thesis will provide a body of evidence to guide decisions about the implementation of safety flooring within an Ontario retirement home. The following are the research questions which will guide the development of this thesis.

1. Is the Canadian population (Age, Sex Proportion, Mass, Height, BMI) representative of the retirement home population?
2. Does the updated model exhibit consistent directionality?
3. Are there differential benefits on hip fracture outcomes when considering: a) Sex; b) Location of safety flooring?
4. Are there differential benefits on economic outcomes when considering: a) Sex; b) Location of safety flooring?

Chapter 2: Literature Review

Hip fractures are frequently observed in the older adult population and are characterized by a fracture of the upper/proximal femur in the general region of the pelvic bone. Hip fractures can be partitioned into multiple categories such as femoral neck, intertrochanteric, subtrochanteric etc. dependent on the location of the fracture. However, regardless of the type of fracture, these injuries typically present a set of consistently negative outcomes. Like failure in other load bearing mechanical structures, fractures occur when an applied force exceeds the tolerance or load bearing capability of the bone. Since the femur is necessary for facilitating locomotion and supporting the body's weight while standing and during gait, hip fractures present a challenge to the performance of activities of daily living. These activities are complicated by a generally precipitous reduction in individual mobility. Such fractures therefore necessitate the acquisition of assistive devices such as wheelchairs to ensure that changes to mobility can be mitigated. Aside from the reduction in mobility hip fractures also present an economic burden particularly to the provincial governments which typically bear the costs associated with post-fracture intervention such as surgery and rehabilitation. But the most concerning outcome for elderly adults following hip fracture is the high associated mortality rate, where 20% of elderly adults die within one year (Ioannidis et al., 2009; Jiang et al., 2005). The following will present a summary of the current literature on the prevalence and risk factors associated with hip fractures in elderly adults.

2.1 Hip Fracture: Prevalence and Incidence

Hip fractures are a frequent occurrence in the elderly adult population in Canada and globally. They are responsible for 7% of all fall-mediated injuries in Canadian older adult populations. However, they are disproportionately represented when subsequent hospitalization is required, accounting for greater than one third of such cases.

Both the incidence and prevalence of hip fractures exhibit a direct relationship with age, with older adults suffering a greater number of hip fractures when compared to younger adults **Figure 1**. A study conducted by Jean et al. (2013) which considered the relationship between age and hip fracture rates in Canada between 1985 and 2005 determined that hip fracture rates are relatively constant for individuals between the ages of zero and sixty. However, for adults above sixty there was a subsequent exponential increase in the hip fracture rates (Jean et al., 2013). It should also be noted that while hip fractures may occur due to other reasons, approximately 95% of such cases in older adult populations occur as a result of a fall (Stevens & Olson, 2000; Wolinsky et al., 2009).

Hip fractures also occur more frequently in older adult females when compared to older adult males. Hopkins et al. (2012) determined that approximately 73% of the hip fractures occurring in Canada between 2007 and 2008 occurred in older adult women. Hopkins et al. (2012) also estimated the lifetime risk of hip fracture for elderly adults at approximately 12.1% for females and 4.6% for males indicating an almost three-fold difference between hip fracture risk over the lifespan for males and females. These figures represent a general reduction when compared to estimates performed in 1989 which recorded a 14% and approximately 5.2% lifetime risk of hip fractures for older adult women and older adult men respectively (Kanis et al., 2002). This decrease in hip fracture rates was also observed by Jean et al. (2013) who described approximately 31.8% and 25.0% reductions in age-adjusted hip fracture rates for female and male older adults from 1985 to 2005 (per 100 000 person years).

Between 2010 and 2011 there were 25,495 hospitalizations associated with a hip fracture which represented approximately one third of the approximately 78,330 fall related hospitalizations (Canadian Community Health Survey, 2012). According to the Canadian Institute for Health Information, Hospital Morbidity Database approximately 256,011 injurious falls were suffered by Canadian older adults between 2009 and 2010. Approximately 50% of those falls occurred in the home while 17% occurred in residential institutions. Though it is difficult to obtain an accurate figure for the total number of falls occurring per year, evidence suggests that one third of older adults fall at least once per year (Blake et al., 1988; Campbell et al., 1989). Applying this estimate to Canada, approximately 2.4 million Canadian older adults should experience at least one fall per year. However, due to factors such as recall bias and mental deficiencies in older adults this number likely underestimates the total number of falls. Based on recordings of Canadian older adult hospitalizations in 2010/2011 a total of 25,495 were attributed to hip fracture (Canadian Community Health Survey, 2012). The previous figures suggest that approximately 10% of falls in the older adult population lead to an injury. Furthermore, approximately 10% of fall injuries are due to a hip fracture, the assumption being that all hip fractures require hospitalization. It is therefore concerning when additional evidence implicates falls as being responsible for 95% of hip fractures (Stevens & Olson, 2000; Wolinsky et al., 2009).

Tinetti et al. (1988) define a fall as ‘a subject's unintentionally coming to rest on the ground or at some other lower level, not as a result of a major intrinsic event (e.g., stroke or syncope) or overwhelming hazard’ yet this concept is not always intuitive. Falls can be partitioned into multiple categories depending on the orientation of the faller when they initially contact the floor (forward, backward, lateral). Lateral falls onto the hip are intimately connected to investigations about hip fractures as the loading pattern due to such falls lead to an increase in the risk of hip fractures when compared to other fall orientations. Additionally, one could consider the height from which a fall occurs, a fall from a greater height would lead to a greater impact velocity and subsequently impact energy, than a fall from a lesser height. Such a fall would intuitively increase the loading experienced at the hip and lead to a greater risk of injury when compared to a fall from a lesser height. Following, from the previous thoughts, when mentioning a fall, consideration should then be directed toward the actual change in height experienced by the hip from the beginning of the fall till an impact event occurs. Such considerations appreciate the difference between each fall and could possibly allow for better discrimination between groups of people who fracture when falling and groups who do not. This is implicitly considered within the probabilistic mechanistic model of Martel et al. (2020) since older adults possess a range of possible heights. Finally, factors such as the use of limbs to arrest the momentum of the body and modulate the impact velocity of a fall could be investigated, such actions could serve to reduce the risk of hip fracture. The purpose of this short discussion is to impress on readers that, characterizing a fall and its effects on a person is a challenging task and simple statistical measures may not always provide enough insight into the risk of hip fractures associated with them.

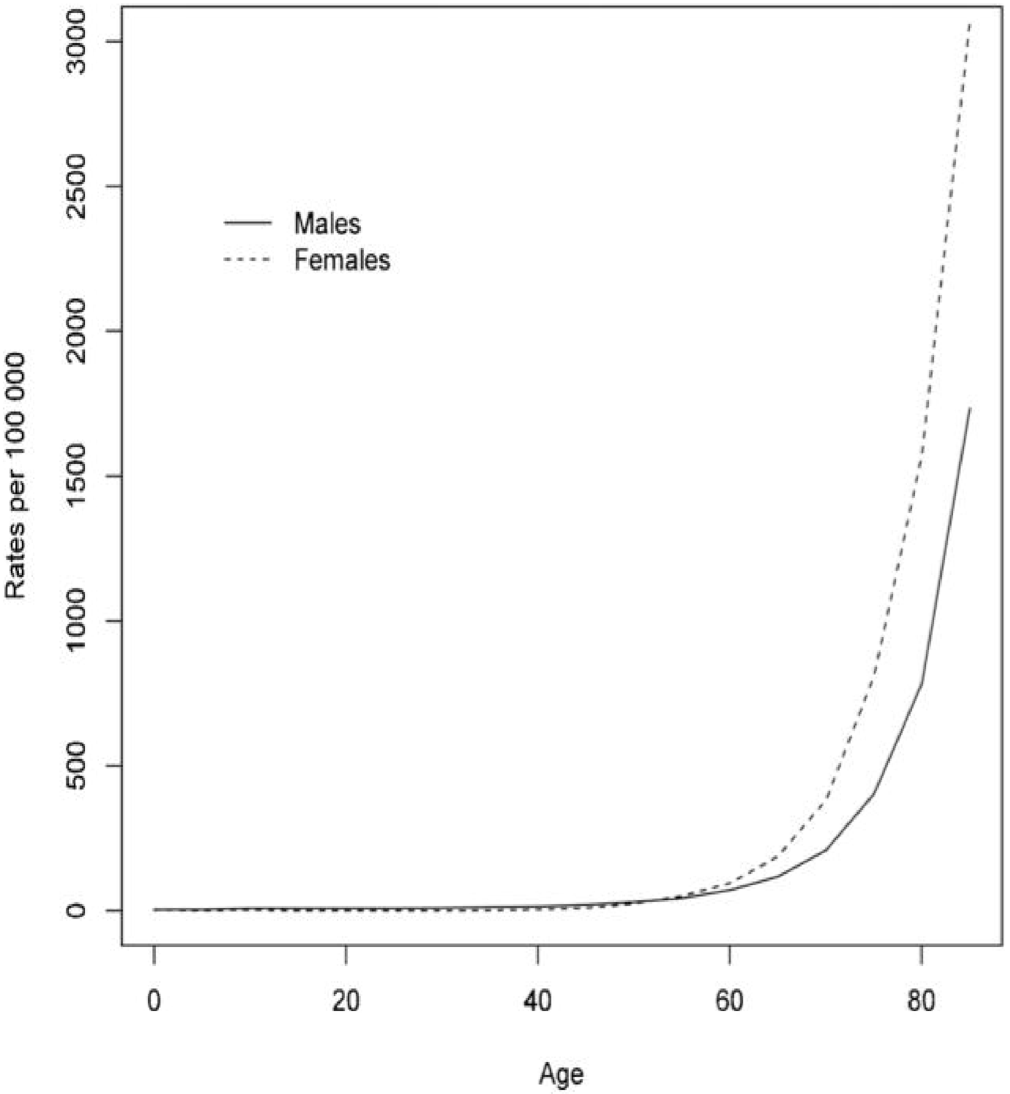

Figure 1 : Visualization of sex-specific age hip fracture rates. From Trends in hip fracture rates in Canada: An age-period-cohort analysis by S. Jean, S. O'Donnell, C. Lagace, P. Walsh, C. Bancej, J.P. Brown, S. Morin, A. Papaioannou, S. B. Jaglal, W. D. Leslie, (2013). Journal of Bone and Mineral Research, 28, 1284. Copyright 2013 by American Society for Bone and Mineral Research.

2.2 Hip Fracture: Financial Consequences

One of the obvious negative outcomes associated with a hip fracture is the considerable costs associated with hospitalization, surgery, and rehabilitation which are required after such an injury. A study occurring in 1995/1996 in the Hamilton-Wentworth region of Ontario determined that the average one-year cost of a hip fracture was $26,527 dollars (Wiktorowicz et al., 2001). Additionally, Wiktorowicz et al. (2001) determined that this value could be increased if the hip fractured older adult was subsequently placed in a long-term care facility. Ultimately, Wiktorowicz et al. (2001) estimated a total annual cost of 650 million dollars associated with treating hip fractures and any related complications occurring within the first year after the hip fracture is sustained.

Data from other countries has also shown a consistently elevated financial demand associated with older adult hip fractures. In the United Kingdom, Leal et al. (2016) estimated an expenditure of £14,163 per patient for the first-year post fracture hospital costs. In Australia, Tarrrant et al. 2020 estimated an expenditure of between $22,000 to $32, 000 Australian dollars for the acute care following a hip fracture. While in the United States, Adeyimi and Delhougne (2019) determined the costs associated with intertrochanteric hip fractures were $52,512 United States dollars per fracture. They further placed a multi-billion-dollar figure on the yearly hip fracture related expenditure within the United States of America of which approximately 50% was due to intertrochanteric hip fractures, (Adeyimi & Delhougne, 2019).

Further decomposition of hip fracture related costs by Nikitovic et al. (2013) show that most component costs associated with post fracture treatment and recovery are larger for older adult males when compared to older adult females. The costs associated with acute hospitalization, same day surgery, emergency visits, complex continuing care, and physician services are all greater for older adult males (Nikitovic et al., 2013). The costs associated with rehabilitation, long term care, home care and prescription medications are all greater for older adult females, (Nikitovic et al., 2013). Overall greater directly attributable post hip fracture costs are associated with older adult males, (Nikitovic et al., 2013). The decomposition of costs also shows that the increased costs for older adult males remains consistent across all recorded age ranges Nikitovic (2013). Evidently, a considerable economic burden is associated with societies providing older adults medical care after a hip fracture event. These non-trivial costs, particularly in countries such as Canada, Australia and the United Kingdom are borne by their respective governments. The minimization of these costs could facilitate the redistribution of monies to other areas, medical or otherwise. Therefore, any insights which could facilitate a reduction in fall fracture incidence would allow for increased economic savings.

2.3 Hip Fracture: Risk Factors

To understand hip fractures and the risk they pose to older adult populations, it is necessary to determine risk factors and subsequently quantify the risk posed by each. This section will introduce a selection of the most salient risk factors present in the literature. Figure 1 obtained from Jean et al. (2013) visualizes two risk factors associated with hip fractures, individual sex, and individual age. Females suffer a disproportionate number of hip fractures when compared to males (Blake et al., 1988; Campbell et al., 1989; Jean et al., 2013). In 2008 an estimate of the total number of hip fractures within Canada was set at approximately 22000 individuals over the age of 50 (Hopkins et al., 2012). 73% percent of the hip fractures observed were female, additionally, 64% of the hip fractures occurring in women occurred in women older than 80 years (Hopkins et al., 2012).

The literature clearly exhibits consistent agreement on factors which are associated with hip fracture. The disproportionate hip fracture relationship between female and male older adults tends to increase with age (Hopkins et al., 2012). Increasing age is correlated with an increasing risk of falling and subsequently sustaining a hip fracture (Campbell et al., 1989). However, the relationship observed between age and hip fracture incidence is modulated by a complex interrelationship between other factors which are themselves influenced by age. For example, as an individual ages, changes to balance and gait patterns are observed (Winter et al., 1990). Additionally, reduced functioning of the sensorimotor control system (Lord et al., 1996), increased mediolateral instability (Rogers et al., 2001) and an increased number of compensatory steps secondary to a perturbation (McIlroy and Maki, 1996) are observed with increases in age. These changes which all negatively influence an older adults' ability to maintain balance may precede the increased fall risk observed. Another relationship exists between bone mineral density (BMD) and bone strength with both factors exhibiting decreases with increasing age (Akdeniz et al., 2009; Fatayerji et al., 1999). Ferdous and Luo (2015) used finite element modelling to assess hip fractures, they observed an inverse relationship between the BMD of the proximal femur and the risk of suffering a hip fracture after a lateral fall. Ferdous and Luo (2015) also implicated body weight as being a factor which modified hip fracture risk during lateral falls this agreed with previous research conducted by Robinovitch et al. (1997 b) which showed a relationship between body weight and peak impact force experienced at the hip during lateral falls.

Additional factors which have been implicated in falls and subsequent fractures include the simultaneous ingestion of multiple pharmaceutical drugs (prescription medications), while another factor is utilizing assistive devices (Blake et al., 1988; Campbell et al., 1989). Other factors include a family history of hip fracture, smoking and drinking, oral glucocorticoid consumption, presence of rheumatoid arthritis and previous osteoporotic fractures (Kanis et al., 2008).

Finally, the location of an individual within a retirement home may be related to an elevated risk of falling and subsequently, hip fractures. Literature on the spatial characteristic of falls has indicated a higher risk for older adults' falls within their rooms (Stevens et al., 2014; Painter & Elliot, 2009). Additionally, falls in the bathroom are twice as likely to precede injury when compared to a fall in the living room, (OR = 2.4, 95% CI = 1.2 – 4.9), (Stevens et al., 2014). These observations have also been supported in the more recent work of Cleworth et al. (2021). Some of the risk factors presented within this section possess predictive capability and therefore utility when considering the development of mathematical models to assess fall fracture risk as will be subsequently discussed.

2.4 Hip Fracture: Mechanism

A general assessment of how the hip is affected/loaded during a lateral fall can be summarized by the Factor of Risk concept. The Factor of Risk is a ratio between the magnitude of the force applied to or experienced by the femur and the tolerance of the femur (Hayes, 1991). The greater the ratio of the applied force to the tolerance of the femur the greater the chance of a hip fracture occurring during an event. Concomitantly, the smaller the ratio of the applied force to the tolerance of the femur the less the chance of a hip fracture. Dufour et al. (2012) showed that elevated FOR values exhibited a strong relationship with the development of future hip fractures (a 1 SD increase in the value of the FOR corresponded to approximately 80% and 41% increases in fracture risk for males and females respectively. Therefore, to reduce the risk of a fracture during a fall it is insightful to determine methods/techniques which may either reduce the magnitude of the impact force or increase the tolerance of the femur or a combination of both (subsequently the FOR) **Figure 2**.

When considering the fractional expression which generates the FOR in an individual it is important to appreciate the role of the applied load or impact force in determining its magnitude **Figure 3**. The tolerance of the femur under typical conditions remains relatively constant, requiring variation in the FOR to be modulated primarily by changes to the impact force experienced by the hip. Impact force is directly correlated to the energy associated with the impact; therefore, a greater impact force is associated with greater impact energy. Using the rudimentary but fundamental principle of conservation of energy the gravitational potential energy of the hip is converted to kinetic energy while an individual is falling. On impact this kinetic energy is absorbed by the non-rigid biological tissues overlying the rigid femur. The impact force is determined by modelling the pelvis as a mass attached to a stiff spring system.

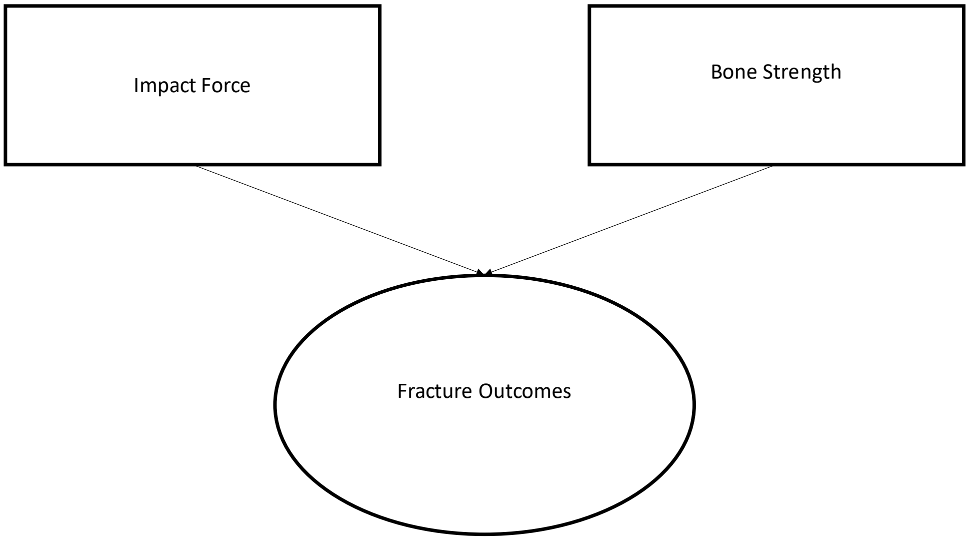

Figure 2: Visualization of the dependency of fracture outcomes on bone strength and the impact force/ applied load. Adapted from Development and Application of a Probabilistic/Mechanistic Model to Investigate the influence of Safety flooring on Population-Level Hip Fracture Risk by D. Martel, 2017, UWSpace. Retrieved 08/20/23 from https://uwspace.uwaterloo.ca/handle/10012/18362. Copyright 2017 by Daniel Martel.

Though the equations presented are simplifications which make assumptions about the properties of the biological tissues, they have been utilized previously by Robinovitch et al. (1997 b). Robinovitch et al. (1997 b) used equation (2.1):

$$Impact\ Force(N) = \sqrt{2ghmk} \qquad (\mathbf{2.1})$$

To estimate the impact force where 'm' represents the effective mass of the object, 'k' represents the effective stiffness of the object and 'h' represents the vertical height through which the effective mass falls to contact the impact site, the assumption is that the force associated with the impact is directed through a point. This equation highlights the dependence of impact force on the mass of an object, stiffness of the object and velocity at which the object contacts the floor which is itself dependent on the height from which a fall occurs. Therefore, when considering lateral falls onto the hip in human subjects it is evident that the impact force is quantified by knowledge of the height of the hip relative to the surface it contacts, the mass of the subject's hip pelvis complex and the effective stiffness of the hip pelvis complex. Apart from Robinovitch et al. (1997 b), this simplified equation has been employed to predict impact forces by (Bouxsein et al., 2007; Dufour et al., 2012; Van Den Kroonenberg et al., 1996). It has also been improved to facilitate the generation of more complex pelvic models, an example being the Voigt model which allowed for the consideration of damping (Bhan et al., 2014; Laing & Robinovitch, 2010; Levine et al., 2013; Robinovitch et al., 1991).

In a lateral fall, the variable 'h' in Equation 2.1 represents the vertical distance through which the effective mass must descend before it impacts the surface under consideration (Van Den Kroonenberg et al. (1995). However, Dufour et al. (2012) employed a centre of mass reference corresponding to 51% of total subject height. Martel (2017) employed a similar process using a normal distribution of values obtained from Chandler (1975), to generate values which were a fraction of the older adult's height. Previous studies which have utilized the lateral pelvis release method (Bhan et al., 2014; Laing & Robinovitch, 2010; Levine et al., 2013; Robinovitch et al., 1997a, Robinovitch et al., 1991) highlight the increasing relationship between pelvis release height and impact force, where increasing the release height of a subject increases the subsequent impact force.

The variable 'm' in Equation 2.1 represents mass another factor which modulates impact force. An increase in mass increases the gravitational potential energy of an object and subsequently the kinetic energy it possesses before impact. However, 'm' does not necessarily represent the total mass of the subject in a lateral hip impact (Van Den Kroonenberg et al. (1995). Robinovitch et al. (1991), therefore described an effective mass, effective mass being "influenced by all body segments moving with a nonzero downward velocity at the time of hip impact" (Robinovitch et al., 2009). The effective mass therefore contributes to the quantification of energy possessed by the segments of the body which influence the peak impact force experienced at the hip during a lateral fall. Subsequent considerations by Levine et al. (2013) have defined effective mass as the steady state force recorded by the force plate divided by the usual value of acceleration due to gravity.

The final variable '*k*' in Equation 2.1 represents the stiffness of the hip pelvis complex, this value is obtained from modelling the entire pelvic structure as a mass equivalent to the effective mass with a weightless spring attached which is compressed while absorbing impact energy (Robinovitch et al., 1997b). During a lateral fall onto the hip the spring-mass model represents the impact with the mass compressing the spring as kinetic energy of the falling mass deforms the spring. This spring mass model has been shown to accurately predict peak impact force (Robinovitch et al., 1997b). Robinovitch et al. (1991) fitted an exponential curve to experimental data and estimated average stiffness values of 90440 N/m for males and 71060 N/m for females. Subsequent experiments have led to reduction in the stiffness estimates, specifically 25194 N/m in females and 34271 N/m in males (Levine et al., 2013).

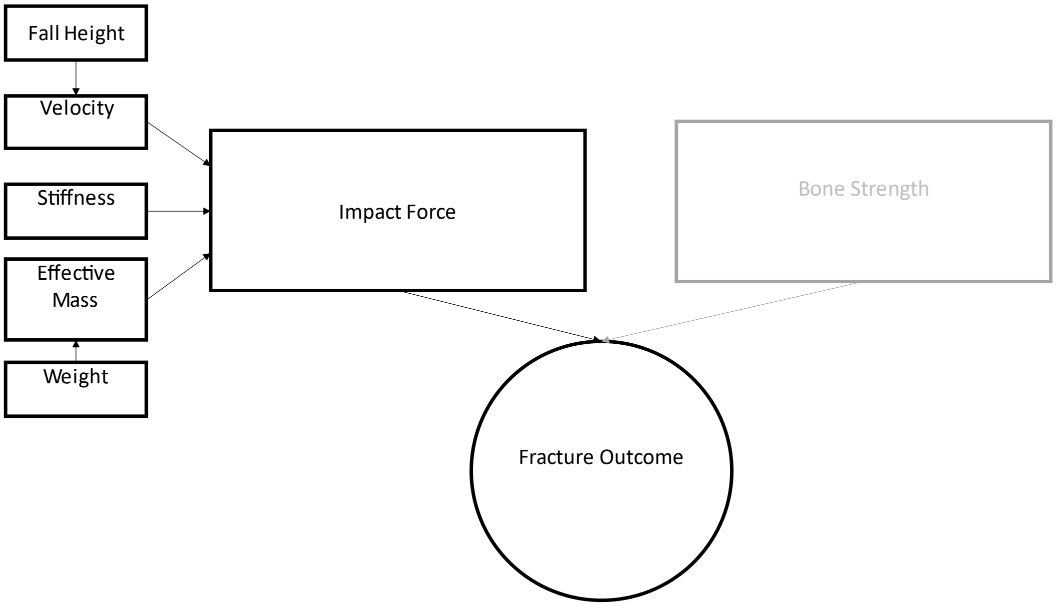

Figure 3: Visualization of the contributing variables to the impact force or load experienced at the hip. Adapted from Development and Application of a Probabilistic/Mechanistic Model to Investigate the influence of Safety flooring on Population-Level Hip Fracture Risk by D. Martel, 2017, UWSpace. Retrieved 08/20/23 from https://uwspace.uwaterloo.ca/handle/10012/18362. Copyright 2017 by Daniel Martel.

While the magnitude of the impact force is fundamental in generating the FOR, the tissue tolerance which constitutes the denominator also requires consideration **Figure 5**. This quantity represents the strength of the bone or its resistance to fracturing when a load is applied. There are ethical and other challenges associated with obtaining accurate numerical values for the tolerance of bones in-vivo. This lack of feasibility has led to values being obtained through in-vitro channels such as cadaveric testing. In the literature, the tolerance values of interest are obtained through a simulated lateral impact to an excised cadaveric femur, a few studies which employed some variation of this technique to determine the tolerance and physical characteristics of the femur for verifying which attributes possessed predictive capability include (Bouxsein et al., 1995; Chappard et al., 2010; Cheng et al., 1997; Dall'Ara et al., 2013). Most of these studies have shown that both bone mineral density and bone mineral content of the femur correlate with the fracture threshold (r^2 ranging from 0.78 to 0.88), (Bouxsein et al., 1995; Chappard et al., 2010; Cheng et al., 1997; Dall'Ara et al., 2013).

As bone mineral density (BMD) quantifies the density of selected minerals within bone and is correlated with femur strength, it has the potential to predict hip fracture risk. Aside from its predictive capabilities it is relatively simple to obtain in-vivo measurements using X-ray technology. Dual energy X-ray Absorptiometry (DXA) is the preferred method to obtain bone mineral measurements, in this procedure the absorption of X-rays is directly proportional to the density of minerals contained within the bone. BMD explains a large percentage of variance when used to predict fracture thresholds (Ferdous & Luo, 2015), subsequently it is employed in predictive equations which provide insight into fracture risk (Roberts et al., 2010). Clearly BMD is correlated with bone strength and therefore fracture risk, however it is even more insightful to consider additional factors which influence BMD. In males femoral neck BMD undergoes a linear decrease of approximately 21% between the ages of 20 and 79 (Fatayerji et al., 1999). In females a similar decrease occurs between the ages of 40 and 75 (Skrzek et al., 2011). Hannan et al. (1992) observed a linear decrease in proximal femur BMD in older adults from ages 68 to 98, this decrease was not significantly different between males and females. However, it has been observed that older females suffer from a greater number of hip fractures (Jean et al., 2013), suggesting that the rate of decrease of BMD is not responsible for increasing fracture risk. A possible explanation may be derived when considering that Hannan et al. (1992) also observed a consistently lower BMD value in females when compared to males. These differences were also consistently lower when considering spatially distinct regions of the femur (Hannan et al., 1992). Gong et al. (2016) however, described a significant difference in femoral neck BMD in a cohort of age matched older adults, older females possessed significantly lower BMD than older males. Differences also existed when considering cross-sectional area and cross-sectional moment of inertia, highlighting additional variation in bone geometry which could potentially influence bone strength (Gong et al., 2016).

Femoral BMD is also influenced by other factors. Ahn et al. (2014) observed that fat mass and BMD were inversely related, while lean muscle mass and BMD were directly related. A meta-analysis considering the interaction between BMI and BMD and their influence on fracture risk was particularly elucidating. Without consideration of BMD the relative risk of hip fracture exhibited a decreasing relationship with increasing BMI, suggesting that low BMI individuals were at a greater risk of fracturing. However, when BMD was considered the relationship between BMI and hip fracture morphed into a curve which was still decreasing but with a smaller slope with higher fracture risk at low and high BMI values (De Laet et al., 2005) **Figure 4**.

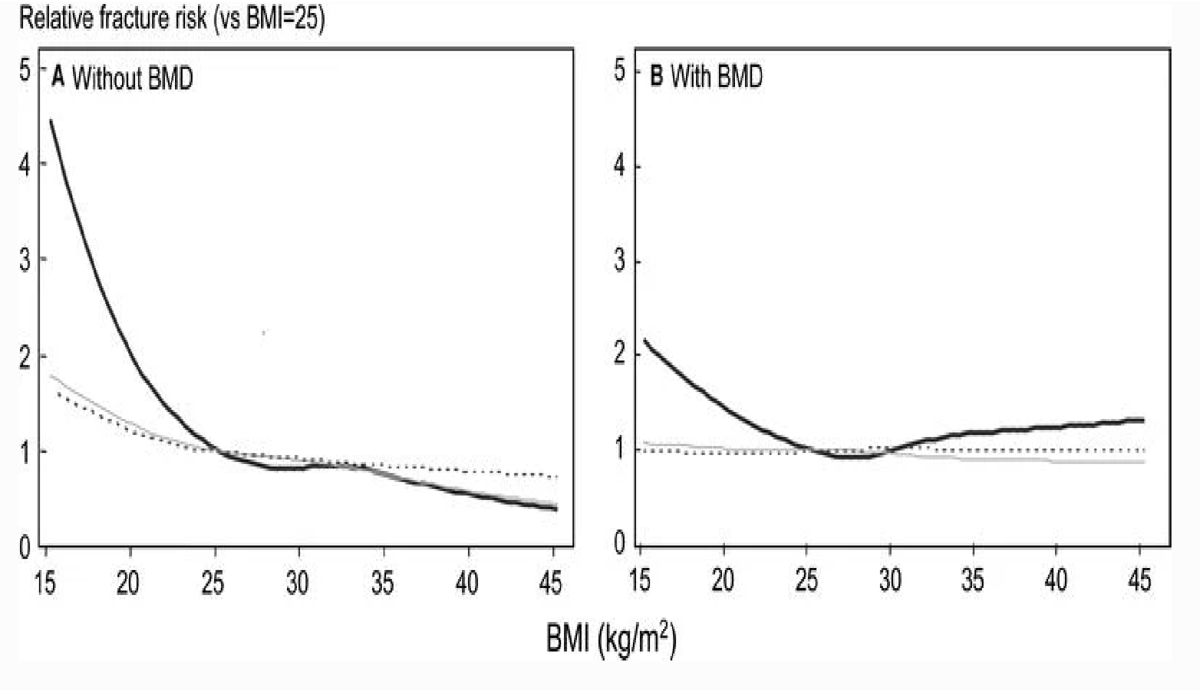

Figure 4: Visualization of the relative hip fracture risk at different levels of BMI compared to a reference BMI of 25. The inclusion of bone mineral density reduces the relative hip fracture

risk. From Body mass index as a predictor of fracture risk: a meta-analysis by C. De Laet, J.A. Kanis, A. Oden, H. Johanson, O. Johnell, P. Delmas, J.A. Eisman, H. Kroger, S. Fujiwara, P. Garnero, E.V. McCloskey, D. Mellstrom, L.J. Melton (III), P.J. Meunier, H.A.P. Pols, J. Reeve, A. Silman, A. Tenenhouse, (2005). Osteoporosis International 16, 1335. Copyright 2005 by Osteoporosis International.

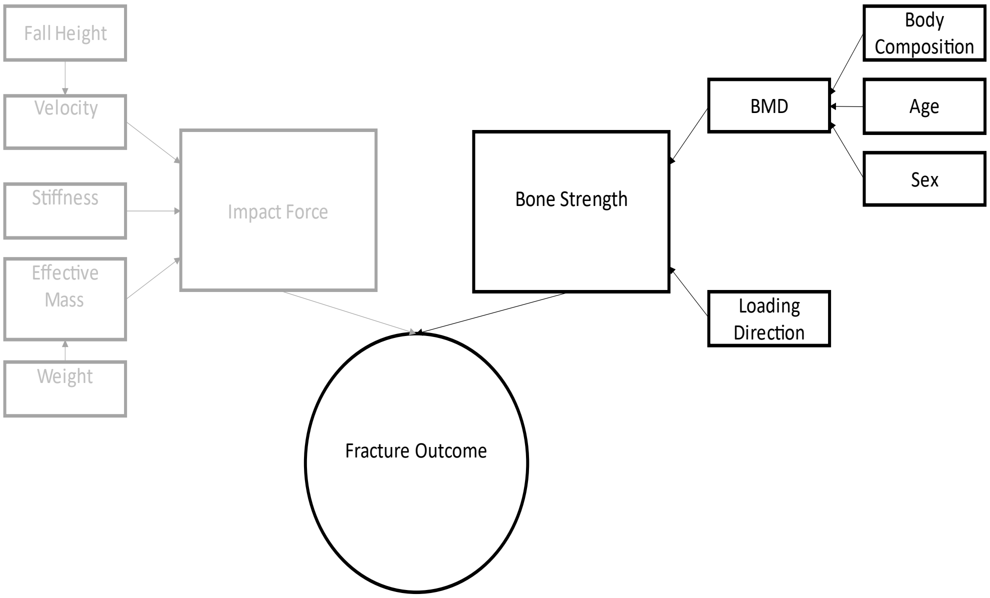

Figure 5: Visualization of the contributing variables to the bone strength or bone tolerance. Adapted from Development and Application of a Probabilistic/Mechanistic Model to Investigate the influence of Safety flooring on Population-Level Hip Fracture Risk by D. Martel, 2017, UWSpace. Retrieved 08/20/23 from https://uwspace.uwaterloo.ca/handle/10012/18362. Copyright 2017 by Daniel Martel.

While the decrease in femoral BMD with age may increase the risk of fracture in older adults during a lateral fall onto the hip, it is insightful to also consider the properties of bone and the mechanism by which fracture occurs. Bone can be divided into two categories, cancellous bone and cortical bone each with differing properties related to their biological function, Morgan et al. (2018). Bone obeys Wolff's law which postulates that bone is influenced by its loading history bones subjected to consistent loading will become stronger, while bones devoid of loading will become weaker (Robling & Turner, 2009). Aside from being adaptable to applied stress and formed from the amalgamation of two structurally distinct biomaterials, bone also possesses the properties of viscoelasticity and being anisotropic, Morgan et al. (2018). The property of viscoelasticity ensures that bone exhibits behaviours such as stress relaxation and creep as well as variable responses to variable loading rates. The property of anisotropy ensures that bone's resistance to deformation depends on the direction of force application. In a lateral fall onto the hip the superior surface of the greater trochanter experiences a compressive load while the inferior surface experiences a tensile load (De Bakker et al., 2009). This is in sharp contrast to the typical loading pattern of the greater trochanter while an individual is standing where the superior surface of the greater trochanter experiences tensile loading and the inferior surface compression (De Bakker et al., 2009) **Figure 6**. Wolff's law in this case may explain the risk of fracture in such a situation since the typical loading patterns of standing may increase the tolerance of the inferomedial portion of the neck of the greater trochanter to sudden applied loads. A sudden change to the loading pattern therefore exposes the superolateral portion of the neck of the greater trochanter to an atypically large force which it is less able to resist. This notion is supported by data in the literature which shows an average greater bone mineral density in the inferomedial aspect of the neck of the greater trochanter compared to the superomedial aspect in a group of 250 men (Yang et al., 2012).

Returning to the concept of FOR, the larger the FOR the greater the risk of suffering a hip fracture during the impact phase of a fall. Subsequently, any considerations about the risk of hip fractures should include interventions which may reduce the FOR and concomitantly the incidence and/or severity of injury observed. Reductions to the FOR can occur due to either a decrease in the applied force and/or an increase in the tolerance of the bone. Increasing a bone's resistance to fracture can be accomplished through interventions such as weight training (Kerr et al., 2001; Gader, 2018) and proper nutrition (Gader, 2018; Uusi-Rasi, 2008). However, Tai et al. (2015) mentioned that increases to bone density are unlikely to be clinically significant as an intervention to reduce fractures. Accordingly, there is value in exploring other approaches to reducing hip fracture risk i.e., interventions to reduce applied loads.

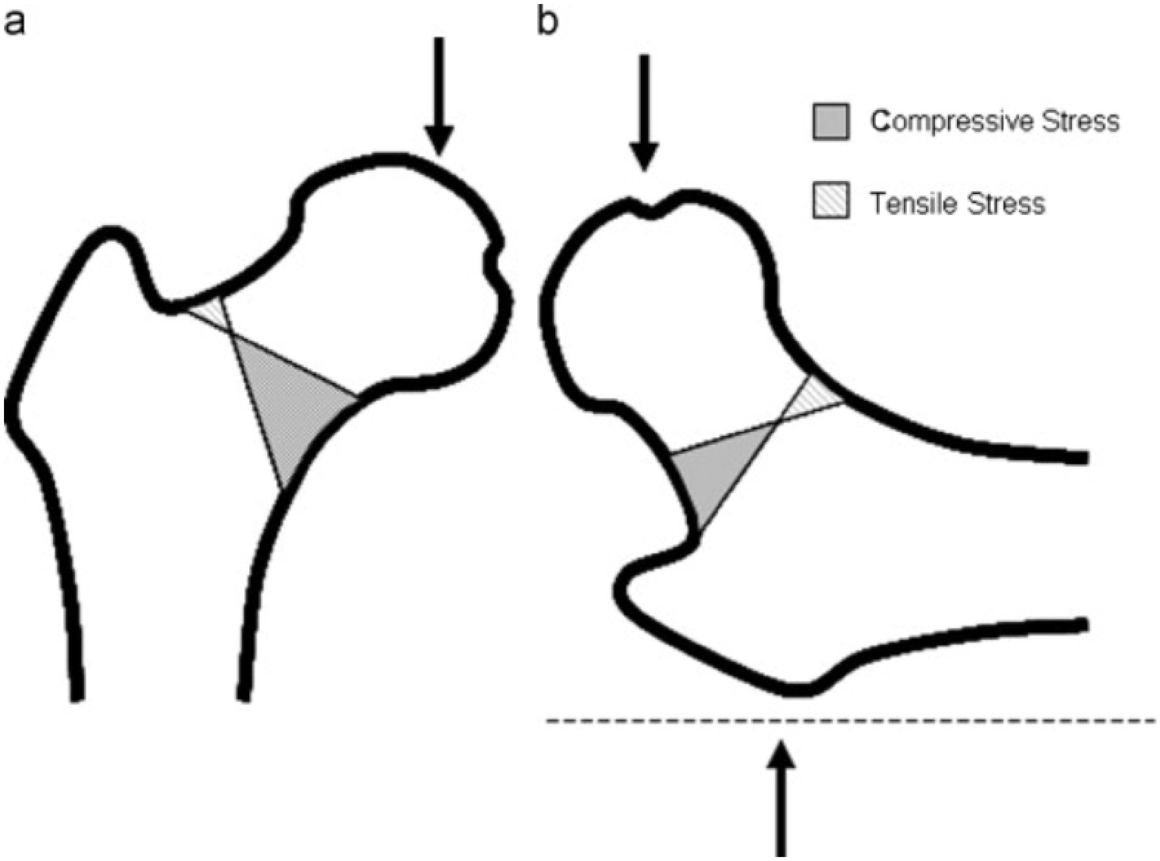

Figure 6: Visualization of the compression and tension profiles of the greater trochanter neck during a) walking and b) lateral loading e.g., impact during a sideways fall (from De Bakker et al., 2009). From During sideways falls in proximal femur fractures initiate in the superolateral cortex: Evidence from high-speed video of simulated fractures by P.M. de Bakker, S.L. Manske, V. Ebacher, T.R. Oxland., P.A. Cripton, P. Guy, (2009). Journal of Biomechanics, 42, 1918. Copyright 2009 by Elsevier Ltd.

2.4.1 Intrinsic Modulators of Hip Fracture

This section will approach the considerations of reducing the FOR from the perspective of reducing the applied force. Force reduction considerations may consider a combination of intrinsic and extrinsic modulators. An example of an intrinsic modulator is the trochanteric soft tissue thickness (TSTT) of a particular individual. Previous research has shown that this soft tissue which overlays the greater trochanter could absorb/modulate impact energy thereby, reducing the peak impact forces experienced on the femur by approximately seventy-one Newtons per meter of soft tissue thickness (71 N/mm), (Robinovitch et al., 1995). Body mass index (BMI) is positively correlated with TSTT (Maitland et al., 1993), and previous research by Levine et al. (2013) has shown a decrease in peak force (experienced during lateral falls onto the hip) when normalized to body weight in higher BMI individuals. Therefore, the evidence supporting an energy absorbing role during lateral falls onto the hip by TSTT possesses a measure of credibility. In contrast extrinsic modulators are engineered to reduce hip fracture risk and encompass systems such as hip protectors and safety flooring.

2.4.2 Extrinsic Modulators of Hip Fracture

Hip protectors overlay the greater trochanter and absorb and redirect impact energy during a fall concomitantly reducing the force experienced at the proximal femur during a lateral fall. Laing and Robinovitch (2009) observed variable benefits from hip protections dependent on factors such as impact velocity, soft tissue stiffness and even hip geometry. Additionally, the effectiveness of hip protectors is dependent on user compliance (Van Schoor et al., 2002). If older adults are uncomfortable with wearing hip protectors or simply forget, then the effectiveness of the protector consequently declines.

In contrast to hip protectors, safety flooring removes the issues surrounding user compliance. Safety flooring is a type of specially engineered flooring which reduces the peak impact loads associated with an impact event (Bhan et al., 2014; Glinka et al., 2013; Laing & Robinovitch, 2009). Additionally, attenuation values up to 50% for femoral neck impact forces have been observed with safety flooring (Laing & Robinovitch, 2009). These studies suggest that safety flooring may possess the ability to reduce the occurrence of hip fractures due to falls in older adult populations. LaChance et al. (2017) performed a scoping review of safety flooring considering biomechanical effectiveness, clinical effectiveness, cost-effectiveness, and workplace safety, they determined that safety flooring holds promise for the prevention of fall-related injuries. Additionally, LaChance et al. (2017) indicated that further investigations were required to determine if safety flooring could; a) translate its biomechanical laboratory effectiveness to real-world settings, b) be an economically viable intervention for the reduction of hip fractures and c) be integrated into workplace settings without negatively impacting worker performance. However, the evidence from the only large-scale clinical study contradicts the biomechanics literature, Mackey et al. (2019). Mackey et al. (2019) determined that there was no significant difference in serious fall related injuries suffered between older adults in rooms with or without safety flooring in long term care settings. Drahota et al. (2022) performed a systematic review of the safety flooring literature and found that the highest quality study found no significant benefit of safety flooring on falls and hip fractures, while lower quality studies found potential benefits of safety flooring on hip fracture incidence. The results of Mackey et al. (2019) highlight a potential disconnect between the theory of safety flooring and its implementation but are important as an addition to the biomechanics literature on safety flooring. The conflicting results from clinical and laboratory approaches suggest that more insight into safety flooring effectiveness particularly in older adult settings is required. Challenges to obtaining such information include the large costs associated with implementing safety flooring in areas where hypotheses can be made and tested. Additionally, the length of time required to install safety flooring and collect sufficient data related to older adult fall characteristics may be considerable. These challenges could potentially be mitigated by the development of an accurate predictive model formulated around the FOR principle. Though the theory of safety flooring is well established, the efficacy or physical utility remains questionable and therefore requires further analysis.

2.5 Economic Evaluation of Safety Flooring

Aside from the biomechanical and clinical assessments of safety flooring effectiveness it is also necessary to consider the economic feasibility of safety flooring as a hip fracture reduction intervention. Intuitively, even if safety flooring is effective at reducing the number of hip fractures observed in older adult settings, implementing it on a large scale may be limited by the necessary costs to implement safety flooring technology. Subsequently, decision-makers may be conflicted between expending funds to facilitate the implementation of safety flooring or remaining with the less costly standard flooring alternative. An economic evaluation will therefore provide further insights into the possible implementation of safety flooring within an older adult setting.

Economic evaluations can be one of three types: cost-effectiveness, cost-utility, or cost-benefit (Hoch & Dewa, 2005). Their overall purpose is to compare two courses of action or interventions to determine which provides the most benefit or is the most efficient (Hurley, 2010). To achieve this goal, the evaluations value the costs and consequences of each course of action, however the methods in which the consequences are valued differ between each type (Hurley, 2010). The cost effectiveness evaluation typically values the outcomes in their natural units (Hurley, 2010). As a relevant example, when using a cost effectiveness evaluation to assess the benefit of implementing safety flooring within a retirement home one consequence could be the number of hip fractures prevented. The natural units are subsequently integrated into a ratio known as the incremental cost effectiveness ratio (ICER) (Hurley, 2010). The cost utility evaluation is similar however, it places a different value on consequences, this value known as the quality adjusted life year (QALY) also considers differences in functional outcomes for individuals (Hurley, 2010). This type of valuation is summarized in a numerical value known as the incremental cost utility ratio. Finally, the cost benefit evaluation attempts to generate a valuation for consequences as a monetary figure (Hurley, 2010). This type of evaluation is by construction more time-consuming than the others; however, it allows for comparisons between different types of interventions. For this thesis the cost effectiveness evaluation was performed since natural units are better understood outside of advanced economic inquiry and the evaluation was simpler to perform. The literature in this domain (economic evaluations of safety flooring) is limited; however, the evidence generally supports the implementation of safety flooring.

Latimer et al. (2013) performed a cost-utility analysis to determine the effectiveness of safety flooring placed within a hospital in the United Kingdom. This analysis was based on a randomized controlled trial using safety flooring as an intervention to reduce fall related injuries, Markov modelling was used for the economic evaluation to extrapolate observations past the end of the data collection period. There were two groups, one group had safety flooring installed into a ward bay while the other group retained the usual standard flooring. Latimer et al. (2013) observed a non-significant increase in the incidence of falls but a non-significant decrease in the incidence of injuries. The analysis accounted for the differential effect of falls using quality-adjusted life years. The costs and consequences which were considered included intervention costs, hospital costs, post-discharge health care and social care costs as well as patient mortality and quality of life. Where necessary, a discount rate of 3.5% per annum was used. Questionnaires were used at 3 months post release from the hospital to obtain quality of life estimates. Survival times were estimated for the participants based on the number of people alive at 3 months post release. Latimer et al. (2013) indicated that there was a cost reduction of 843 GBP (British Pounds) per patient when using safety flooring as well as a QALY loss of 0.006 for an approximate ICER of 134,903 GBP. The cost saved per QALY lost exceeded the 20,000 GBP criterion value for the safety flooring to be cost effective, and Latimer et al (2013) indicated that safety flooring was cost saving in the base case. The model was especially sensitive to the fall incidence rate therefore, Latimer et al. (2013) ultimately determined that safety flooring could be cost effective if it did not result in an increased fall risk.

Ryen and Svensson (2016) performed a cost effectiveness analysis based on a cohort Markov simulation model to determine the potential influence of safety flooring in Swedish residential care facilities. Within the model one cohort entered a care facility with standard flooring, while the other cohort entered a care facility with safety flooring. The older adults were considered to be in one of three states at any time: 'healthy', 'hip-fracture', or 'dead'. They used a societal perspective to allocate costs and consequences, therefore consumption and production costs as well as the cost of added life years were considered. Some of the costs included in the analysis were those related to rehabilitation, general practitioner visits, physical therapy, and ambulances. A discount rate of 3% per annum was used   with a time horizon of ten years. Ryen and Svensson (2016) stated that there was an average savings of 2786 Swedish Krona for an average gain of 0.02 QALY's for everyone. The associated ICER was then approximately one hundred and forty thousand Swedish Krona. Ryen and Svensson (2016) also noted that the omission of the cost of added life years led to an enhancement of the cost-saving properties. Ryen and Svensson (2016) observed that even when model parameters were allowed to vary sixty percent (60%) of the simulations resulted in cost savings when compared to standard flooring and that a further twenty percent (20%) generated a cost per quality adjusted life year figure which was below the threshold of 500,000 Swedish Krona to implement safety flooring. Ryen and Svensson (2016) indicated that using their assumptions safety flooring in residential care facilities was cost effective in the base case. In fact, they indicated that the effectiveness of safety flooring must be below 25% before the safety flooring is not cost effective i.e., above the threshold of 500,000 Swedish Krona. Also, even after doubling the cost of the safety flooring, safety flooring remained cost effective, having an ICER of 256,000 Swedish Krona.

Zacker and Shea (1998) performed both cost effectiveness and cost benefit analyses to assess the utility of safety flooring when compared to standard flooring for the reduction of hip fractures in an

American nursing home. For both analyses they adopted the societal perspective to quantify the costs and consequences. Zacker and Shea (1998) presented the results of their cost-benefit analysis in two formats, the first format considered the direct medical costs avoided while the second method included additional indirect costs estimated as willingness to pay. The results of their cost-effectiveness were reported using the cost per life-years saved and they employed a discount rate of 5%. Zacker and Shea (1998) considered the costs to manufacture and install the floor, the costs to maintain and replace, finally they considered the cost of screening residents older adults who may have benefitted from safety flooring. Zacker and Shea (1998) expected the main benefits from the safety flooring would be the direct medical costs avoided, indirect morbidity avoided, and indirect mortality avoided due to non-occurrence of falls. Zacker and Shea (1998) assumed that the fall rate was the same between floor types therefore the differential reduction in hip fracture incidence was due to hip fracture incidence on each flooring type. When only direct costs avoided were considered the authors estimated a cost-benefit ratio of 0.61, however, when indirect costs were included, this ratio decreased to 0.06. For the cost effectiveness a figure of -$3,118 per life year saved was obtained. A sensitivity analysis concluded that the assertion that safety flooring was 50% effective in preventing hip fractures was the most sensitive to change. The authors concluded that once the safety flooring was effective in reducing hip fractures its implementation would be cost saving.

While these studies supported the implementation of safety flooring in older adult settings, none of them were performed in a Canadian context therefore the translation of such evidence to Canadian retirement home settings is not immediately evident. Additionally, none of these studies considered the differential effect of location on fall incidence, therefore the differential effect of safety flooring location on the ICER was unknown. Finally, none of these studies considered the sex-specific effect of safety flooring on fracture incidence, therefore the influence of older adult sex on the ICER is unknown.

2.6 Approaches for predicting hip fracture risk.

The negative implications of hip fractures in the older adult populations have guided multiple inquiries into the mechanisms of fracture as well as interventions to reduce fracture. However, the quantity of literature on mathematical models specifically directed towards hip fractures is limited. While the FOR is not a model but an estimator of hip fracture risk it has been foundational in mathematical models created by Bouxsein et al. (2007) and Dufour et al. (2012) to predict hip fracture risk. These mathematical models were generated by the amalgamation of multiple fracture related estimations such as predicted impact force (Robinovitch et al., 1991), force attenuation (Robinovitch et al., 1995), bone strength (Roberts et al., 2010) and the FOR (Hayes et al. 1991). The inputs to these models were individualized characteristics specific to subjects selected from a cohort which led to a presentation of individualized hip fracture risks. The hip fractures risks provided by the model were then contrasted with observations made on the cohorts of older adults. Dufour et al. (2012) obtained a significant difference in FOR between hip fracture and non-fracture cohorts. In addition, an interesting observation was a considerably lower average factor of risk for females when compared to males (Fracturing Male = 1.00, Non-fracturing Male = 0.87, Fracturing Female = 0.49, Non-Fracturing Female = 0.40). While the FOR successfully differentiated between fracture status within each sex, an ideal estimator should (theoretically) be centred about a FOR value of zero for both sexes. Additionally, the FOR values as stated do not represent the established hip fracture trend where older adult females are more at risk of suffering a hip fracture. If the FOR was a better estimator of hip fracture risk, then older adult females would have had greater FOR than older adult males.

Towards addressing these issues, Martel et al. (2020) and Martel (2017) introduced the concept of the normalized FOR (nFOR) which generates an estimator of hip fracture risk normalized by the 50%ile probability of sex-specific hip fracture risk. The output of the Dufour et al. (2012) model indicated promise in predictive capability as injury criterion values could be used to partition the population of older adults into fracture and non-fracture cases. Martel et al. (2020) and Martel (2017) subsequently generated injury criterion values which could be used to estimate the hip fracture risk within a population. Another model employed to assess or predict hip fracture risk is the finite element model generated by Ferdous and Luo (2015). Bone density measurements were used to generate subject specific models which were subsequently input into fall and impact simulations (Ferdous & Luo 2015).

These hip fracture risk quantifications models can be characterized as mechanistic in nature, highlighting their dependence on physical principles. However, other models exist such as the Fracture Risk Assessment Tool (FRAX) and Canadian Association of Radiologist and Osteoporosis Canada (CAROC) risk assessment tool. FRAX provides a ten-year probability of suffering from either a major osteoporotic or hip fracture in exchange for a set of twelve clinical risk factors. These factors are age, sex, weight, height, previous fracture history, parental fracture history, smoking status, use of glucocorticoids, presence of rheumatoid arthritis, secondary osteoporosis, alcohol consumption and femoral neck bone mineral density (Kanis et al., 2008). CAROC also provides a ten-year probability, but it indicates the level of risk (Low, moderate, high) associated with the probability value. The inputs to CAROC are also clinical risk factors and include bone mineral density of the hip or lumbar spine, age, gender, fracture history and steroid use. Like most risk prediction tools, FRAX and CAROC are limited to assessments or predictions of hip fracture outcomes associated with singular subjects. Therefore, they are unable to make predictions about fracture risk on a population level without considerable effort.

Martel et al. (2020), recognizing the limitation of these models, embedded the mechanistic model of Dufour et al. (2012) within a probabilistic framework to simulate fracture risk for large populations. The general principle employed by Martel et al. (2020) is that a population with characteristics obtained from known Canadian distributions could be generated and the factor of risk for each individual determined. This model also generates a distribution of the FOR values obtained from the simulations, representing overall hip fracture risk in a simulated population. The utility of such output is the ability to generate predictions about a population, dependent on information about how input characteristics are distributed within the population. An example would be to predict the number of fractures which would be observed within a retirement home consisting of older adults with a higher-than-normal BMD. It is this predictive capability of the Martel et al. (2020) model with its potential for being modified to target different populations under variable conditions which motivated the direction of this thesis.

2.7 Probabilistic-Mechanistic Model of Martel et al. (2020)

The Martel (2017) model was based on the creation of virtual individuals which were a model representation of older adults, possessing numerical attributes for a combination of physical and other characteristics. The virtual individuals were subjected to a lateral fall onto their hip and specific FOR values were determined for each virtual individual. The initial model framework is presented in **Figure 7** and further described in text below.

The physical characteristics which the virtual individuals were assigned included age, sex, mass, and height. These physical characteristics were then involved in the calculation of other physical characteristics which were subsequently involved in the calculation of factor of risk values. Height and mass were combined according to generate the BMI equation (2.2):

$$BMI = \frac{Mass\ (kg)}{Height^2\ (m^2)} \tag{2.2}$$

where mass and height were represented in units of kilograms and meters respectively. BMI was subsequently used to estimate the TSTT according to the regression equation (2.3) of LaFleur (2016):

$$TSTT = -2.22\ (s) + 0.33\ (BMI) - 3.31 \tag{2.3}$$

where *'s'* is a dichotomous variable used to represent sex (0 = female, 1 = male). The TSTT was then used to estimate the impact force attenuation due to soft tissue according to the equation (2.4) of Robinovitch et al. (1995):

$$Soft\ Tissue\ Attenuation\ (N) = 71\ (N/mm)\ x\ TSTT\ (mm) \tag{2.4}$$

The net impact force was calculated using equations (2.1) and (2.4):

$$Net\ Impact\ Force(N) = Impact\ Force - Soft\ Tissue\ Force\ Attenuation \tag{2.5}$$

The sex-dependent femoral bone mineral density was determined according to the regression equation (2.6) of LaFleur (2016):

$$Femoral\ neck\ BMD\ (g/cm^2) = -0.006(a) + 0.058(s) + 0.005(m) + 0.818 \tag{2.6}$$

where 'a' represented an age in years and 's' was a dichotomous variable used to represent sex (0 = female, 1 = male) and 'm' represented the total body mass. Bone mineral density was subsequently employed in the determination of bone strength using the equations of Roberts et al. (2010):

$$Femoral\ Strength(N) = 8207 * \left(Femoral\ neck\ BMD\ (g/cm^2)\right) - 568.62 \tag{2.7}$$

Finally, the FOR which is a simple indicator of hip fracture risk due an applied force (Hayes, 1991) was determined according to the following:

$$Factor\ of\ Risk = \frac{Net\ Impact\ Force\ (N)}{Femoral\ Strength\ (N)} \tag{2.8}$$

The values used to determine the factor of risk were generated using equations (2.5) and (2.6).

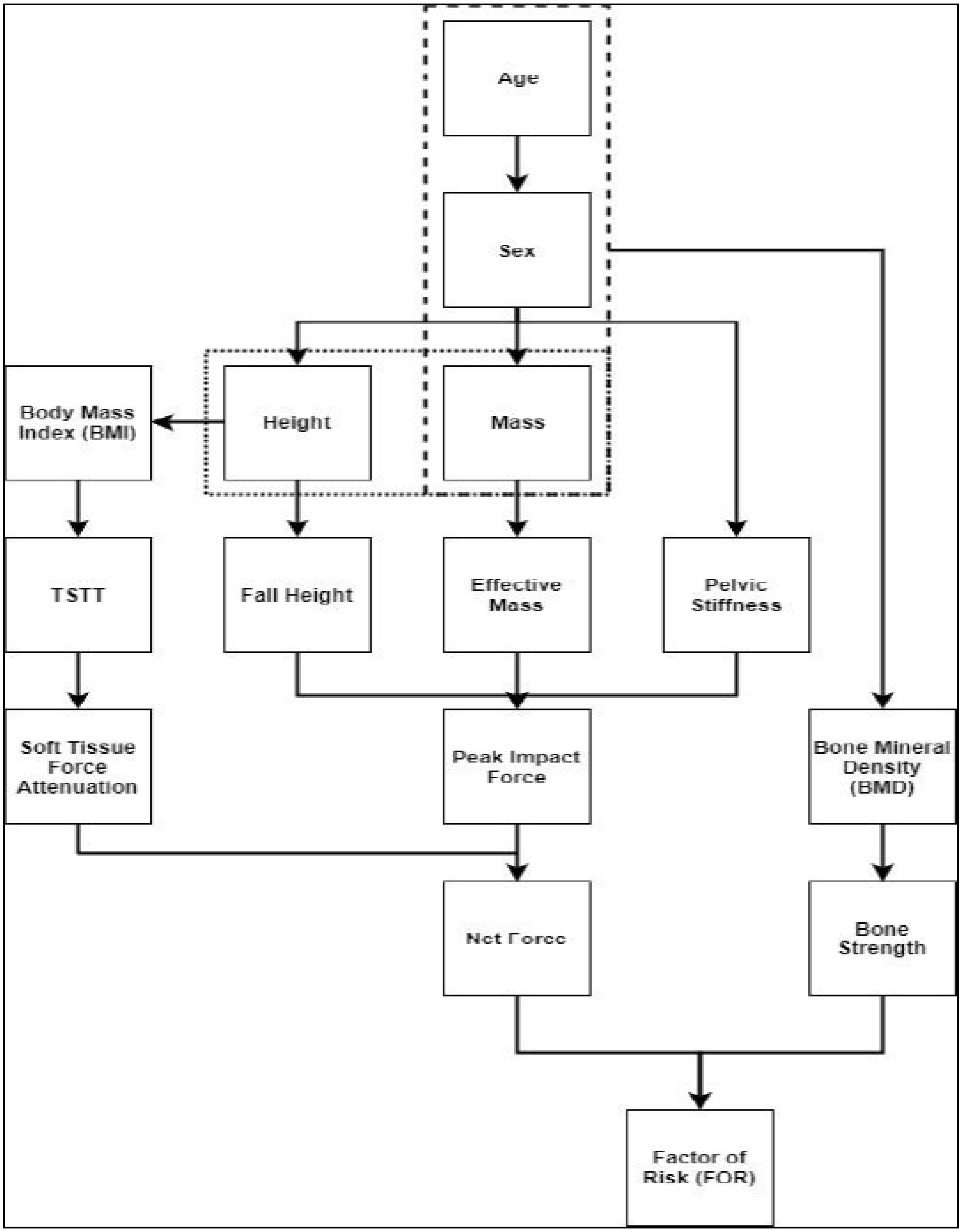

Figure 7: Visualization of the inputs and outputs of the original probabilistic mechanistic model with intermediate variables included. From Development and Application of a

Probabilistic/Mechanistic Model to Investigate the influence of Safety flooring on Population-Level Hip Fracture Risk by D. Martel, 2017, UWSpace. Retrieved 08/20/23 from https://uwspace.uwaterloo.ca/handle/10012/18362. Copyright 2017 by Daniel Martel

Martel (2017) generated a set of functions to represent the distribution of variables such as age, mass, and height of older adults within the Canadian population. Importantly, the hip fracture model distinguished between male and female older adults using separate processing paths to determine the factor of risk for males when compared to females. The general model was divided into two parts; the probabilistic part generated a virtual individual and assigned numerical values corresponding to different physical attributes. The mechanistic part transformed the physical attributes into FOR values and generated a sex specific distribution of FOR values. Random numbers were generated in the probabilistic model to exploit the one-to-one nature of the inverse cumulative distribution function (CDF). The inverse CDF method was used to obtain the numerical values of variables such as mass, and height for a single virtual individual. This process was repeated until the entire population of virtual individuals each possessing a complete set of physical attributes has been generated in entirety. Finally, the physical attributes of the generated population of virtual individuals were input into the mechanistic model to generate FOR distributions which quantified the population-level risk of hip fracture. The beauty of combining a probabilistic model with a mechanistic model was that the probabilistic model incorporated naturally occurring variations observed within a population. Therefore, the outputs theoretically represented what was expected when considering population characteristics i.e., population variability.

To assign the age variable to a virtual individual Martel (2017) fitted a polynomial function to Stats Canada demographic data. This polynomial then estimated the probability density function of the ages of the Canadian population for one year age increments from sixty to one hundred (60-100). A probability density function was subsequently defined from the polynomial as:

$$p(a) = -0.0000127(a^2) - 0.027456(a) + 1.475331 \qquad \mathbf{(2.9)}$$

Where 'a' corresponds to the age in years between sixty and one hundred (60-100). A uniformly distributed random variable between 0 and 1 could subsequently be generated and the inverse CDF method used to obtain a unique age which was then assigned to the specific virtual individual. A similar process was used by Martel (2017) to assign the dichotomous sex variable (Male or Female) to the virtual individual. However, instead of a polynomial function being fit to the data, an age specific male to female ratio was determined for each age using Stats Canada data. If the uniformly distributed variable was less than or equal to the proportion of males in the age bin, then the virtual individual was assigned the sex 'Male' otherwise it was assigned the sex 'Female'. This separation of virtual adults into male and female categories allowed for the sex-specific generation of information about hip fracture risk. Sex-specific consideration prevented hip fracture risk from being overestimated in male VIs and underestimated in female VIs when compared to the overall population. The variables for height were determined by fitting polynomials to sex-specific Stats Canada data. The resulting probability density functions were represented by:

$$Females: p(h) = -25.9947(h^2) + 82.7646(h) - 65.5944 \qquad (\mathbf{2.10})$$

$$Males: p(h) = -24.6223(h^2) + 84.6544(h) - 72.4768 \qquad (\mathbf{2.11})$$

The variables for mass were determined by fitting polynomials to sex-specific Stats Canada data. The resulting probability density functions were represented by:

$$Females: p(m) = 0.0001786(m^3) - 0.0045(m^2) - 0.3663(m) - 9.3676 \qquad (\mathbf{2.12})$$

$$Males: p(m) = 0.00010730(m^3) - 0.0032(m^2) - 0.3101(m) - 9.4198 \qquad (\mathbf{2.13})$$

Finally, the pelvis was modelled as a spring mass system during impact to generate the pelvic stiffness value. Robinovitch et al. (1991) had previously determined these values to be 90440 N/m and 71060 N/m for males and females respectively. However, more recent investigations performed by Levine et al. (2013) reported lower values of 34271 N/m and 25194 N/m for males and females respectively these lower estimates were used by Martel (2017). Subsequently the following sex specific distributions were used to obtain pelvic stiffness values for males and females:

$$Males: K \sim N(34271, 9464^2) \qquad (\mathbf{2.14})$$

$$Females: K \sim N(25194, 6126^2) \qquad (\mathbf{2.15})$$

The preceding discussion described how Martel (2017) assigned physical attributes to VIs. The following restates the calculations employed within the mechanistic model and their role in determining the risk of hip fracture for VIs. Equation 2.1 was first presented by Robinovitch (1991) to predict the impact forces associated with a lateral fall onto the hip. Martel (2017) used this equation to quantify lateral fall hip impact forces. This equation highlights a dependence of the impact force on the acceleration due to gravity 'g', effective mass 'm', change in height during a fall 'h' and stiffness of the pelvis 'k'. Equation (2.4) from Robinovitch (1995) indicates that every millimetre of trochanteric soft tissue facilitates a 71 Newton reduction in the force experienced at the hip. This was used within the mechanistic part of the model to determine the force attenuation provided by trochanteric soft tissues. Equation (2.3) was obtained from Lafleur (2016) and specified the magnitude of trochanteric soft tissue overlaying the greater trochanter. The net force experienced at the hip during a lateral impact was calculated by considering the difference between the actual impact force and the soft tissue attenuation according to Equation (2.4). Equation (2.7) was obtained from Roberts et al. (2010) and specified an estimated femoral strength which depended on the BMD concentrations determined in equation (2.6). Martel (2017) used this equation to quantify the strength of the femur. This equation indicated a linear relationship between the bone mineral density and femoral bone strength. Femoral strength provided numerical insight into the femur's ability to resist fracture from the forces experienced during a lateral fall onto the hip.

Martel (2017) considered the fall height of a virtual individual to be dependent on a normally distributed random variable known as the fall height ratio. This fall height ratio was derived from the work of Chandler et al. (1975) who characterized the ratio of centre of mass height to total body height. The distribution of the fall height ratio was described as follows. (Where the notation $6.24e^{-5}$ represents 6.24 multiplied by 10^{-5}):

$$HR \sim N(0.5857, 6.24e^{-5}) \qquad \mathbf{(2.16)}$$

The fall height indicated the loss of gravitational potential energy or the gain of kinetic energy and determined the impact forces which are experienced at the older adult hip during a lateral fall. To determine fall height 'h' the VI's height was multiplied by the fall height ratio. Martel (2017) also considered the effective mass of the body involved in the lateral impact to be dependent on a normally distributed random variable the effective mass ratio. This effective mass ratio was derived from work in Martel (2018). The sex-specific distributions of the effective mass ratio were described as follows:

$$Male: EM \sim N(0.467, 0.043) \qquad \mathbf{(2.17)}$$

$$Female: EM \sim N(0.553, 0.029) \qquad \mathbf{(2.18)}$$

Effective mass accounts for the fact that some segments of the body are not responsible for the energy changes related to an impact in a lateral fall onto the hip, therefore the total mass of the body is an inaccurate variable when considering equation (2.1). To determine subject effective mass '*m*' the VI's mass was multiplied by the effective mass ratio.

The preceding equations (2.1-2.18) were used to determine a final FOR value which provided insight into an older adult's hip fracture risk. Martel (2017) and Martel et al. (2020), embedded consistent and reasonable variability into the probabilistic mechanistic model to capture the natural variance observed in most populations. This is immediately a strength of his probabilistic approach for quantifying hip fracture risk in older adult populations. Another strength of the probabilistic mechanistic model presented by Martel et al. (2020) was its stability. The model consistently generated population FOR distributions having high levels of agreement with previous and/or subsequent simulations. Martel (2017) and Martel et al. (2020) validated the outputs of the probabilistic mechanistic model by running a simulation using data from Dufour et al. (2012) to specify virtual individual characteristics and comparing the output of the program (FOR) with the FOR means observed by Dufour et al. (2012). An a-priori inclusion exclusion criteria of retaining the simulation if FOR mean values were within 0.05 FOR units from the Dufour et al. (2012) sample means was established to determine acceptable simulations during the validation phase. This process was repeated for ten simulations with the inclusion exclusion criteria remaining consistent, all the simulations provided model outputs which were within the inclusion criteria. The outcome of the validation process was confidence that the model could consistently generate hip fracture risk distributions which agreed across simulations. Another strength of the probabilistic model was the agreement between epidemiological studies and the model output. Martel et al. (2020) observed an increase in hip fracture risk with increasing age for older adult males and females which agreed with the work of (Kanis et al. 2002; Jean et al. 2013) see Figure 10. Additionally, Martel et al. (2020) observed a greater hip fracture risk in older adult females, this agreed with the hip fracture literature (Kanis et al. 2002; Leslie 2009; Hopkins et al. 2012; Jean et al. 2013) see **Figure 9** and **Figure 10**. Both Laing (2006), and Laing and Robinovitch (2009) addressed the attenuation of impact force in the presence of safety flooring. Therefore, to consider the effect of safety flooring on hip fracture risk, Martel (2017) added a module to facilitate the estimation of older adult hip fracture risk in the presence of safety flooring (**Figure 8**). This modification generates the expected FOR values for all virtual individuals but also calculates an intervened factor of risk (IFOR) which considers the attenuation of impact force by safety flooring within its calculations. When safety flooring was considered to be part of the fall, Martel (2017) observed a population-wide reduction in hip fracture risk.

The Martel et al. (2020) model, though capable of performing both single and group assessments of fracture risk, possessed one obvious limitation. The model could only estimate hip fracture risk for a population of virtual individuals falling in a homogenous location. Alternatively stated, the Martel et al. (2020) model is insensitive to where a fall occurs within a facility and can only consider falls on one type of flooring. Accordingly, the model did not have the resolution to explore the effects of location specific interventions (e.g., safety flooring). This thesis addressed this limitation by incorporating fall-location capacity, driven by real world data on fall locations from a retirement home.

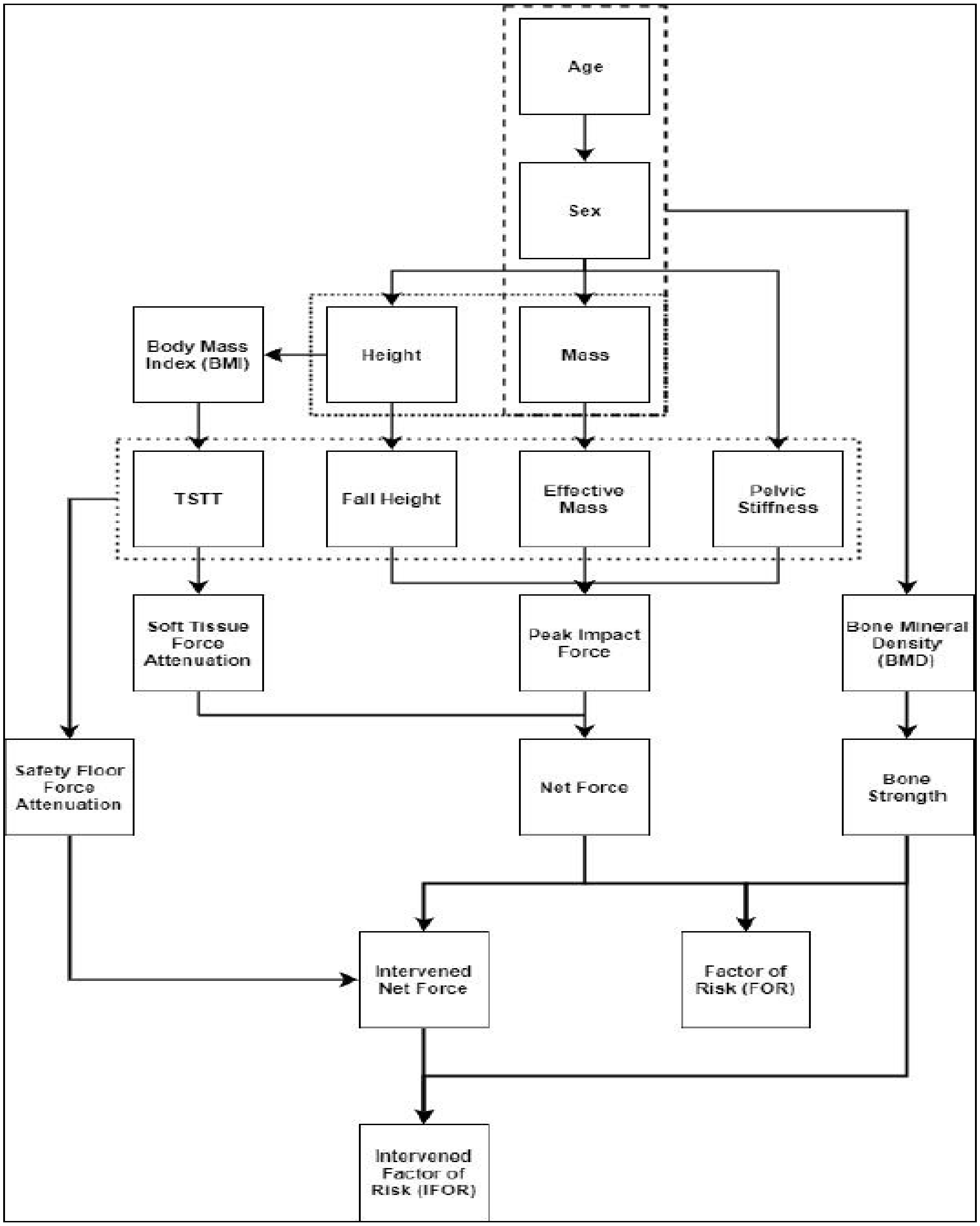

Figure 8: Visualization of the inputs and outputs of the originally modified probabilistic mechanistic model with intermediate variables included. From Development and Application of a Probabilistic/Mechanistic Model to Investigate the influence of Safety flooring on Population-

Level Hip Fracture Risk by D. Martel, 2017, UWSpace. Retrieved 08/20/23 from https://uwspace.uwaterloo.ca/handle/10012/18362. Copyright 2017 by Daniel Martel.

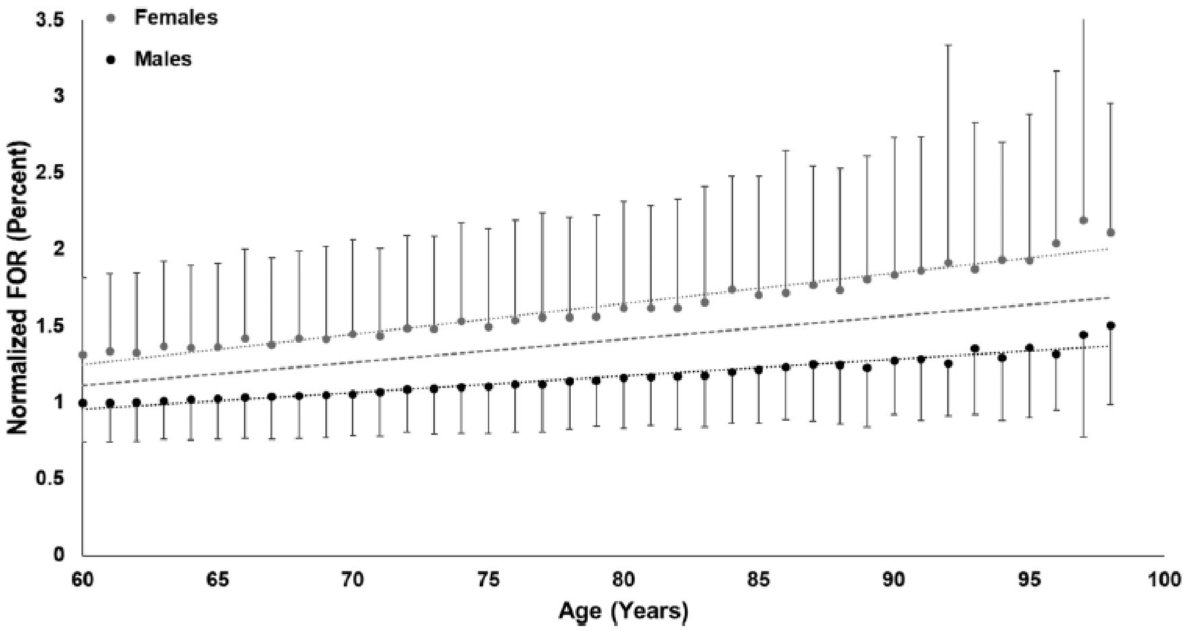

Figure 9: Visualization of the age-related increase in nFOR values for Females (grey) and Males (black). From Predicting population level hip fracture risk: a novel hierarchical model incorporating probabilistic approaches and factor of risk principles by D. Martel, M. Lysy, A. Laing, (2020). Computer Methods in Biomechanics and Biomedical Engineering, 23, 1210. Copyright 2020 by Taylor and Francis.

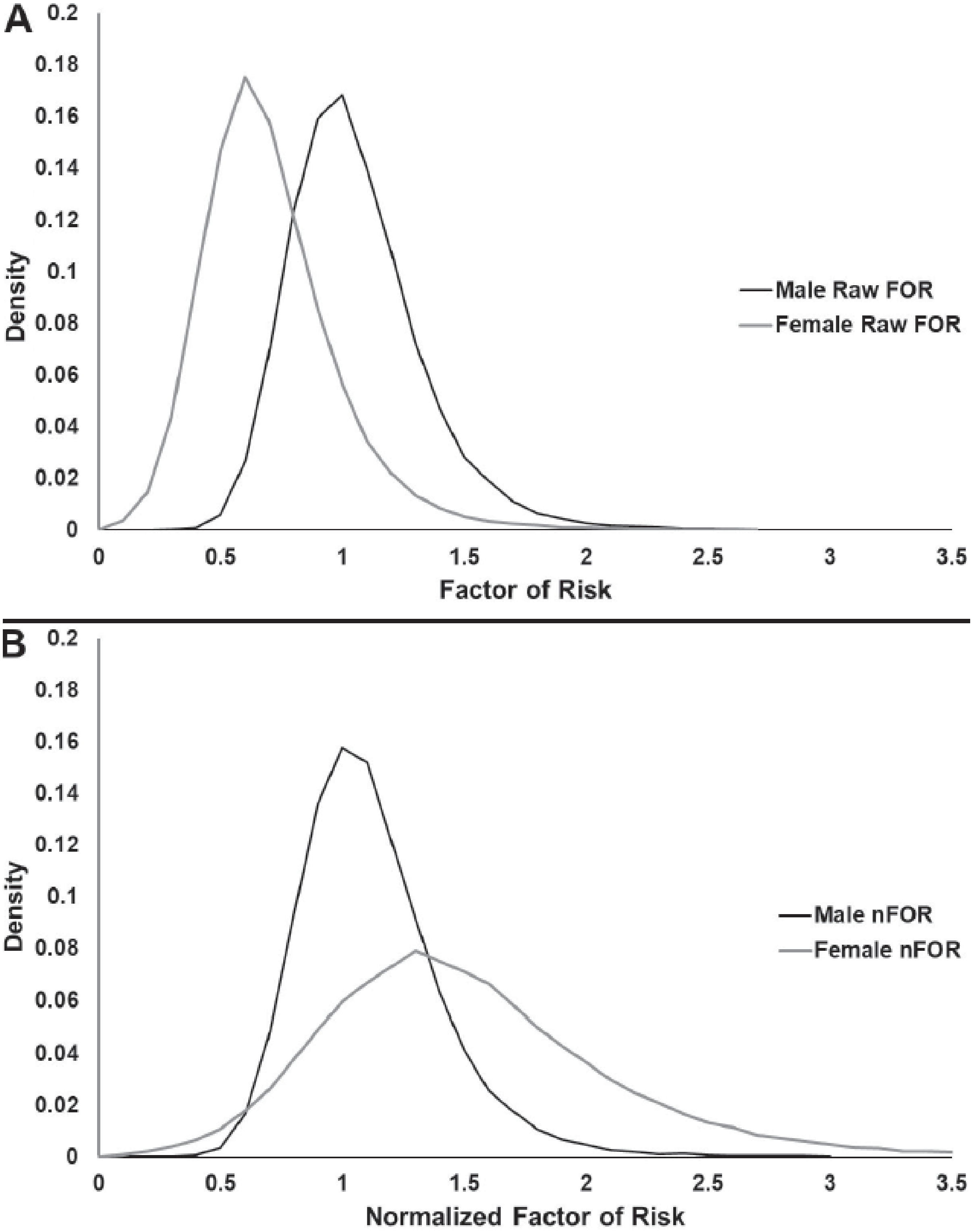
A
Density
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5
2
2.5
3
3.5
Factor of Risk
Male Raw FOR
Female Raw FOR
B
Density
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5
2
2.5
3
3.5
Normalized Factor of Risk
Male nFOR
Female nFOR

Figure 10: Visualization of male (black) and female (grey) probability distributions for A) FOR and B) nFOR. From Predicting population level hip fracture risk: a novel hierarchical model incorporating probabilistic approaches and factor of risk principles by D. Martel, M. Lysy, A. Laing, (2020). Computer Methods in Biomechanics and Biomedical Engineering, 23, 1209. Copyright 2020 by Taylor and Francis.

2.8 Summary of Gaps Within the Literature

From the literature review it was evident that gaps existed within the hip fracture modelling and economics literature. There was no information about whether the Canadian older adult population was representative of an arbitrary older adult subpopulation. If a VI population was generated within the Martel (2017), Martel et al. (2020) model it would have Canadian characteristics and a Canadian estimate for hip fracture risk. These characteristics and the estimated hip fracture risk may have differed from the actual characteristics and hip fracture risk of the subpopulation of interest. Hypothesis 1 attempted to determine if the Canadian population could be used to make inferences about a retirement home population. To achieve this, the simulated input and output estimates of populations having the Canadian and retirement home characteristics were compared to determine if they were statistically the same.

Additionally, the hip fracture model quantified hip fracture risk occurring within a population for only two situations. The first situation is when the entire population is constrained to falling on standard flooring and the second situation is when the entire population is constrained to falling on safety flooring. This was discussed by Martel (2017) and Martel et al. (2020); however, the literature provided no insight into hip fracture risk when the population is unconstrained to falling on a specific type of flooring. The proposed modifications to the existing hip fracture model, which is presented in Chapter 3, attempted to create a hip fracture model capable of addressing this limitation. The modified model was then able to quantify hip fracture risk for the scenario when a subset of the population falls on standard flooring while the remainder falls on safety flooring. This scenario is an attempt at modelling the placement of safety flooring within some but not all rooms of a retirement home and will be facilitated by the work of Cleworth et al. (2021). Furthermore, the work of Cleworth et al. (2021) indicated that most falls occur within the bedroom and bathroom of retirement homes; however, the literature provided no insight into whether placing safety flooring into a location with more falls will reduce the population hip fracture risk compared to other locations with less falls. This gap in the literature was addressed by hypothesis 4. Considering the prohibitive costs of safety flooring, the output of the modified hip fracture model will add to the gaps in the hip fracture modelling literature by increasing its scope of application.

It is unclear whether the hip fracture model could provide expected outputs when applied to a different population. From Martel (2017) and Martel et al. (2020) we know that the model predicted more fractures for older adult women than older adult men. We also know that when the entire population fell on safety flooring there was a reduction in the population hip fracture risk. However, these observations were made with a population having Canadian characteristics. Though we expect to see similar with a population having retirement home characteristics, we have no idea if such expectations will be supported by the model outputs. Hypothesis 2 will attempt to determine if the presence of safety flooring facilitates a reduction in the retirement home population's hip fracture risk. While hypothesis 3 will attempt to determine whether the presence of safety flooring facilitates the sex-related differences in hip fracture risk. In the previous paragraph mention was made about increasing the model's applicability by removing constraints on the type of flooring the simulated population could fall on. Hypothesis 4 further attempted to determine whether the sex-related differences in hip fracture risk persisted in such situations. This information will add to the hip fracture literature by supporting or refuting the generalizability of the model assumptions when applied to different populations.

Finally, no economic evaluation had been conducted which considered the implementation of safety flooring within a Canadian retirement home. The economic evaluations conducted have occurred in Sweden, (Ryen & Svensson, 2016), the United Kingdom, (Latimer et al., 2013), and America, (Zacker & Shea, 1998) respectively. It is likely that differences in hip fracture costs as well as other economic considerations occur which prevent the direct translation of results from these countries to Canada. Additionally, none of the economic evaluations have attempted to consider the influence of safety flooring location on costs and savings. Cleworth et al. (2021) provided the spatial distribution and frequency of falls within Ontario retirement homes which presented a way to consider the influence of safety flooring location on costs and savings. Finally, none of the economic evaluations have attempted to consider the influence of sex on costs and savings. Nikitovic et al. (2013) provided sex-specific one-year direct healthcare costs following a hip fracture, which could be used to determine the influence of sex on costs and savings. Hypotheses 5 and 6 attempted to fill these gaps in the hip fracture literature by leveraging the population level hip fracture quantification of the model to a) determine if safety flooring is an economically viable alternative to standard flooring (independently and partitioned according to sex) and b) quantify the potential savings provided by switching from standard to safety flooring within a Canadian retirement home (independently and partitioned according to sex). This information will add to the literature by providing Canadian specific hip fracture economic information.

2.9 Hypotheses

The following are the hypotheses which guided the progression of this thesis:

1. The populations characteristics of the simulated populations (Age, Sex, Mass, Height, BMI) are the same for simulations run using the Canadian data distribution or the Ontario retirement home data distribution.
2. As a reduction in surface stiffness will mechanistically reduce applied impact force, the implementation of safety flooring everywhere in an Ontario retirement home would reduce the nFOR and number of hip fractures compared to only standard flooring.
3. The implementation of safety flooring within a simulated Ontario retirement home will have a greater reductive effect on the nFOR and subsequently number of hip fractures in simulated males compared to simulated females.
4. The implementation of safety flooring within the bedroom and bathroom will have a greater reductive effect on the nFOR and subsequently number of hip fractures of simulated older adults compared to other locations within a simulated Ontario retirement home.
5. The implementation of safety flooring within a simulated retirement home should lead to a) greater savings (based on costs saved associated with prevented hip fractures) for simulated males compared to simulated females b) a reduced incremental cost effectiveness ratio (ICER) for simulated males compared to simulated females.
6. The implementation of safety flooring within the bedroom/bathroom of an Ontario retirement home should lead to a) greater savings (based on costs saved associated with prevented hip fractures) compared to any other arrangement of safety flooring b) a reduced incremental cost effectiveness ratio (ICER) compared to any other arrangement of safety flooring.

Chapter 3: Methods

The Methods section of this thesis is divided into five separate parts, each linked to the thesis objectives mentioned in the first chapter. The first subdivision of this section will be directed towards assessing data obtained from an Ontario retirement home about the physical characteristics of its older adult populations. This data will include the distribution and descriptive statistics of characteristics such as age, height, mass, and BMI within the Ontario retirement home and will be compared to the same output from the Martel et al. (2020) model based on Canadian population data obtained from Statistics Canada. Comparing the Ontario retirement home data to the Canadian data allowed for a better understanding of how the results of this thesis could be applied to the general Canadian population. The second subdivision of this section will provide a comprehensive explanation of the underlying principles used by Martel et al. (2020) to generate their model output. The third subdivision describes the modifications that were implemented to the Martel et al. (2020) model to allow for hip fracture risk estimation and hip fracture predictions in an Ontario retirement home setting. The fourth subdivision provides an economic assessment of safety flooring in this setting. The fifth subdivision considers how this modified hip fracture model was used to generate the results, with dependent variables explicitly defined. Finally, the sixth subdivision of this section will present the statistical approaches which were used to test the thesis hypotheses.

3.1 Ontario Retirement Home Data Processing

The Martel et al. (2020) model generated a population of one-hundred thousand (100,000) older adults which possessed the distribution characteristics of the Canadian population. An explicit goal of this thesis was to generate a similarly sized population of older adults which possessed the distribution characteristics of an Ontario retirement home. Though, the retirement home older adults are a subset of the Canadian older adult population, it was uncertain if the distribution characteristics were the same. Accordingly, the first action within this thesis included extracting relevant information about the retirement home older adults for comparison to the Canadian population.

A Microsoft Excel spreadsheet was obtained from Schlegel Villages, which contained the age, gender, height, and mass information for 2697 older adults in the retirement home and 1585 older adults who were previously within the retirement home. Ethics approval was obtained from the Office of Research Ethics at the University of Waterloo, Waterloo, Ontario (ORE # 43852 Correlating Physical and Environmental Factors to Body Mass Index in Older Adults) to access this spreadsheet for a secondary analysis of data.

The spreadsheet was transferred into MATLAB (MATLAB R2022a, MathWorks, Natick, Massachusetts, USA) for data processing. The data was saved in an appropriate data structure, subsequently, all missing and zero heights, weights and ages were assigned a value of NaN. All entries with NaN age values and empty strings for gender were removed. Next, entries with age values less than sixty (< 60) or greater than one hundred (> 100) were removed (N = 3813). The remaining entries were partitioned according to sex, generating female and male retirement home data structures (F and M). The sizes of the datasets F and M were recorded (F = 2484, M = 1329) to determine the number of older adult females and older adult males respectively. The means and standard deviations of F & M were obtained for mass and height separately. Female entries with masses outside of the range [mean ± 3SD] were excluded from F and male entries with masses outside of the range [mean ± 3SD] were excluded from M to obtain mass filtered datasets (F1 and M1). F1 = 62.83 ± 16.13 kg, M1 = 76.49 ± 17.73 kg, F1+M1 = 67.51 ± 17.91 kg. Female entries with heights outside of the range [mean ± 3SD] were excluded from F and male entries with heights outside of the range [mean ± 3SD] were excluded from M to obtain height filtered datasets (F2 and M2). F2 = 1.58 ± 0.08 m, M2 = 1.72 ± 0.10 m, F2+M2 = 1.62 ± 0.11 m. The means and standard deviations of F1 and M1 were used to determine the sex-specific distributions of retirement home mass. The means and standard deviations of F2 and M2 were used to determine the sex-specific distributions of retirement home heights. The number of entries in F and M corresponding to each age from 60 to 100 inclusive were recorded to generate sex-specific age frequency plots. A decision was made to incorporate the relationship between weight and height into the model using regression see (Appendix D), therefore the distributions F1 and M1 as well as F2 and M2 were not used for any further analyses. However, the number of older adult females and males obtained as the number of entries in F and M as well as the sex proportions see (Table E 2 in Appendix E) were subsequently used within the probabilistic model to generate older adults with retirement home characteristics. Male and female heights were determined using regression equations depending on age and sex, while male and female masses were determined using regression equations depending on age, sex, and height. When these regression equations were integrated into the model flow, they determined height and mass due to the values of an older adult's age and sex in the case of height and age, sex, and mass in the case of mass.

The age frequencies, sex proportions at each age, mass, height, and BMI distributions were known from the Canadian population data as generated within the virtual individual generation module in Martel et al (2020). Accordingly, to address the first hypothesis comparisons were made between these distributions in the Martel et al. (2020) mode and the updated model from this thesis to determine whether there were significant differences between the Ontario retirement home and Canadian older adult populations with respect to age, sex, mass, height, and BMI distributions **Figure 11**.

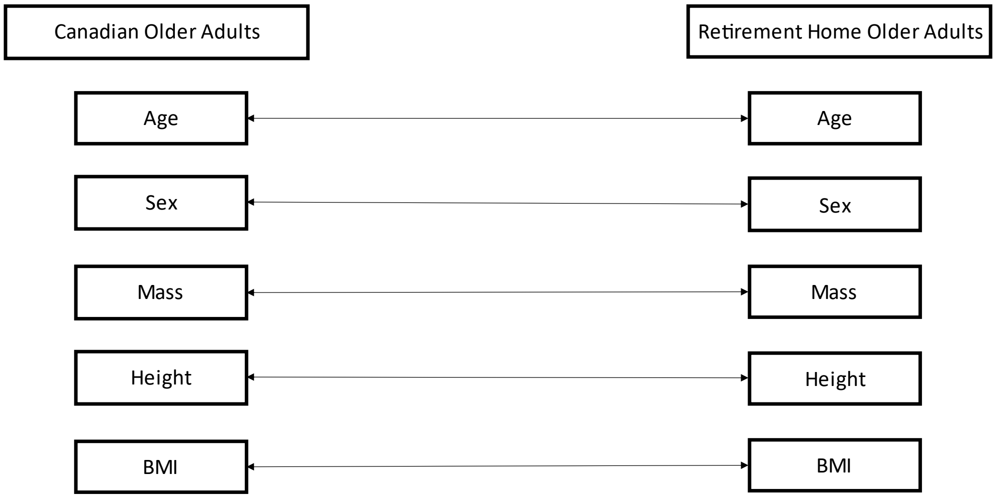

Figure 11: Visualization of the characteristics which are compared between the Canadian and Ontario Retirement Home Older Adult Populations

3.2 Modifications to the Probabilistic Mechanistic Model

The second objective for this thesis included two modifications to the probabilistic mechanistic model, which aimed to improve the predictive capabilities of the program. The model was used to quantify hip fracture risk for a group of virtual individuals, all of whom were considered to fall on standard flooring, or all of whom are considered to fall on safety flooring. After modifications the model estimated hip fracture risk for a group of virtual individuals within an Ontario retirement home with variable placement of safety and standard flooring.

The first modification was the creation of a module which generated an additional variable for the virtual individual which acted as a location variable. This fall location variable localized the virtual individuals within rooms consistent with observed fall data as presented in Cleworth et al. (2021). This modification facilitated the representation of falls within a retirement home in the context of the probabilistic model.

The second modification added a module which incorporated a second location variable called the safety flooring location variable to specify the location of safety flooring within a retirement home. This module extracted information about the location of virtual individual falls using the fall location variable and determined if safety flooring was present at the fall location using the safety flooring location variable. If a virtual individual fell within a room with standard flooring, then FOR values were calculated. However, if a virtual individual fell within a room with safety flooring, then iFOR were calculated **Figure 12**. These modifications exploited the predictive capabilities of the probabilistic mechanistic model to estimate the number of simulated older adults likely to suffer from a hip fracture within an Ontario retirement home with variable placement of safety and standard flooring.

Fall data by Cleworth et al. (2021) representing a four-year period within a group of six retirement home provided the following spatial distribution of falls in older adults: Bedrooms (62.8%), Bathroom (13.5%), Other (8.2%), Walkway (6.3%), Lounge (5.8%), Dining Room (3.0%) and Activity Room (0.4%). The number of falls varied by room with the predominant number of falls occurring in the bedrooms of older adults. The trend of observing higher numbers of older adult falls in the bedroom remained constant even when considering differences between the level of care provided to them, Cleworth et al. (2021).

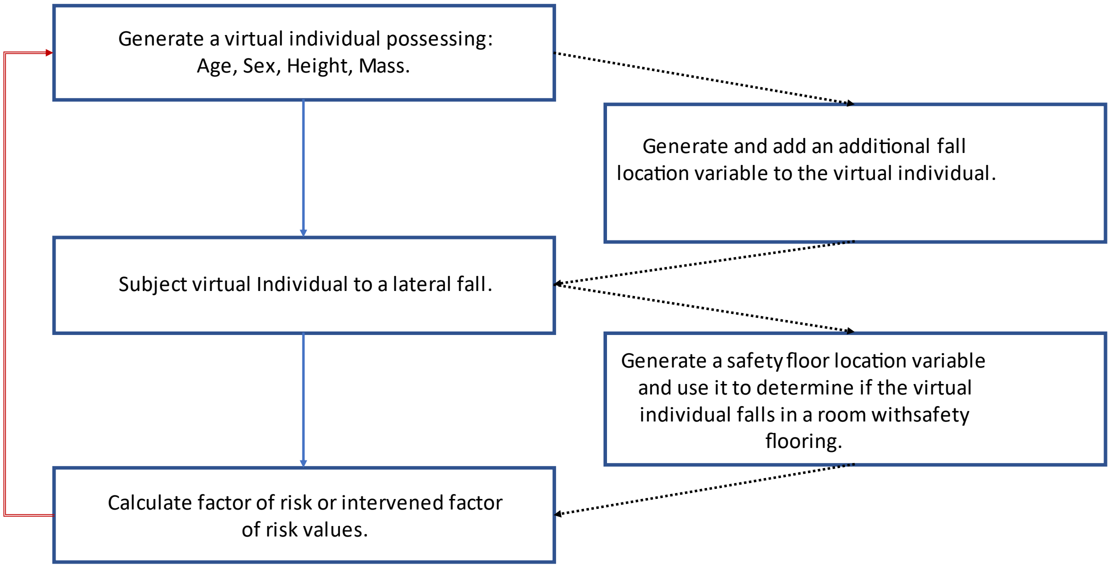

Figure 12: Visualization summarizing the actions performed by the original probabilistic mechanistic model Martel et al. (2020) (blue arrows) and by the modified probabilistic mechanistic model (black arrows).

3.2.1 Fall location variable.

Cleworth et al. (2021) presented seven fall locations from within the six older adult care facilities: Bedrooms (62.8%), Bathroom (13.5%), Other (8.2%), Walkway (6.3%), Lounge (5.8%), Dining Room (3.0%) and Activity Room (0.4%). Subsequently the virtual individual location modification included a unique representation for each of the seven locations. The unique representation was then added as an additional variable to the virtual individual and specified the room in which the virtual individual fell.

To achieve this a uniform (0,1) random variable R was generated for each virtual individual and dependent on the value of the random variable a fall location variable was assigned. The fall location variable was a 7-digit binary variable. Each room was represented by a position in the 7-digit number, the value of each digit was either zero (0) or one (1) where 0 corresponded to the virtual individual being absent from a room and 1 corresponded to the virtual individual being present within a room. Since a virtual individual exists in exactly one room each 7-digit number consisted of six zeros and a solitary one.

The following describes the random variable generated for each virtual individual and the criteria for assigning a room to the virtual individual:

$$R \sim U(0,1) \tag{3.1}$$

R was defined to be a uniform (0,1) random variable which gave an equal probability of R taking any numerical value between zero (0) and one (1).

Table 1: Representation of the assignment criteria used to generate a fall location variable.

Location	Assignment Criteria	Fall location variable
Activity Room	$0.000 \leq R \leq 0.004$	0000001
Dining Room	$0.004 < R \leq 0.034$	0000010
Lounge	$0.034 < R \leq 0.092$	0000100
Walkway	$0.092 < R \leq 0.155$	0001000
Other	$0.155 < R \leq 0.237$	0010000
Bathroom	$0.237 < R \leq 0.372$	0100000
Bedroom	$0.372 < R \leq 1.000$	1000000

Table 1 shows the assignment criteria used to generate the fall location variable while **Figure 13** outlines the process to assign a fall location variable to a virtual individual. A uniform (0,1) random variable R was generated for each virtual individual. The value of R specified a 7-digit number corresponding to a location. As an example, if R had a value greater than 0.372 but less than 1 the associated 7-digit number was equal to 1000000 which located the virtual individual within the bedroom. This process was repeated for all the virtual individuals generated within the simulation. When implemented into the program this modification created virtual individuals which fell in rooms with the same proportion as observed from the Ontario retirement home.

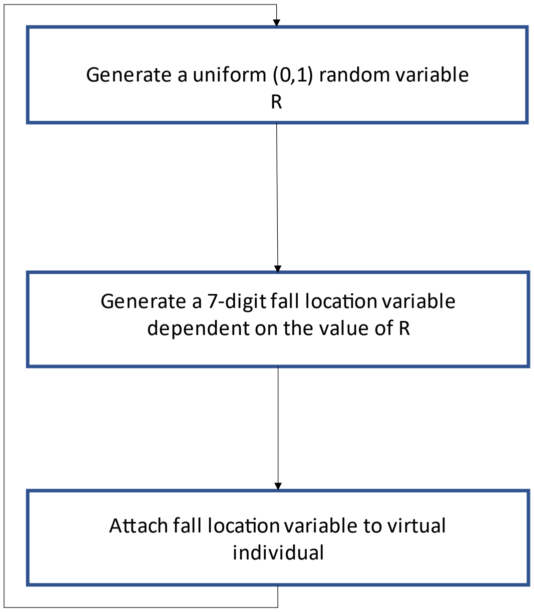

Figure 13: Visualization of the process to assign a fall location variable to a virtual individual.

3.2.2 Safety Flooring Location Variable

The second modification added a location variable which represented the location of the safety flooring within the retirement home. Coupled with the retirement home locations presented in Cleworth et al. (2021) the safety flooring location variable specified the location of safety flooring within the Ontario retirement home and could be varied to represent any arbitrary combination of safety and standard flooring. Coupled with the fall location variable the model would provide either a FOR or iFOR value to quantify hip fracture risk. FOR values were provided when the virtual individual fell on standard flooring and iFOR values were provided when the virtual individual fell on safety flooring. This modification embraces the differential effect of floor type on older adult hip fracture risk.

The modification to the model consisted of creating a module with a safety flooring location variable and comparison and decision-making capabilities. The floor was a dichotomous variable (safety or standard) and was in seven locations, this information was encoded with a 7-digit binary number. Each position within the safety flooring location variable was assigned to a particular room with a value of one (1) indicating the presence of safety flooring and a value of zero (0) indicating the presence of standard flooring **Table 2**. A comparison between the safety floor location variable and the fall location variable was performed within the safety floor location module. **Figure 14** provides a visualization of the comparison and decision-making process which occurred within the module.

Once the safety flooring location variable had been specified, the modified model needed to determine if a virtual individual was in a location with safety flooring or standard flooring. To determine the type of flooring on which a fall occurred a comparison between the safety flooring location variable and the fall location variable was made. There were two possible outcomes for this comparison. The fall location variable and the safety flooring location variable possessed a one (1) at the same position in which case the virtual individual had fallen in a location with safety flooring. The fall location variable and the safety flooring location variable did not possess a one (1) at the same position, in this case the virtual individual had fallen in a location with standard flooring. With the first outcome the iFOR was the appropriate output while with the second outcome the FOR was the appropriate output.

It should be noted that, within the safety flooring module the model can perform hip fracture assessments for the population of older adults for any of the 128 possible combinations of safety and standard flooring. Therefore, one or more combinations of safety and standard flooring can be considered for a single population during one simulation. For this thesis, the model only considered the change in hip fracture risk for a single population, where the location of an older adult is fixed but the presence of safety flooring is variable. This minimizes inter population variability. However, if different populations are to be considered then the model would need to be run again i.e., a new simulation performed. In this regard it is possible to consider the effect of safety flooring placement on hip fracture risk in different populations as well. The safety flooring module can accept as an input a matrix consisting of one SFLV (specified arrangement of safety and standard flooring) or a matrix consisting of multiple SFLVs (specified arrangements of safety and standard flooring). Depending on the choice of SFLV inputs into the module the output is also a matrix with each column corresponding to the nFOR values of the population of older adult for one SFLV (arrangement of safety and standard flooring). Therefore, in section 3.4 when multiple SFLVs are mentioned they correspond to one matrix containing multiple SFLVs being input into the module and the population nFORs are recorded from each corresponding column within the output matrix.

Table 2: Representation of safety floor locations using the safety flooring location variable.

Location of Safety Flooring	**Safety Floor Location Variable**
Activity Room	0000001
Dining Room	0000010
Lounge	0000100
Walkway	0001000
Other	0010000
Bathroom	0100000
Bedroom	1000000
Bedroom + Bathroom	1100000
No Rooms	0000000
All Rooms	1111111

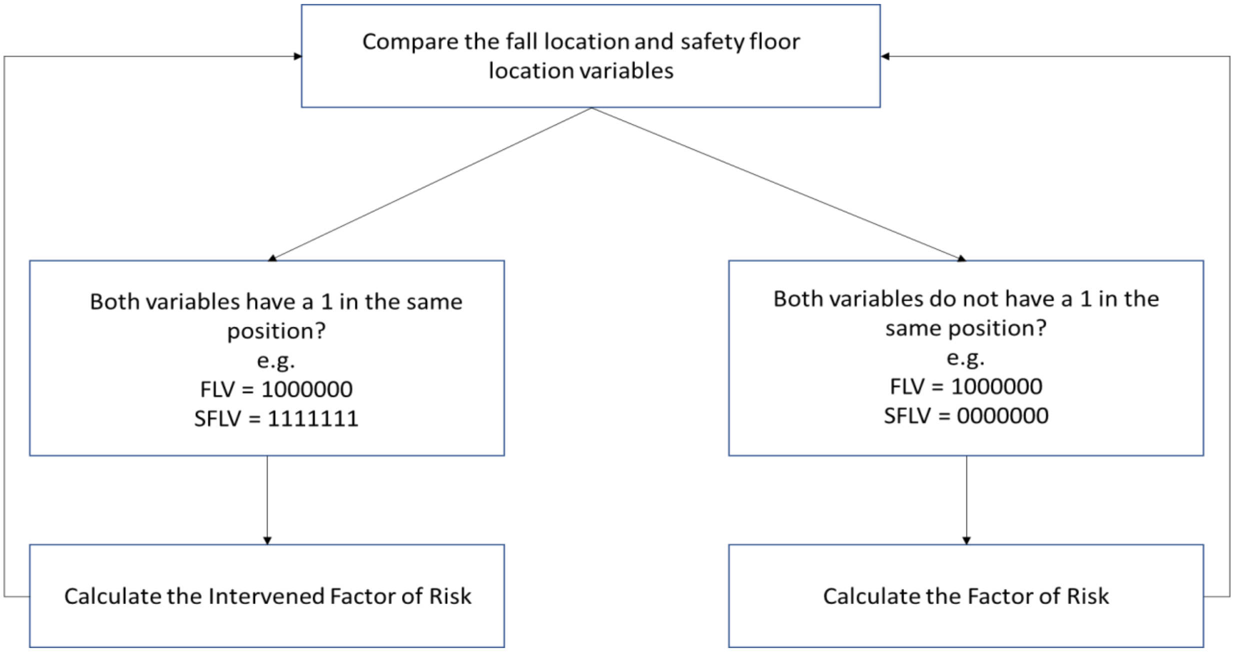

Figure 14: Visualization of the process for determining whether a factor of risk (FOR) or intervened factor of risk (iFOR) is assigned to the virtual individual.

Figure 15 presents the updated flow of the probabilistic mechanistic model. The fall location module with its bold outline generated and added a fall location variable to the virtual individual within the simulation. This fall location variable then became an input into the safety floor location module. The safety floor location module also with a bold outline compared the safety floor location variable and the fall location variable ultimately deciding whether FOR or iFOR values were assigned to the virtual individual.

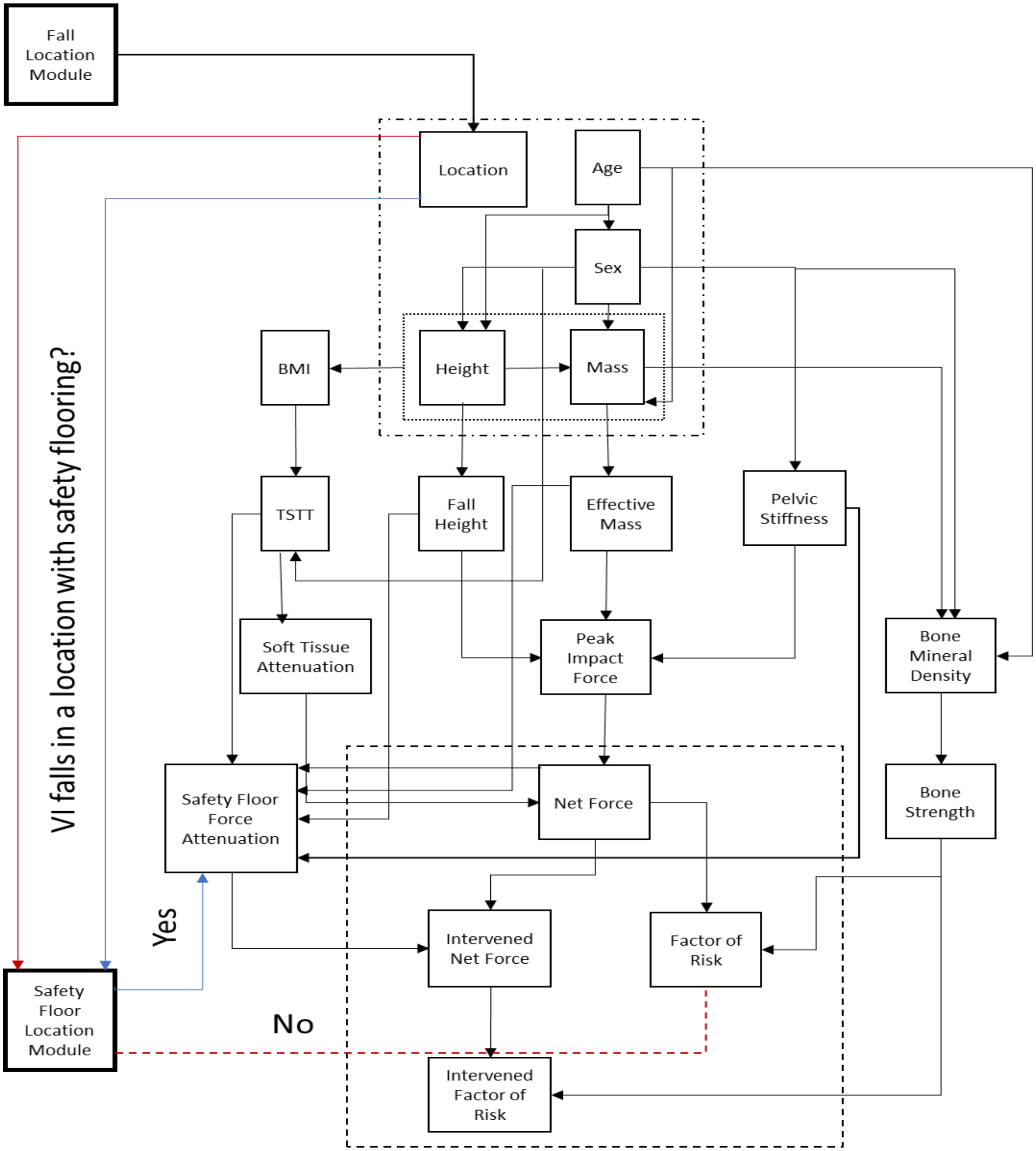

Figure 15: Visualization of the modifications to the hip fracture model. The orange (FOR) and blue (IFOR) connections highlight the role of the safety floor location module in determining the final model output for each virtual individual. The safety floor location module is activated and selects intervened factor of risk values if the VI falls in a location with safety flooring.

3.3 Hip Fracture: Economic Assessment

The final component of this thesis involved an economic evaluation, to determine the effectiveness of using safety flooring to reduce the occurrence of hip fractures in an Ontario retirement home. The effectiveness of safety flooring was determined in two ways. The first quantified the savings experienced due to an expected reduction in older adult hip fractures, using age and sex-specific one-year attributable post fracture expenditures presented by Nikitovic et al. (2013). The second considered the reduction in older adult hip fractures mediated by safety flooring when compared to the baseline condition of standard flooring and the incremental cost to place safety flooring as an alternative to standard flooring.

3.3.1 Hip Fracture: Savings

Attributing a patient-specific monetary value to hip fractures is challenging as multiple factors such as the length of a hospital stay, and severity of the fracture may interact to influence the expenditure for unique cases. However, Nikitovic et al. (2013) estimated the average one-year attributable post fracture expenditure for older adult females and males partitioned according to their ages (See **Table 3**). If safety flooring reduced the number of hip fractures suffered by older adults, then the difference in hip fractures occurring would be equivalent to a reduction in the hip fracture expenditure. Subsequently, these were reasonable first estimates to include in an economic evaluation for the purpose of estimating safety flooring mediated savings.

The first step towards quantifying savings due to a reduction in the number of hip fractures mediated by safety flooring (for a specific arrangement of safety and standard flooring) was to determine the difference between the total number of fractures occurring for the specific arrangement of safety and standard flooring and the baseline where standard flooring was located everywhere. This difference was the total number of hip fractures prevented.

$$\Delta_{fx} = N_b - N_h \qquad (\mathbf{3.2})$$

Where Δ_{fx} = The total number of hip fractures prevented. N_b = The number of hip fractures estimated with the baseline of standard flooring present everywhere within the model and N_h= The number of hip fractures estimated for the specific arrangement of safety and standard flooring. The second step towards quantifying savings was determined by multiplying the number of hip fractures prevented by their associated attributable one-year hip fracture cost as presented by Nikitovic et al.

(2013). The following equation represents the total savings associated with the estimated reduction in hip fractures mediated by safety flooring.

$$S_{fx} = \Delta_{fx} * C_{fx} \tag{3.3}$$

Where S_{fx} = Total savings for hip fractures prevented, Δ_{fx} = Total number of hip fractures prevented, C_{fx} = Cost of one hip fractures prevented. Equations 3.2 and 3.3 are simplifications of the required calculations since the total number of hip fractures prevented can be decomposed into the sex-specific hip fractures prevented and the sex specific number of hip fractures prevented can further be decomposed into the number of age-specific hip fractures prevented (See **Figure 16**). These sex and age-specific decompositions of the number of hip fractures mirror the decomposition of attributable one-year costs presented by Nikitovic et al. (2013).

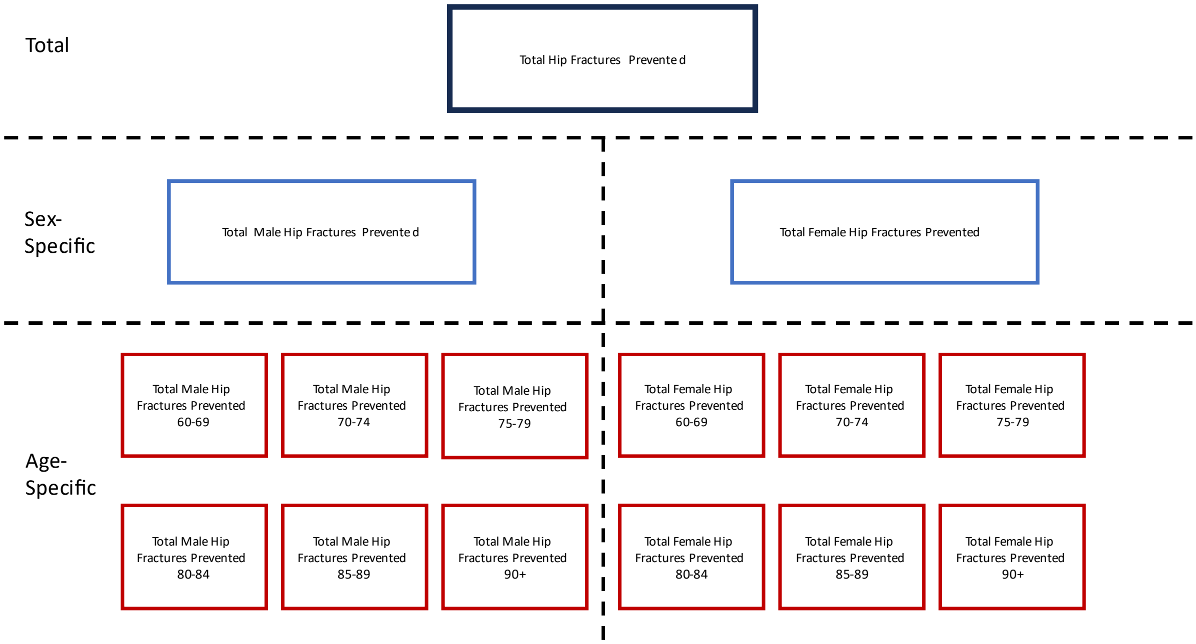

Figure 16: Figure showing the decomposition of the total (black) number of hip fractures prevented by safety flooring into sex-specific (blue) and age-specific (red) quantities.

Therefore, equations 3.2 and 3.3 become equations 3.4 and 3.5. Where Δ_{fx}^{as} = total number of hip fractures prevented for a specified age group (a) and sex (s) and C_{fx}^{as} = directly attributable cost of hip fracture for a specified age group (a) and sex (s).

$$\Delta_{fx} = \sum_{s}\sum_{a}\left(\Delta_{fx}^{as}\right) \qquad \mathbf{(3.4)}$$

$$S_{fx} = \sum_{s}\sum_{a}\left(\Delta_{fx}^{as} * C_{fx}^{as}\right) \qquad \mathbf{(3.5)}$$

Table 3: 1-Year directly attributable hip fracture costs for Canadian older adults partitioned according to sex and age based on Nikitovic et al. (2013). These values were incorporated into the estimated monetary cost savings for each hip fracture prevented by safety flooring.

Age	**Female Costs ($)**	**Male Costs ($)**
All	36,929	39,479
66-69	38,866	39,852
70-74	37,877	42,878
75-79	38,487	42,378
80-84	38,004	39,553
85-89	37,034	37,809
90+	33,414	33,972

Note. Adapted from Table 3 in Direct health-care costs attributed to hip fractures among seniors: A matched cohort study. M. Nikitovic, W. Wodchis, M. Krahn, and S. Cadarette, (2013). Osteoporosis International, 24(2), p664. Copyright 2013 by Springer Nature.

3.3.2 Safety Flooring: Costs

Since the health care monetary savings associated with hip fractures prevented represent savings for governmental healthcare systems, the previous figures highlighted the benefits of using safety flooring when considered from a societal perspective. However, this thesis also considered an alternative approach which incorporated the cost of a health intervention (i.e., the estimated cost per hip fracture prevented).

This analysis of safety flooring related benefits was facilitated by considering the estimated incremental cost to place safety flooring within an Ontario retirement home and the consequences of placing safety flooring i.e., a reduction in the number of hip fractures. The cost per hip fracture prevented value from this analysis is the incremental cost effectiveness ratio (ICER). This approach is usually considered within a cost effectiveness analysis. In this context, the cost (for each arrangement of safety and standard flooring) was simply the estimated incremental difference (Δ_c) to place safety flooring instead of standard flooring into an Ontario retirement home. In contrast the consequences (for each arrangement of safety and standard flooring) were the estimated number of hip fractures prevented by safety flooring (Δ_{fx}). There are a variety of commercially available safety flooring systems and a similar range of costs associated with materials and installations. Based on discussions with safety flooring manufacturers and retirement home stakeholders where safety flooring was recently implemented (Kalra et al., 2023), the incremental cost of safety flooring (relative to standard flooring) considered in this thesis was \$11.70 per square foot comprised of \$7.50 and \$4.20 per square foot for materials and labour respectively. To determine the incremental cost of placing safety flooring in an Ontario retirement home, the surface area of a representative Ontario retirement home was estimated using its floor plan (data provided by a residential care industry partner; see **Table 4**). The floor plan indicated that 221 rooms were present within the retirement home. Accordingly, towards representing the costs associated with intervening on the 100,000 older adults simulated in this thesis, all cost values were multiplied by 100000/221 - (i.e., a factor of 452.5). **Table 4** presents the estimated surface areas of different rooms/locations within an Ontario retirement home – these data were used to estimate the incremental cost to implement safety flooring according to the following equations:

$$SA_t = \sum_{l} SA_l \qquad (3.6)$$

$$\Delta_c = \sum_l \left(\Delta_f * SA_l\right) \tag{3.7}$$

Where SA_l is the total estimated area of the room location as identified by Cleworth et al. (2021), SA_t is the total estimated surface area of the retirement home obtained from summing over all the locations. Δ_c is the total incremental cost of placing safety flooring within the retirement home and Δ_f is the incremental cost of safety flooring per square foot. The incremental cost of placing safety flooring within any location Δ_l was simply the following.

$$\Delta_l = \Delta_f * SA_l \tag{3.8}$$

Once the incremental cost of placing safety flooring (Δ_c) and the estimated reduction in hip fractures due to safety flooring (Δ_{fx}) were known, the ICER was calculated using the following equation:

$$ICER = \frac{\Delta_c}{\Delta_{fx}} \tag{3.9}$$

3.4 Model Application

The modifications which were presented in Section 3.2 facilitated the estimation of hip fracture risk within a simulated Ontario retirement home. The original model presented by Martel (2017) and Martel et al. (2020) generated a population of Canadian virtual individuals (VIs), subjected each VI to a fall on either standard or safety flooring, and then provided population-level FOR distributions. The updated model presented within this thesis generated a population of retirement home VIs, subjected each VI to a fall, and then provided population-level FOR distributions for specific arrangements of safety and standard flooring within a retirement home facility. The FOR distributions provided a simple quantification tool to estimate hip fracture risk. When coupled with sex-specific FOR injury criterion values included in Martel (2017) and Martel et al. (2020) they allowed for estimates to be made about the number of hip fractures occurring within the generated population. This section will indicate how both the original model presented by Martel (2017) and Martel et al. (2020) and the updated model presented in this thesis were applied to address the hypotheses. All FOR values which were less than zero were set to zero within the model.

It should be noted that in the model application phase to determine a population with retirement home characteristics the model was run exactly once. Since the basis of the model was the probabilistic mechanistic hip fracture model presented in Martel (2017) which was tested for stability, there was confidence that the model output would remain 'stable' across multiple trials. By remaining stable, the means and standard deviations (of the model outputs) are expected to only differ minimally if another simulation generating a new population is run. Therefore, to address the hypotheses of this this thesis the results of one simulation of the updated model was used to make comparisons to the output of one simulation of the Martel (2017), Martel et al. (2020) model.

Table 4: Table of estimated retirement home surface area and net cost of laying safety flooring. Column with N = 221 corresponds to the costs estimated for the retirement home with 221 rooms, Column with N = 100,000 corresponds to the scaled-up costs estimated for the entire simulated population.

Location	Area (m^2)	Area (ft^2)	Cost ($) (N =221)	Cost ($) (N =100000)
Nowhere (Reference)				
Activity Room	27.78	299.06	3500	1562080
Dining Room	800.17	8612.92	100772	44987129
Lounge	326.57	3515.18	41128	18360521
Walkway	2240.81	24119.83	282202	125983035
Other	1438.00	15478.49	181099	80847477
Bathrooms	2845.03	30623.64	358297	159953846
Bedrooms	13649.48	146921.74	1718985	767403746
Bedrooms & Bathrooms	16494.50	177545.38	2077281	927357591
Everywhere	21001.26	226055.69	2644852	1180737310

3.4.1 Canadian vs Ontario Retirement Home Older Adult Comparison

To determine if the Ontario retirement home was a representative sample of the Canadian population. The original model presented in Martel et al. (2020) was run once to generate a population of 100,000 VIs with Canadian characteristics. In what follows this Canadian population obtained from running the Martel et al. (2020) model is referred to as C1. The male and female proportions, age distributions, mass distributions, height distributions and BMI distributions of C1 were saved for further analysis. Next the updated model presented in this thesis was run once to generate a population of 100,000 VIs with Ontario retirement home characteristics. In what follows this retirement home population obtained from running the updated model is referred to as R1. The male/female proportions, male/female ages, male/female masses, male/female heights, and male/female BMI distributions of R1 were saved for further analysis. These distributions (for C1 and R1) were saved as .csv files in Microsoft Excel and then transferred to the R statistical programming language (R Core Team, 2022) for statistical analysis. The proportions of female and male older adults (for both C1 and R1) were manually transmitted to the R statistical programming language (R Core Team, 2022) for statistical analysis.

3.4.2 Effect of Safety Flooring on Overall Hip Fracture Risk

To determine the effect of safety flooring (everywhere vs nowhere) on the Ontario retirement home's older adults' hip fracture risk, nFOR distributions from the updated model (R1) were used. All VIs were assigned fall location variables (FLVs) within the updated model which were then compared to SFLVs of 0000000 and 1111111 within the safety floor location model. These SFLVs simulated the installation of standard flooring everywhere (0000000) and safety flooring everywhere (1111111). The safety floor location module then outputs the appropriate FOR and nFOR distributions for older adult falls on standard flooring only and safety flooring only. These distributions (for R1) were saved as .csv files in Microsoft Excel and then transferred to the R statistical programming language (R Core Team, 2022) for statistical analysis. Further, the sex-specific number of VI's with nFOR values ≥ 1 was determined to generate the number of hip fractures estimated by the FOR principle (see Figure 10). The hip fracture estimates were manually transmitted to the R statistical programming language (R Core Team, 2022) for statistical analysis.

3.4.3 Effect of Floor Location on Hip Fracture Risk

To determine the effect of safety floor location on the Ontario retirement home's older adults' hip fracture risk, nFOR distributions from the updated model (R1) were used. SFLVs of 0000000, 0000001, 0000010, 0000100, 0001000, 0010000, 0100000, 1000000, 1111111, and 1100000 corresponding to i) safety flooring nowhere within the facility; ii) only in the activity room; iii) only in the dining room; iv) only in the lounge; v) only in the walkway; vi) only in the 'other' rooms; vii) only in the bathroom; viii) only in the bedroom; ix) safety flooring everywhere; x) only in the bedroom and bathroom. These SFLVs simulated the installation of safety flooring into each floor location condition. The safety floor location module then output each location's FOR and nFOR distributions These distributions (for R1) were saved as .csv files in Microsoft Excel and then transferred to the R statistical programming language (R Core Team, 2022) for statistical analysis. Additionally, the location-specific number of VI's with nFOR values ≥1 was determined to generate the number of hip fractures estimated by the FOR principle. The hip fracture estimates were manually transferred to the R statistical programming language (R Core Team, 2022) for statistical analysis.

3.4.4 Effect of Sex on Hip Fracture Risk

To determine the effect of safety floor location on the Ontario retirement home's older adults' hip fracture risk the same nFOR distributions from 3.4.3 were used i.e. (R1). The location-specific number of VI's with nFOR values ≥1 was determined and decomposed to generate the number of sex-specific hip fractures estimated by the FOR principle. The hip fracture estimates were manually transferred to the R statistical programming language (R Core Team, 2022) for statistical analysis.

3.4.5 Effect of Sex on Safety Flooring Mediated Savings and ICER

3.4.5.1 Sex-Specific Safety Flooring Mediated Savings

To determine the influence which sex had on the safety flooring mediated savings the updated model was run twice with a specific set of parameters to generate two unisex (female only and male only) populations of Ontario retirement home older adults each with 100,000 VIs. In what follows the female only retirement home population obtained from running the updated model is referred to as RF1, while the male only retirement home population obtained from running the updated model is referred to as RM1. SFLVs of 0000000, 0000001, 0000010, 0000100, 0001000, 0010000, 0100000, 1000000, 1111111, and 1100000 corresponding to i) safety flooring nowhere within the facility; ii) only in the activity room; iii) only in the dining room; iv) only in the lounge; v) only in the walkway; vi) only in the 'other' rooms; vii) only in the bathroom; viii) only in the bedroom; ix) safety flooring everywhere; x) only in the bedroom and bathroom, were used within the safety floor location module to obtain each location's unisex nFOR distributions. This process was performed on both RF1 and RM1 i.e., (The female only population's nFOR was obtained for each of the specified location and the same was done for the male only population's nFOR. The nFOR for the same population was determined at each location i.e., (the same population located in the same locations were subjected to falls where the only change was the location of safety flooring). The location-specific number of VI's (for both RF1 and RM1) with nFOR values ≥1 was determined to generate the location-specific number of hip fractures estimated by the FOR principle. Custom code was written in MATLAB (MATLAB R2022a, MathWorks, Natick, Massachusetts, USA) to calculate the savings mediated by hip fracture reductions using equations 3.4 and 3.5 and **Table 3**.

3.4.5.2 Sex-Specific Safety Flooring ICER.

To determine the influence which sex had on the ICER the nFOR distributions from 3.4.5.1 corresponding to both (RF1 And RM1) were used. Additionally, custom code was written in MATLAB (MATLAB R2022a, MathWorks, Natick, Massachusetts, USA) to calculate the sex-specific ICERs for each location using equations 3.6-3.9 and **Table 4**.

3.4.6 Effect of Location on Safety Flooring Mediated Savings and ICER.

3.4.6.1 Location-Specific Safety Flooring Mediated Savings.

To determine the influence which the location of safety flooring had on the safety flooring mediated savings the nFOR distributions provided by the updated model from section 3.4.2 i.e., (R1) were used. SFLVs of 0000000, 0000001, 0000010, 0000100, 0001000, 0010000, 0100000, 1000000, 1111111, and 1100000 corresponding to i) safety flooring nowhere within the facility; ii) only in the activity room; iii) only in the dining room; iv) only in the lounge; v) only in the walkway; vi) only in the 'other' rooms; vii) only in the bathroom; viii) only in the bedroom; ix) safety flooring everywhere; x) only in the bedroom and bathroom, were used within the safety floor location module to obtain each location's sex-specific nFOR distributions. The sex-specific number of VI's (for each location) with nFOR values ≥1 was determined and summed to generate the location-specific number of hip fractures estimated by the FOR principle. Custom code was written in MATLAB (MATLAB R2022a, MathWorks, Natick, Massachusetts, USA) to calculate the savings mediated by hip fracture reductions using equations 3.4 and 3.5 and **Table 3**.

3.4.6.2 Location-Specific Safety Flooring ICER

To determine the influence which the location of safety flooring had on the ICER when implementing safety flooring the nFOR distributions provided by the updated model from 3.4.2 i.e., (R1) were used. Additionally, custom code was written in MATLAB (MATLAB R2022a, MathWorks, Natick, Massachusetts, USA) to calculate the location-specific ICERs for each location using equations 3.6-3.9 and **Table 4**.

3.5 Statistical Analysis

To test the hypotheses associated with this thesis a set of statistical analyses were performed in the R statistical programming language (R Core Team, 2022) using the rstatix package, Kassambra (2023). The statistical analyses were guided by the characteristics of the data obtained as well as the specific questions which constitute the hypothesis. A summary of the following is included in **Table 5**.

The first hypothesis posited that the characteristics of the Ontario retirement home population and the Canadian population would be the same. The data associated with this hypothesis were the simulated distributions for age, sex, mass, height, and BMI. Age, height, mass, and BMI were continuous variables, subsequently to determine if the distributions obtained from both populations were the same a two-tailed T-test was employed. Sex was considered to be a proportion. Therefore, to determine if the proportion was the same across both populations a two-proportion Z-test was employed. In both cases an α value of 0.05 was used to determine significance.

The second hypothesis posited that since safety flooring reduced the loads experienced at the hip, the presence of safety flooring within the simulated retirement home would contribute to a reduction in the nFOR and subsequently number of hip fractures. The variable associated with this hypothesis was the nFOR distributions of the simulated population when there was standard flooring everywhere and safety flooring everywhere. Since the nFOR was a continuous variable, a one-tailed paired T-test was employed to test the hypothesis that the nFOR distribution associated with safety flooring was significantly less than the nFOR distribution associated with standard flooring. An α value of 0.05 was used to determine significance. The number of hip fractures were considered as a proportion. Therefore, to determine if the proportion of hip fractures occurring with safety flooring was significantly less than the number of hip fractures occurring with standard flooring the two-proportion Z-test was used. An α value of 0.05 was used to determine significance.

The third hypothesis posited that the presence of safety flooring within the simulated retirement home would have a larger reductive effect on the nFOR and number of hip fractures in older adult males when compared to older adult females. The variable associated with this hypothesis was the nFOR of the simulated populations for the selected arrangements of safety flooring. Since the nFOR was a continuous variable dependent on two factors (Sex and Safety flooring location) a two-way mixed measure Analysis of Variance (ANOVA) was used to test for significant differences between older adult male nFOR and older adult female nFOR. Sex was an independent measure or between groups factor. An α value of 0.05 was used to determine significance. Rejection of the null hypothesis occurred whenever the test statistic calculated had a p-value less than 0.05. Where necessary, significant interactions, simple main effects and main effects were interpreted. The number of hip fractures variable was considered as a proportion, subsequently, the two-proportion Z-test was used to determine if the proportion of hip fractures occurring in older adult males was significantly less than the proportion of hip fractures occurring in older adult females These proportions would be considered for selected arrangements of safety flooring. The null hypothesis was rejected if the p-value was less than 0.05.

The fourth hypothesis posited that safety flooring located within the bedroom/bathroom of the simulation would contribute to a greater reduction in the nFOR and number of hip fractures suffered when compared to other locations. The variable associated with this hypothesis was the nFOR distributions of the simulated populations for selected arrangements of safety flooring compared to the base simulation where there is safety flooring within the bedroom and bathroom. Since the nFOR was a continuous variable dependent on two factors (Sex and Safety flooring location) a two-way mixed measure Analysis of Variance (ANOVA) was used to test for significant differences between safety flooring being placed in the bedroom and other arrangements of safety flooring. The location of safety flooring was a repeated measure or a within group factor. Rejection of the null hypothesis occurred whenever the test statistic calculated had a p-value less than 0.05. Where necessary, significant interactions, simple main effects and main effects were interpreted. The number of hip fractures variable were considered as a proportion, subsequently, the two-proportion Z-test was used to determine if the proportion of hip fractures occurring with safety flooring in the bedroom/bathroom was significantly less than the proportion of hip fractures occurring with other arrangements of safety flooring. The null hypothesis was rejected if the p-value was less than 0.05.

Hypotheses five and six had two dependent variables which were single numbers for each condition rather than distributions (cumulative monetary costs saved associated with prevented hip fractures, ICER), therefore statistical tests were not performed for both hypotheses.

Table 5: Summary of the statistical testing approaches for each hypothesis.

Hypothesis	Independent Variables	Dependent Variables	Statistical Tests
1a	1. Population (Canadian vs Ontario Retirement Home)	1. Age 2. Sex 3. Height 4. Mass 5. BMI	1. Two tailed unpaired T-test 2. Two proportion Z-test 3. Two tailed unpaired T-test 4. Two tailed unpaired T-test 5. Two tailed unpaired T-test
2	1. Safety Flooring (Presence or Absence)	1. nFOR 2. Number of Hip Fractures	1. One tailed paired T-test 2. Two proportion Z-test
3	1. Sex (Simulated Male vs Simulated Female.) 2. Safety Flooring Locations	1. nFOR 2. Number of Hip Fractures	1. Two-way mixed ANOVA 2. Two proportion Z-test
4	1. Sex (Simulated Male vs Simulated Female.) 2. Safety Flooring Locations	1. nFOR 2. Number of Hip Fractures	1. Two-way mixed ANOVA 2. Two proportion Z-test

5a	1. Sex (Simulated Male vs Simulated Female.)	1. Savings associated with preventing hip fractures.	- N/A
5b	1. Sex (Simulated Male vs Simulated Female.)	1. ICER	- N/A
6a	1. Safety Flooring Location	1. Savings associated with preventing hip fractures.	- N/A
6b	1. Safety Flooring Location	1. ICER	- N/A

Chapter 4: Results

4.1 Hypothesis 1

Overall, the characteristics of the retirement home VIs were significantly different from the Canadian VIs. From the perspective of sex distribution, there were a greater proportion of females in the retirement home population compared to the Canadian older adult population (**Figure 17**, **Table 6**). Specifically, there were a greater number of females in the retirement home VIs (65,646) compared to the Canadian older adult VIs (53,308), ($\chi^2 = 3158$, $p < .001$). Conversely, there were more Canadian male VIs (46,692) than retirement home male VIs (34,354), ($\chi^2 = 3158$, $p < .001$).

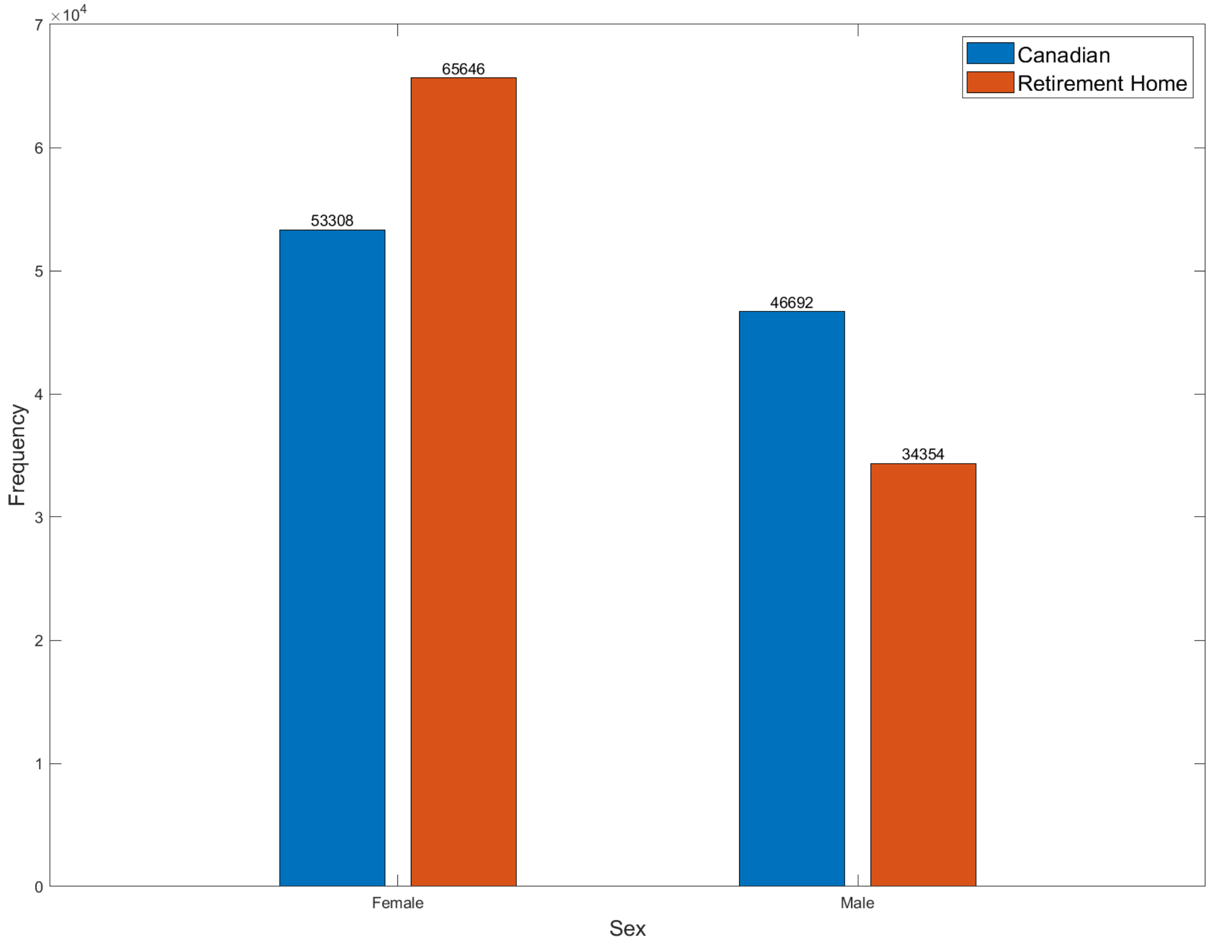

Figure 17: Figure comparing the number of simulated Canadian and Retirement Home VIs.

The retirement home population was significantly older than the Canadian older adult population see **Figure 18**. Specifically, the Canadian VIs mean ± (SD) age was 70.7 ± (8.48) years and the retirement home VIs age was 87.4 ± (6.59) years (t = 494, p < .001). The Canadian female VIs had an age of 71.3 ± (8.84) years, while the retirement home female VIs had an age of 87.6 ± (6.46) years, (t = 355, p < .001). The Canadian male VIs had an age of 69.9 ± (7.98) years, while the retirement home male VIs had an age of 87.2 ± (6.83) years, (t = 330, p < .001).

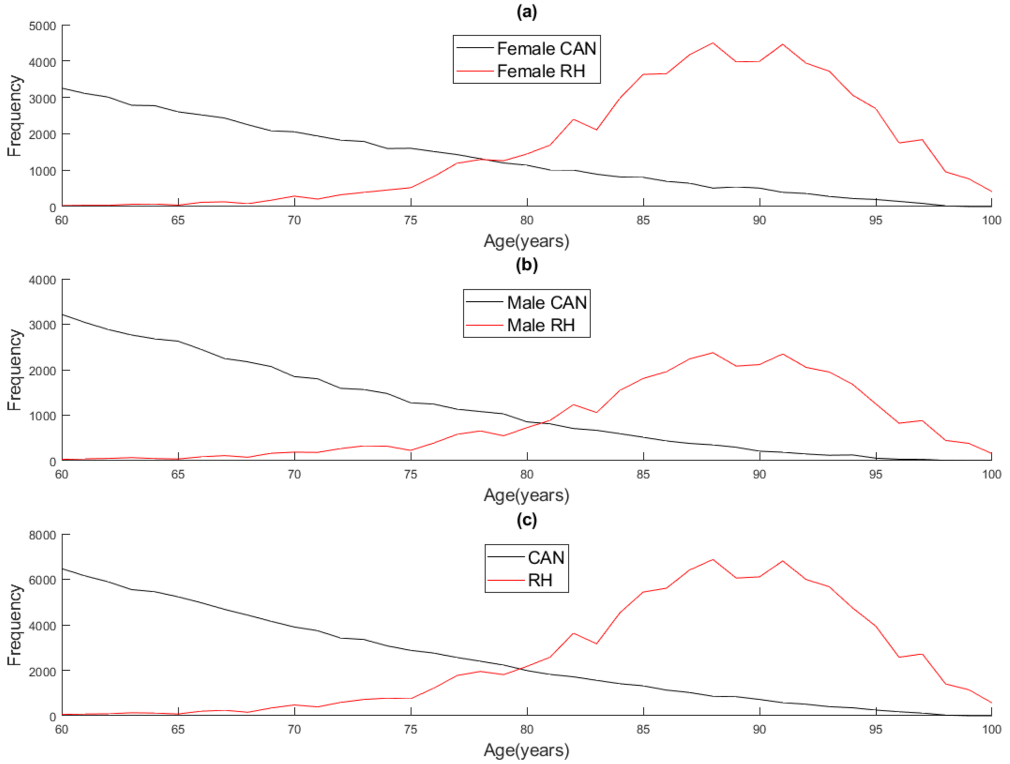

Figure 18: Age distributions of Canadian older adult and retirement home populations for: a) female VIs; b) male VIs; c) all VIs.

The retirement home population was significantly shorter than the Canadian older adult population see **Figure 19**. Specifically, the Canadian VIs had a height of 1.65 ± (0.08) m and the retirement home VIs had a height of 1.63 ± (0.11) m, (t = -53, p < .001). The Canadian female VIs had a height of 1.59 ± (0.05) m while the retirement home female VIs had a height of 1.58 ± (0.09) m, (t = -30, p < .001). The Canadian male VIs had a height of 1.72 ± (0.05) m, while the retirement home male VIs had a height of 1.72 ± (0.09) m, (t = 3, p < .001).

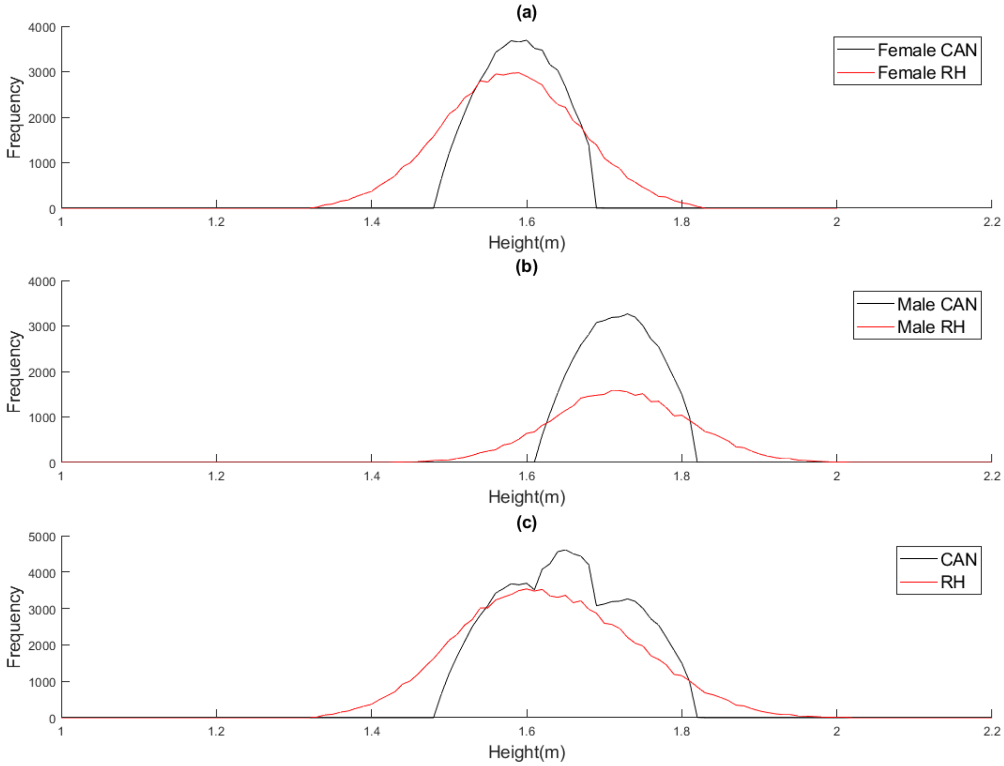

Figure 19: Height distributions of Canadian older adult and retirement home populations for: a) female VIs; b) male VIs; c) all VIs.

The retirement home population was lighter than the Canadian older adult population **Figure 20**. Specifically, the Canadian VIs mass was 77.0 ± (11.89) kg and the retirement home VIs mass was 67.8 ± (15.16) kg, (t = -150, p < .001). The Canadian female VIs had a mass of 71.0 ± (9.42) kg, while the retirement home female VIs had a mass of 63.0 ± (13.58) kg, (t = -120, p < .001). The Canadian male VIs had a mass of 83.8 ± (10.72) kg, while the retirement home male VIs had a mass of 77.0 ± (13.72) kg, (t = -76, p < .001).

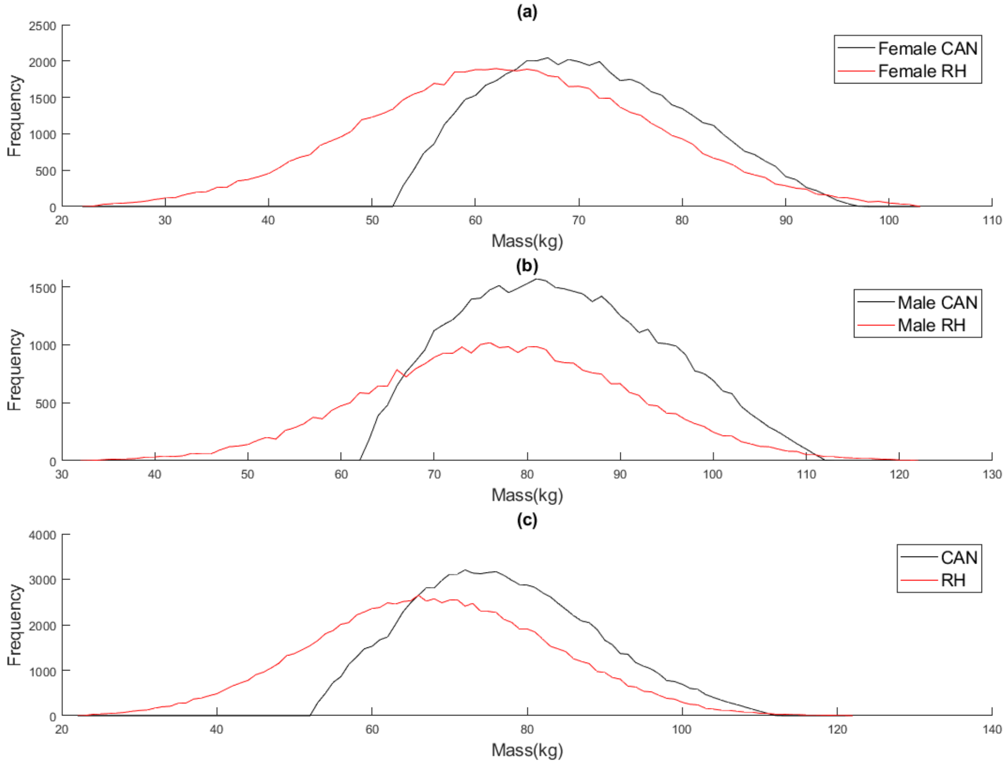

Figure 20: Mass distributions of Canadian older adult and retirement home populations for: a) female VIs; b) male VIs; c) all VIs.

Body Mass Index was significantly lower for the retirement home population compared to the Canadian older adult population **Figure 21**. Specifically, the Canadian VIs BMI was 28.3 ± (4.05) kg/m^2 and the retirement home VIs BMI was 25.6 ± (5.06) kg/m^2, ($t = -132.2$, $p < .001$). The Canadian female VIs had a BMI of 28.2 ± (4.12) kg/m^2 while the retirement home female VIs had a BMI of 25.3 ± (5.29) kg/m^2 ($t = -104.2$, $p < .001$). The Canadian male VIs had a BMI of 28.4 ± (3.98) kg/m^2, while the retirement home male VIs had a BMI of 26.1 ± (4.55) kg/m^2 ($t = -77.0$, $p < .001$).

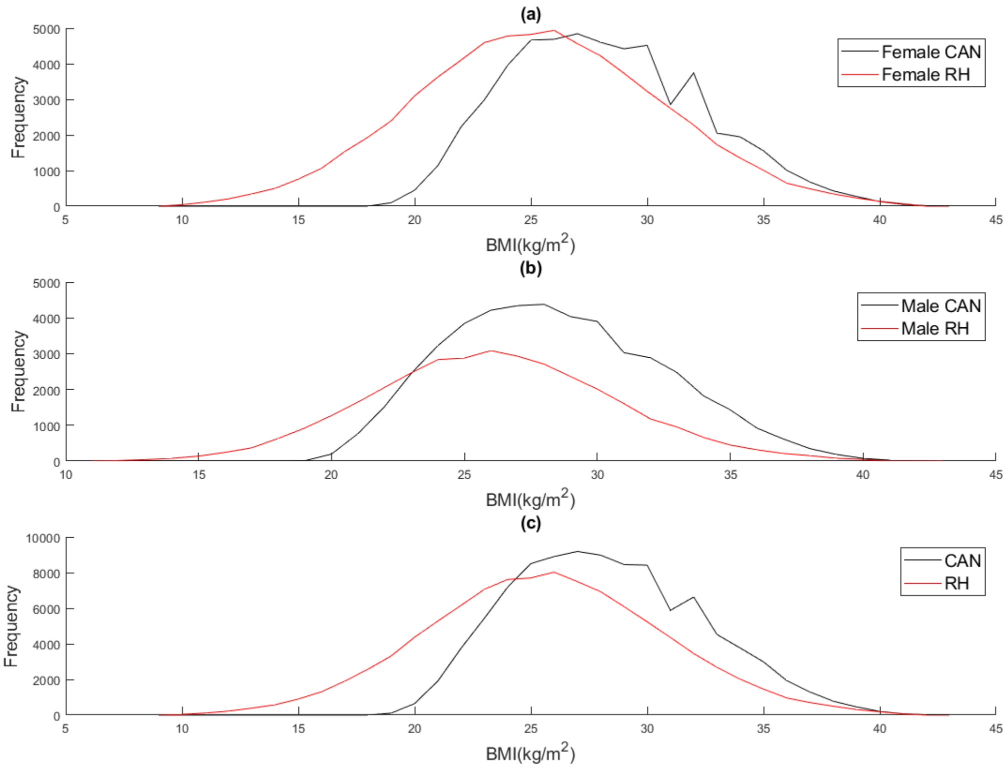

Figure 21: BMI distributions of Canadian older adult and retirement home populations for: a) female VIs; b) male VIs; c) all VIs.

Table 6: Characteristics of the Canadian Older Adult VIs and Retirement Home VIs compared as part of Hypothesis #1.

Variable	Canadian mean (SD)	Retirement Home mean (SD)	% difference*	Test Statistic # ^	p-value
Female N	53308	65646	+23.15	3158	$p < .001$
Male N	46692	34354	-26.42	3158	$p < .001$
Age (years)	70.7 (8.48)	87.4 (6.59)	+23.62	494	$p < .001$
Mass (kg)	77.0 (11.89)	67.8 (15.16)	-11.95	-150	$p < .001$
Height (m)	1.65 (0.08)	1.63 (0.11)	-1.21	-53	$p < .001$
BMI ($kg.m^{-2}$)	28.3 (4.05)	25.6 (5.06)	-9.54	-132	$p < .001$
Female Age (years)	71.3 (8.84)	87.6 (6.46)	+22.86	355	$p < .001$
Male Age (years)	69.9 (7.98)	87.2 (6.83)	+24.75	330	$p < .001$
Female Mass (kg)	71.0 (9.42)	63.0 (13.58)	-11.27	-120	$p < .001$
Male Mass (kg)	83.8 (10.72)	77.0 (13.72)	-8.11	-76	$p < .001$
Female Height (m)	1.59 (0.05)	1.58 (0.09)	-0.63	-30	$p < .001$
Male Height (m)	1.72 (0.05)	1.72 (0.09)	+0.09	3	0.002
Female BMI ($kg.m^{-2}$)	28.2 (4.12)	25.3 (5.29)	-10.28	-104	$p < .001$
Male BMI ($kg.m^{-2}$)	28.4 (3.98)	26.1 (4.55)	-8.10	-77	$p < .001$

[*] Comparison is for retirement home relative to Canadian older adult means, with + representing a higher Retirement Home value.

[#] Test statistic is χ^2 for Female and Male N values (based on Chi-Squared tests), and t for all remaining variables (based on t-tests)

[^] Test statistic rounded to nearest integer

4.2 Hypothesis 2

Overall, the data confirmed that implementing safety flooring everywhere within a retirement home setting significantly reduced both the nFOR and the number of estimated hip fractures (**Figure 22**, **Table 7**). This was true when considering the main effect and simple main effects of safety floor location on the nFOR. When considering the nFOR for both sexes combined, the mean (SD) of nFOR for safety flooring 0.8212 ± (0.61) was 48.32% less than the nFOR for standard flooring 1.5891 ± (0.67) ($t = 274.0$, $p < .001$). When considering the female VIs, the nFOR for safety flooring 0.9793 ± (0.61) was 45.51% less than the nFOR for standard flooring 1.7971 ± (0.72) ($t = 209.2$, $p < .001$). When considering the male VIs, the nFOR for safety flooring 0.5190 ± (0.46) was 56.45% less than the nFOR for standard flooring 1.1917 ± (0.27) ($t = 208.7$, $p < .001$).

The significant effects of safety flooring were also observed when considering the number of estimated hip fractures (**Table 8**). Specifically, the number of hip fractures when the population fell on safety flooring (39400) was 52.52% less than the number of hip fractures when the population fell on standard flooring (82974) ($\chi^2 = 39973$, $p < .001$). When considering the female VIs, the number of hip fractures when the population fell on safety flooring (32864) was 42.50% less than the number of hip fractures when the population fell on standard flooring 57161 ($\chi^2 = 20861$, $p < .001$). When considering the older adult male VIs, the number of hip fractures when the population fell on safety flooring 6536 was 74.68% less than the number of hip fractures when the population fell on standard flooring 25813 ($\chi^2 = 21705$, $p < .001$).

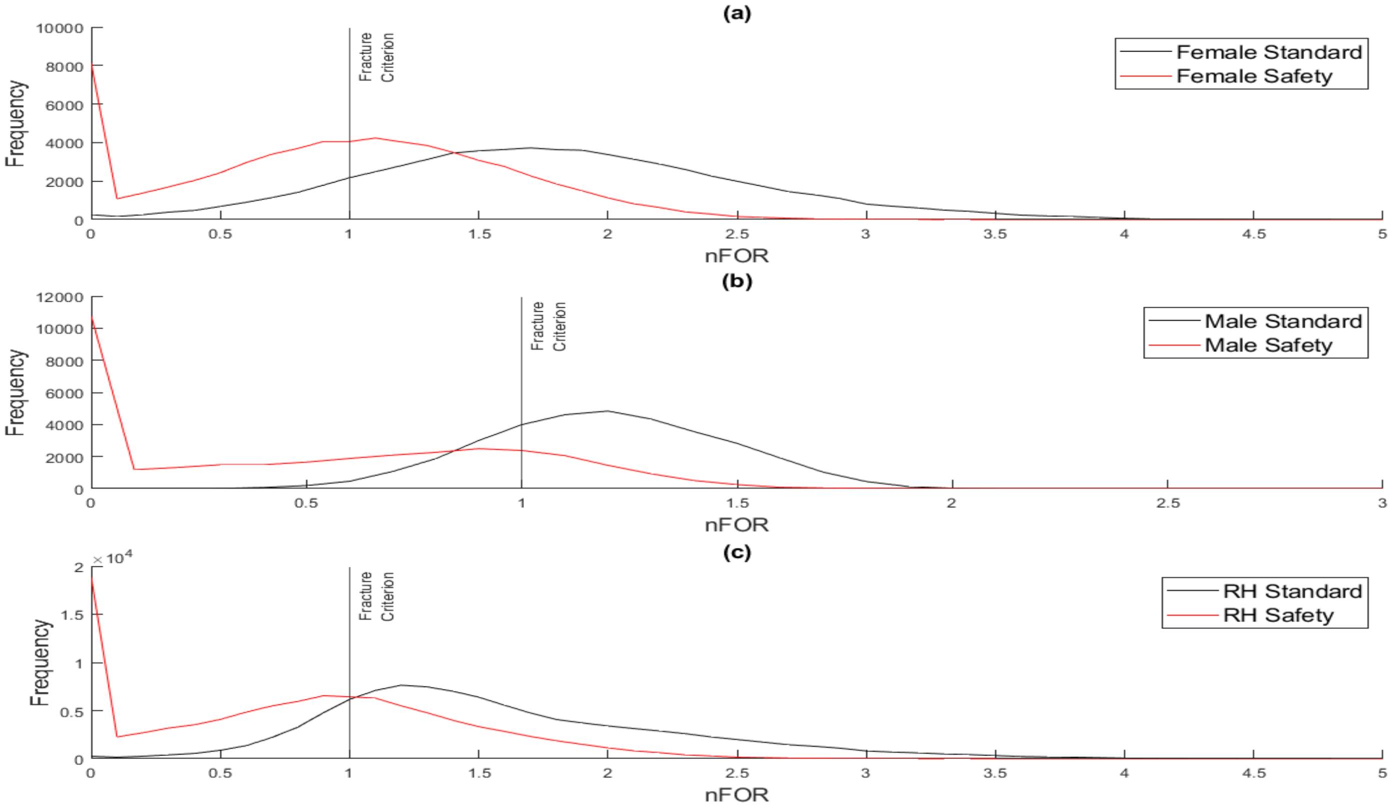

Figure 22: nFOR distributions when the retirement home VIs were subjected to falls on standard (black) and safety (red) flooring for: a) female VIs; b) male VIs; c) all VIs

Table 7: Mean (SD) nFOR for standard flooring compared to safety flooring installed everywhere within a retirement home setting.

Comparison	**Standard**	**Safety**	**% change***	**Statistic (t) #**	**p-value**
All	1.5891 (0.67)	0.8212 (0.61)	-48.32	274	$p < .001$
Female	1.7971 (0.72)	0.9793 (0.61)	-45.51	209	$p < .001$
Male	1.1917 (0.27)	0.5190 (0.46)	-56.45	209	$p < .001$

* Comparison is for safety floor relative to standard floor means, with + representing a higher safety floor value.

\# Statistics rounded to nearest integer.

Table 8: Number of predicted hip fractures for standard flooring compared to safety flooring installed everywhere within a retirement home setting.

Comparison	**Standard**	**Safety**	**% change***	**Statistic (χ^2) #**	**p-value**
All	82974	39400	-52.52	39973	$p < .001$
Female	57161	32864	-42.50	20861	$p < .001$
Male	25813	6536	-74.68	21705	$p < .001$

* Comparison is for safety floor relative to standard floor means, with + representing a higher safety floor value.

\# Statistic rounded to nearest integer.

4.3 Hypothesis 3

Overall, the data[1] confirmed that safety flooring had a significantly greater reductive effect on the male VIs nFOR compared to the female VIs (**Table 11**). When considering the simple main effect of sex at each location, the male nFOR values ranged from 47.00% less than the female nFOR (0.5190 ± (0.46) compared to 0.9793 ± (0.61)) with safety flooring located everywhere to 33.69% less than the female nFOR (1.1917 ± (0.27) compared to 1.7971 ± (0.72)) with safety flooring located nowhere.

Safety flooring also had a significantly greater reductive effect on the number of estimated male hip fractures compared to female estimated hip fractures (**Table 12**). The estimated number of male hip fractures ranged from 80.11% less than the female hip fractures (6,536 compared to 32,864) with safety flooring located everywhere to 54.84% less than the female hip fractures (25,813 compared to 57,161) with standard flooring located everywhere. Even when considering the difference in the sex-specific numbers of simulated older adults, the greater reductive effect on male hip fractures remained (**Figure 23**).

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[1] For Tables 9,10,11,13,14,15 DFn is equal to (Degrees of Freedom numerator) the between groups degrees of freedom, DFd is equal to (Degrees of Freedom denominator) the within groups degrees of freedom, F is the F statistic, p-value (adjusted) is the adjusted p-value used for multiple comparisons, ges is generalized etta squared a measure of the effect size, df is the degrees of freedom.

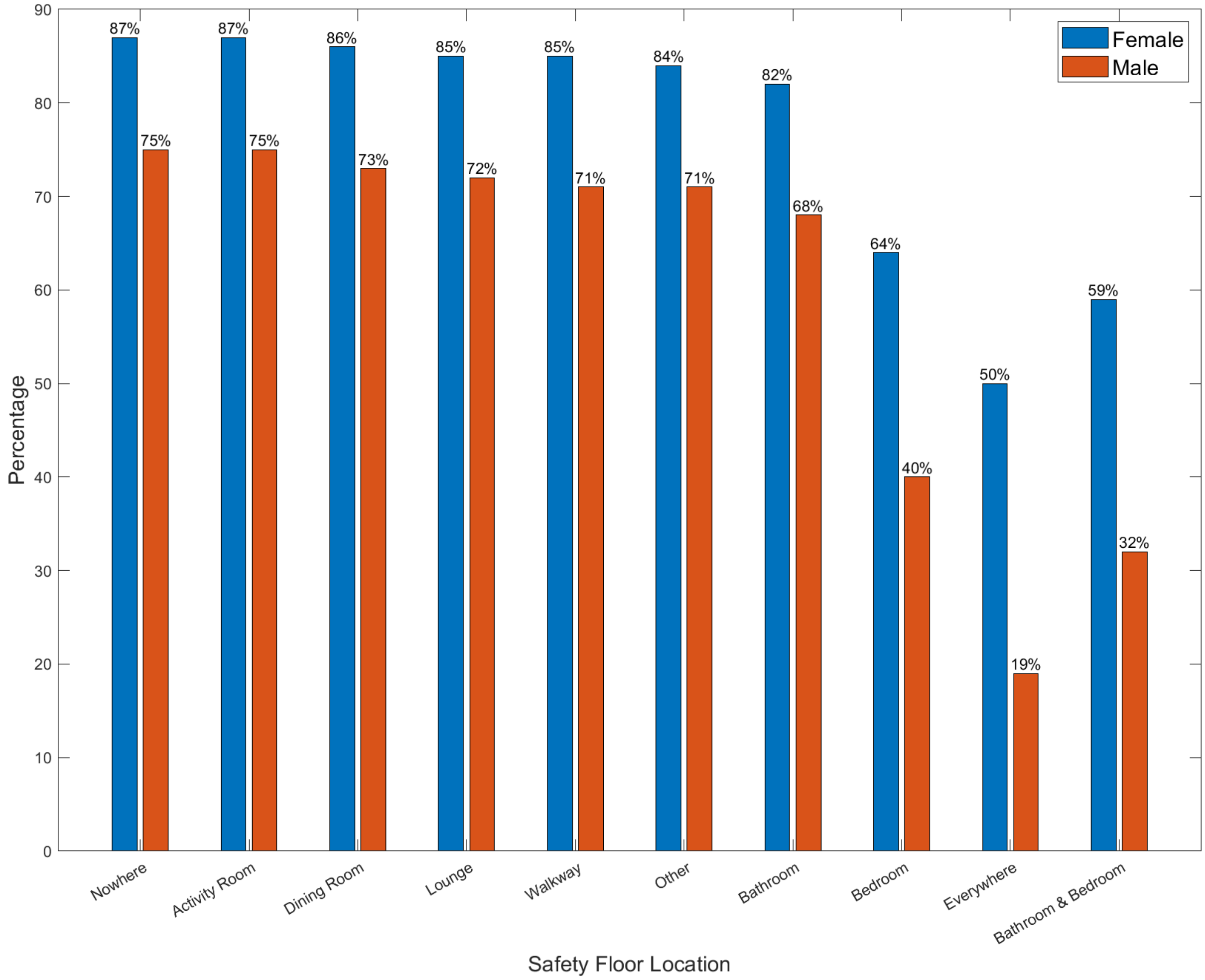


Figure 23: Sex-specific percentage of total simulated older adults (split by sex) who were predicted to suffer hip fractures for various locations of safety flooring.

Table 9: 2-Way Mixed Measures ANOVA used to determine the effect of safety floor location and sex on the nFOR.

Effect	DFn	DFd	F *	p-value	ges
Sex	1	99998	35998	p < .001	0.153
Floor Location	9	899982	31556	p < .001	0.136
Interaction: Sex: Floor Location	9	899982	306	p < .001	0.002

* Statistics rounded to nearest integer

Table 10: Simple main effect analysis to determine the effect of VI sex on nFOR at each level of safety floor location.

Floor Location	Effect	DFn	DFd	F #	ges	p-value (adjusted)
Activity Room	Sex	1	99998	22332	0.183	< .001
Everywhere	Sex	1	99998	14940	0.130	< .001
Bathroom	Sex	1	99998	18128	0.153	< .001
Bathroom and Bedroom	Sex	1	99998	12506	0.111	< .001
Bedroom	Sex	1	99998	12422	0.110	< .001
Dining Room	Sex	1	99998	21437	0.177	< .001
Lounge	Sex	1	99998	20413	0.170	< .001
Nowhere	Sex	1	99998	22540	0.184	< .001
Other	Sex	1	99998	19293	0.162	< .001
Walkway	Sex	1	99998	20161	0.168	< .001

F statistic rounded to nearest integer.

Table 11: Pairwise comparisons to determine if the nFOR of male VIs was less than that of female VIs.

Safety Floor Location	Female nFOR mean (SD)	Male nFOR mean (SD)	Difference (raw) [*]	Difference (%) [*]	Statistic (t) [#]	p-value (adjusted)
Activity Room	1.7933 (0.72)	1.1888 (0.28)	0.6045	-33.71	189	p < .001
Bathroom	1.6900 (0.76)	1.1030 (0.38)	0.5870	-34.73	163	p < .001
Bathroom and Bedroom	1.1729 (0.73)	0.6797 (0.51)	0.4932	-42.05	124	p < .001
Bedroom	1.2799 (0.76)	0.7684 (0.52)	0.5115	-39.96	125	p < .001
Dining Room	1.7739 (0.73)	1.1710 (0.30)	0.6029	-33.99	183	p < .001
Everywhere	0.9793 (0.61)	0.5190 (0.46)	0.4603	-47.00	134	p < .001
Lounge	1.7510 (0.74)	1.1529 (0.33)	0.5981	-34.16	177	p < .001
Nowhere	1.7971 (0.72)	1.1917 (0.27)	0.6054	-33.69	191	p < .001
Other	1.7284 (0.75)	1.1375 (0.35)	0.5909	-34.19	171	p < .001
Walkway	1.7452 (0.74)	1.1475 (0.33)	0.5977	-34.25	175	p < .001

[*] Comparison is for male relative to female means, with + representing a higher male value.

[#] Statistics rounded to nearest integer.

Table 12: Table of the Chi-Squared statistics used to determine if the number of male hip fractures were less than the number of female hip fractures for all arrangements of safety flooring.

Comparison	Female	Male	Difference (raw) *	Difference (%) *	Statistic (χ^2) #	p-value
Safety Nowhere	57161	25813	31348	-54.84	2274	p < .001
Safety Everywhere	32864	6536	26328	-80.11	9097	p < .001
Activity Room	57058	25730	31328	-54.91	2286	p < .001
Dining Room	56451	25220	31231	-55.32	2384	p < .001
Lounge	55835	24694	31141	-55.77	2495	p < .001
Walkway	55652	24538	31114	-55.91	2529	p < .001
Other	55101	24262	30839	-55.97	2440	p < .001
Bathroom	53973	23263	30710	-56.90	2697	p < .001
Bedroom	41760	13707	28053	-67.18	5134	p < .001
Bathroom and Bedroom	38572	11157	27415	-71.08	6230	p < .001

[*] Comparison is for male relative to female means, with + representing a higher male value.

[#] Statistics rounded to the nearest integer.

4.4 Hypothesis 4

Overall, the data confirmed that placing safety flooring in the bedroom and bathroom had a significantly greater reductive effect on older adult nFOR than placing safety flooring in other locations (**Figure 24**, **Table 15**). The nFOR for safety flooring being in the bathroom and bedroom was 1.1729 ± (0.73) for females, 0.6797 ± (0.51) for males and 1.0034 ± (0.70) for both combined.

When considering the main effect of safety flooring location, the nFOR values ranged from 58.37% greater (1.5891 ± (0.67)) when safety flooring was nowhere to 10.05% greater (1.1042 ± (0.73)) when safety flooring was in the Bedroom compared to the nFOR associated with safety flooring being present in the bedroom and bathroom. However, when safety flooring was everywhere the nFOR was 18.16 % less (0.82119 ± (0.61)) than the nFOR associated with placing safety flooring in the bedroom and bathroom. When considering the simple main effects of safety flooring location, the nFOR values ranged from 53.22% greater (1.7971 ± (0.72)) when safety flooring was nowhere to 9.12% greater (1.2799 ± (0.76)) when safety flooring was in the bedroom for older adult females and from 75.33% greater (1.1917 ± (0.27)) when safety flooring was nowhere to 13.05% greater (0.7684 ± (0.52)) when safety flooring was in the bedroom for older adult males when compared to the sex-specific nFORs associated with safety flooring being present in the bedroom and bathroom. However, when safety flooring was everywhere the nFOR was 16.51% less (0.9793 ± (0.61)) for older adult females and 23.64 % less (0.5190 ± (0.46)) for older adult males when compared to the sex-specific nFORs associated with safety flooring being present in the bedroom and bathroom.

The data also confirmed that placing safety flooring in the bedroom and bathroom had a significantly greater reductive effect on the estimated number of hip fractures than placing safety flooring in other locations (**Table 16**). The estimated number of hip fractures for safety flooring being in the bathroom and bedroom was 38572 for females, 11157 for males and 49729 for both combined.

The estimated number of hip fractures ranged from 66.85% greater (82,974) when safety flooring was nowhere to 11.54% greater (55,467) when safety flooring was in the bedroom when compared to the estimated number of hip fractures associated with safety flooring being present in the bedroom and bathroom. However, when safety flooring was everywhere the estimated number of hip fractures was 20.77% less (39,400) than the estimated number of hip fractures associated with placing safety flooring in the bedroom and bathroom. The estimated number of hip fractures ranged from 48.19% greater (57,161) when safety flooring was nowhere to 8.27% greater (41,760) when safety flooring was in the bedroom for older adult females and from 131.36% greater (25,813) when safety flooring was nowhere to 22.86% greater (13,707) for older adult males when compared to the sex-specific estimated number of hip fractures associated with safety flooring being present in the bedroom and bathroom. However, when safety flooring was everywhere the estimated number of hip fractures were 14.80% less (32,864) for older adult females and 41.42% less (6,536) for older adult males when compared to the sex-specific estimated number of hip fractures associated with safety flooring being present in the bedroom and bathroom.

Table 13: Simple main effect analysis to determine the effect of safety floor location on the nFOR at each level of sex.

Sex	Effect	DFn	DFd	F [#]	ges	p-value (adjusted)
F	Floor Location	9	590805	22189	0.136	< .001
M	Floor Location	9	309177	18622	0.278	< .001

[#] F statistic rounded to nearest integer

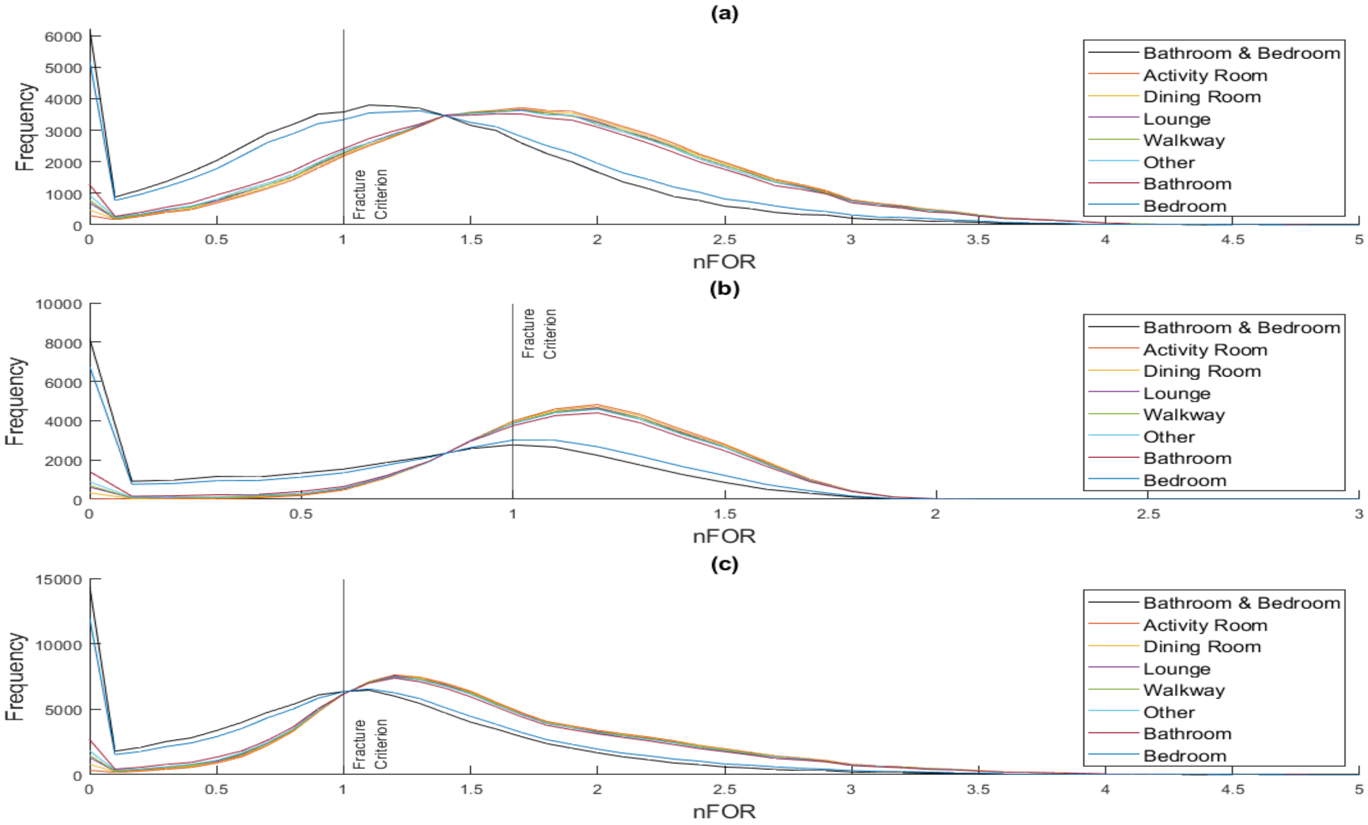


Figure 24: nFOR distributions when safety flooring was located only in the bathroom and bedroom (black) relative to other locations of safety flooring for: a) female VIs; b) male VIs; c) all VI

Table 14: Main effect of safety flooring location on the nFOR.

Location 1	nFOR	Location 2	nFOR	Difference (raw) *	Difference (%) *	Statistic (t) #	df	p-value
Bathroom and Bedroom	1.0034 (0.70)	None	1.5891 (0.67)	0.5857	58.37	-220.46	999999	< .001
		Activity Room	1.5857 (0.67)	0.5823	58.03	-217.56	999999	< .001
		Dining Room	1.5668 (0.68)	0.5634	56.15	-202.99	999999	< .001
		Lounge	1.5455 (0.69)	0.5421	54.03	-187.88	999999	< .001
		Walkway	1.5399 (0.69)	0.5365	53.47	-184.11	999999	< .001
		Other	1.5254 (0.70)	0.522	52.02	-174.74	999999	< .001
		Bathroom	1.4884 (0.71)	0.485	48.34	-192.40	999999	< .001
		Bedroom	1.1042 (0.73)	0.1008	10.05	-77.67	999999	< .001
		All	0.8212 (0.61)	-0.1822	-18.16	106.38	999999	1

Table 15: Pairwise comparisons to determine if the nFOR with safety flooring in the bedroom and bathroom was less than other arrangements of safety flooring. (Only the comparisons between safety flooring being in the bathroom and bedroom and other arrangements of safety flooring are included).

Sex	**Location 1**	**nFOR**	**Location 2**	**nFOR**	**Difference (raw) [*]**	**Difference (%) [*]**	**Statistic (t) [#]**	**p-value**
F	Bathroom and Bedroom	1.1729 (0.73)	None	1.7971 (0.72)	0.6242	53.22	-169.93	p < .001
[redacted]	[redacted]	[redacted]	Activity Room	1.7933 (0.72)	0.6204	52.90	-167.72	p < .001
[redacted]	[redacted]	[redacted]	Dining Room	1.7739 (0.73)	0.6010	51.24	-157.17	p < .001
[redacted]	[redacted]	[redacted]	Lounge	1.7510 (0.74)	0.5781	49.29	-145.61	p < .001
[redacted]	[redacted]	[redacted]	Walkway	1.7452 (0.74)	0.5723	48.79	-142.83	p < .001
[redacted]	[redacted]	[redacted]	Other	1.7284 (0.75)	0.5555	47.36	-135.15	p < .001
[redacted]	[redacted]	[redacted]	Bathroom	1.6900 (0.76)	0.5171	44.09	-148.92	p < .001
[redacted]	[redacted]	[redacted]	Bedroom	1.2799 (0.76)	0.1070	9.12	-60.60	p < .001
[redacted]	[redacted]	[redacted]	All	0.9793 (0.61)	-0.1936	-16.51	82.80	p = 1
M	Bathroom and Bedroom	0.6797 (0.51)	None	1.1917 (0.27)	0.512	75.33	-159.65	p < .001

[redacted]	Activity Room	1.1888 (0.28)	0.5091	74.90	-157.32	p < .001
	Dining Room	1.1710 (0.30)	0.4913	72.28	-144.08	p < .001
	Lounge	1.1529 (0.33)	0.4732	69.62	-132.45	p < .001
	Walkway	1.1475 (0.33)	0.4678	68.82	-129.31	p < .001
	Other	1.1375 (0.35)	0.4578	67.35	-123.60	p < .001
	Bathroom	1.1030 (0.38)	0.4233	62.28	-136.52	p < .001
	Bedroom	0.7684 (0.52)	0.0887	13.05	-52.48	p < .001
	All	0.5190 (0.46)	-0.1607	-23.64	72.60	p = 1

[*] Comparison is for locations relative to bedroom and bathroom nFOR means, with + representing a higher location value.

[#] T statistic rounded to nearest integer.

Table 16: Chi-Squared test statistics used to determine if the number of hip fractures with safety flooring in the bedroom and bathroom was less than for other locations of safety flooring.

Comparison	Bedroom & Bathroom (N)	Comparison (N)	Difference (raw) *	Difference (%) *	Statistic (χ^2) #	p-value
Standard Only	49729	82974	33245	66.85	24750	p < .001
Female Standard Only	38572	57161	18589	48.19	13326	p < .001
Male Standard Only	11157	25813	14656	131.36	12576	p < .001
Safety Only	49729	39400	-10329	-20.77	2158.9	1
Female Safety Only	38572	32864	-5708	-14.80	1000	1
Male Safety Only	11157	6536	-4621	-41.42	1625	1
Bedroom	49729	55467	5738	11.54	660	p < .001
Female Bedroom	38572	41760	3188	8.27	326	p < .001
Male Bedroom	11157	13707	2550	22.86	410	p < .001
Bathroom	49729	77236	27507	55.31	16318	p < .001
Female Bathroom	38572	53973	15401	39.93	8683	p < .001
Male Bathroom	11157	23263	12106	108.51	8531	p < .001
Other	49729	79363	29634	59.59	19186	p < .001
Female Other	38572	55101	16529	42.85	10178	p < .001
Male Other	11157	24262	13105	22.86	10006	p < .001
Walkway	49729	80190	30461	61.25	20381	p < .001

Female Walkway	38572	55652	17080	44.28	10965	p < .001
Male Walkway	11157	24538	13381	119.93	10438	p < .001
Lounge	49729	80529	30800	61.94	20884	p < .001
Female Lounge	38572	55835	17263	44.76	11235	p < .001
Male Lounge	11157	24694	13537	121.33	10687	p < .001
Dining Room	49729	81671	31942	64.23	22636	p < .001
Female Dining Room	38572	56451	17879	46.35	12176	p < .001
Male Dining Room	11157	25220	14063	126.05	11552	p < .001
Activity Room	49729	82788	33059	66.48	24441	p < .001
Female Activity Room	38572	57058	18486	47.93	13155	p < .001
Male Activity Room	11157	25730	14573	130.62	12430	p < .001

[*] Comparison is for locations relative to bedroom and bathroom estimated hip fractures, with + representing a higher location value.

[#] Chi Squared statistic rounded to nearest integer.

4.5 Hypothesis 5

For the simulated populations of 100,000 female and 100,000 male older adults, hip fracture savings ranged from \$5,248,937 (F) and \$8,245,367 (M) to \$1,310,666,701 (F) and \$2,080,354,775 (M) across safety flooring locations (**Figure 25**, **Table 17**). For all locations of safety flooring in the retirement home savings were greater for older adult males and ranged from 53.05% greater (\$40,042,309 (F), \$61,283,665 (M)) in the Dining Room to 61.33% greater (\$81,957,976 (F), \$277,818,059 (M)) in the Bathroom.

ICERs ranged from \$8,497 (F) and \$6,511(M) to \$54,539 (F) and \$40,393 (M) across safety flooring locations (**Figure 26**, **Table 18**). For all location of safety flooring in the retirement home the ICERs were less for older adult males ranging from 18.72% less (\$39,707 (F), \$32,272 (M)) in the Dining Room to 25.94% less (\$54,539 (F), \$40,393 (M)) in the Walkway.

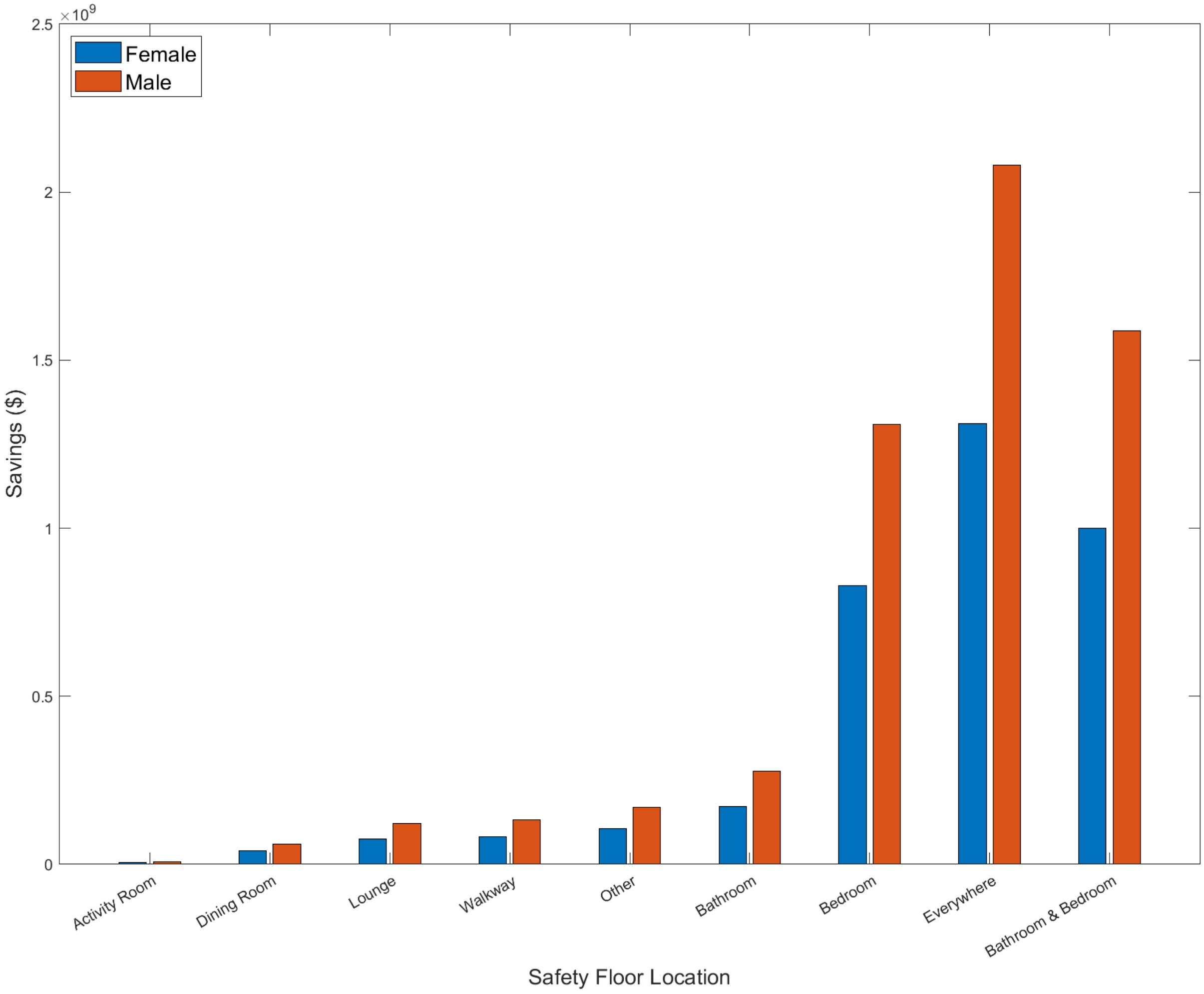


Figure 25: Sex-specific savings (due to hip fractures prevented by safety flooring) for selected locations of safety flooring within an Ontario retirement home. Female and Male population size were each 100,000.

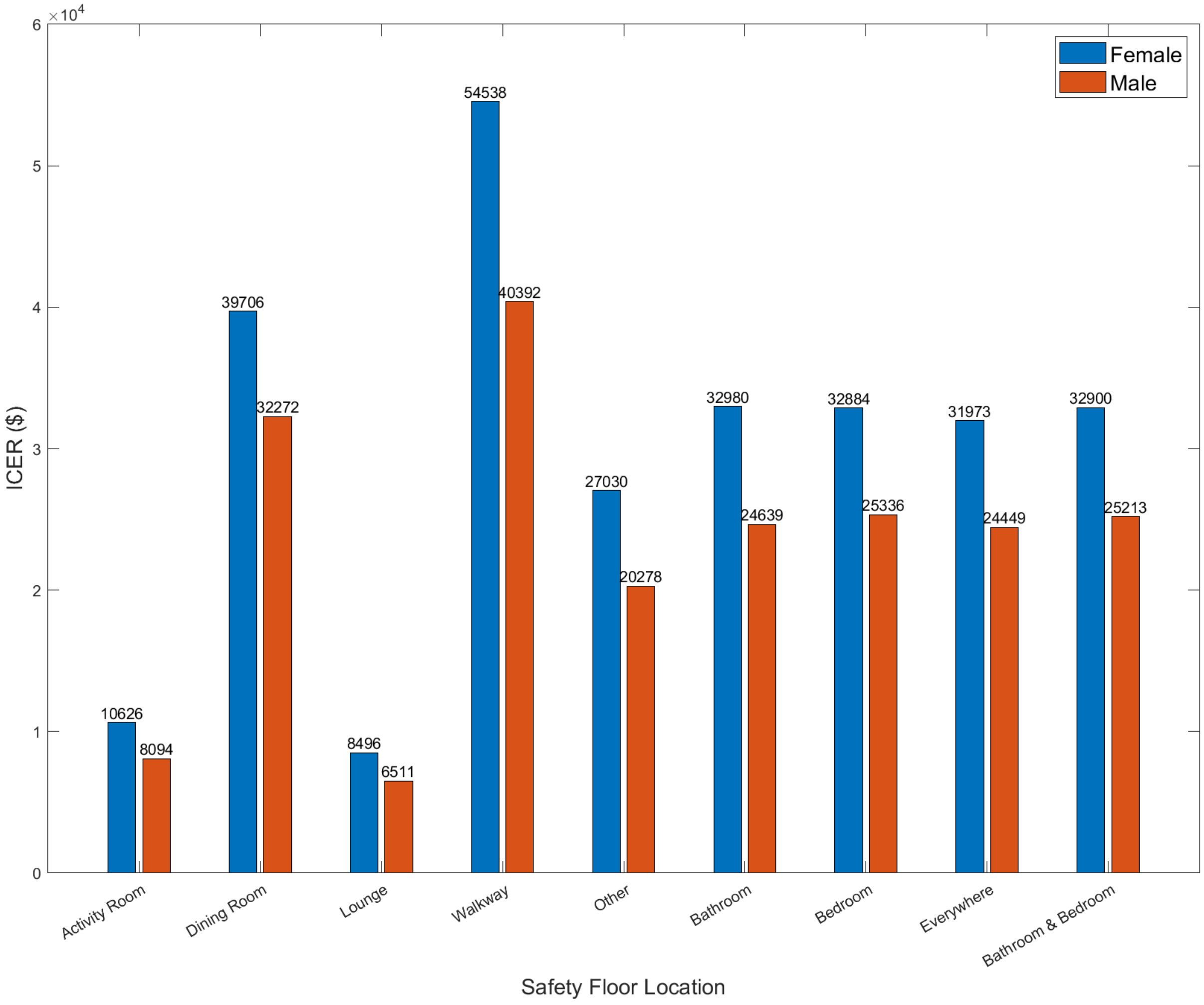


Figure 26: Sex-specific Incremental Cost Effectiveness ratios (ICERs) for selected locations of safety flooring within an Ontario retirement home. Female and Male population sizes were each 100,000.

Table 17: Sex-specific Savings for selected locations of safety flooring within an Ontario retirement home.

Location	Female ($)	Male ($)	Difference ($) (raw)*	Difference (%) *
Activity Room	5248937	8245367	2996430	57.09
Dining Room	40042309	61283665	21241356	53.05
Lounge	76613495	122040238	45426743	59.29
Walkway	81957976	131505384	49547408	60.45
Other	106292877	170151230	63858353	60.08
Bathroom	172199517	277818059	105618542	61.33
Bedroom	828311590	1309310832	480999242	58.07
Everywhere	1310666701	2080354775	769688074	58.72
Bathroom and Bedroom	1000511107	1587128891	586617784	58.63

* Comparison is for male relative to female means, with + representing a higher male value

Table 18: Sex-specific Incremental Cost Effectiveness ratios (ICERs) for selected locations of safety flooring within an Ontario retirement home.

Location	Female ICER ($)	Male ICER ($)	Difference ($) (raw)*	Difference (%) *
Activity Room	10627	8094	-2533	-23.83
Dining Room	39707	32272	-7435	-18.72
Lounge	8497	6511	-1986	-23.37
Walkway	54539	40393	-14146	-25.94
Other	27031	20278	-6753	-24.98
Bathroom	32981	24639	-8342	-25.29
Bedroom	32884	25337	-7548	-22.95
Everywhere	31974	24449	-7525	-23.53
Bathroom and Bedroom	32901	25213	-7688	-23.37

* Comparison is for male relative to female means, with + representing a higher male value

4.6 Hypothesis 6

For the simulated population of 100,000 older adults (65,646 (F), 34,354(M)), hip fracture savings ranged from \$6,722,697 to \$1,567,092,439 across safety flooring locations and was \$1,195,260,987 for the bedrooms and bathrooms which was comparatively greater than most other locations (**Figure 27**, **Table 19**). Compared to the safety flooring being installed in both the bedroom and bathroom the savings ranged from 99.44% less (\$6,722,697) in the Activity Room to 17.27% less (\$988,784,291) in the Bedroom. However, when safety flooring was everywhere the savings were 31.11% more (\$1,567,092,439) than the savings from placing safety flooring in the bedroom and bathroom.

ICERs ranged from \$7510 to \$45253 across safety flooring locations and was \$27895 for the bedroom and bathrooms (**Figure 28**, **Table 20**). Compared to the safety flooring installed in both the bedroom and bathroom the ICERs ranged from 62.23% greater (\$45253) in Walkways to 0.01% greater (\$27899) in the Bedroom. The ICERs also ranged from 69.89% less (\$7510) in the Activity room to 0.07% less (\$27877) in the Bathroom. However, ICERs were relatively similar for the safety flooring installed in the bedroom and bathroom (both together or individually) or throughout the entire facility.

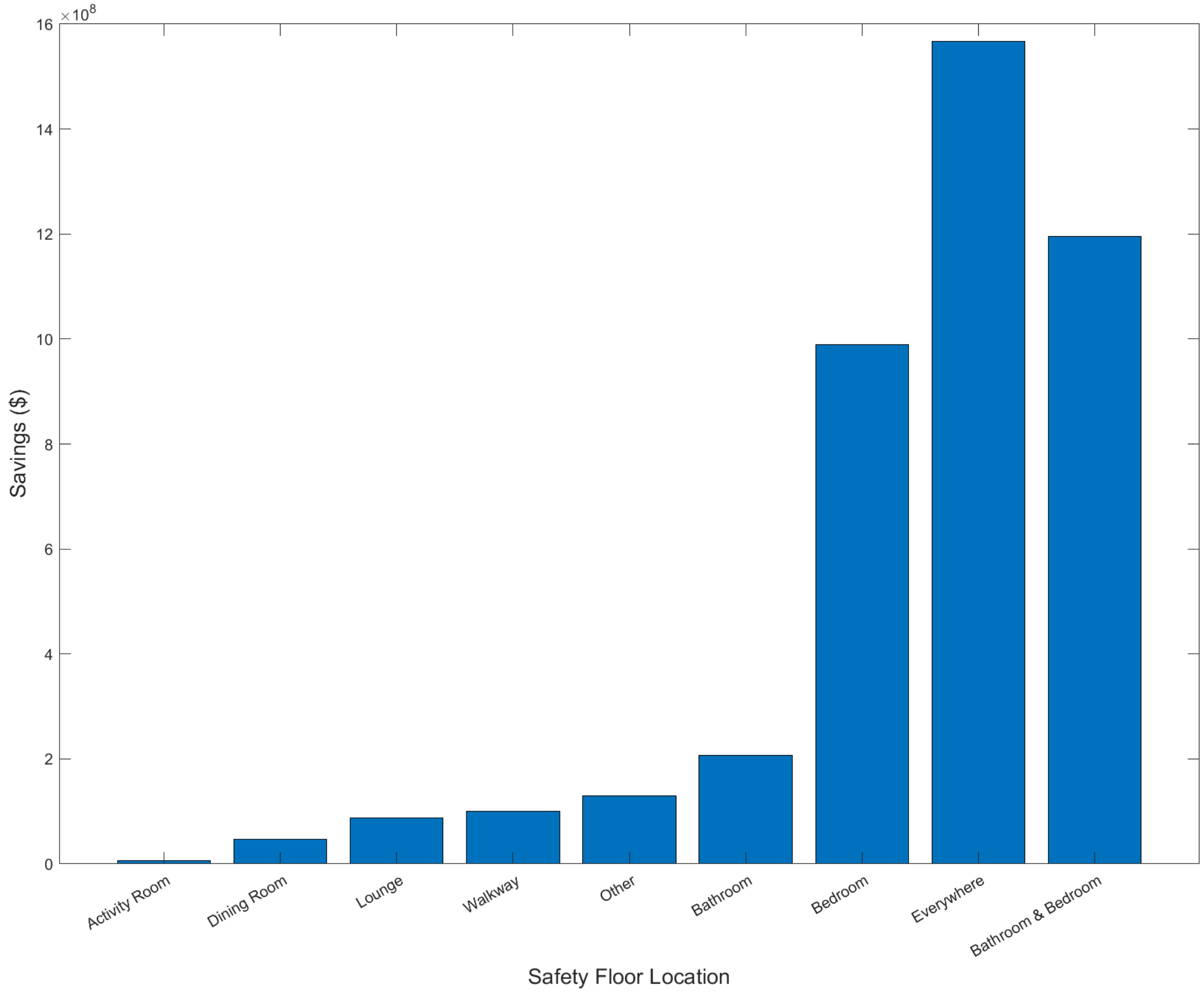


Figure 27: Location-specific savings (due to VI hip fractures prevented by safety flooring) for various arrangements of safety flooring.

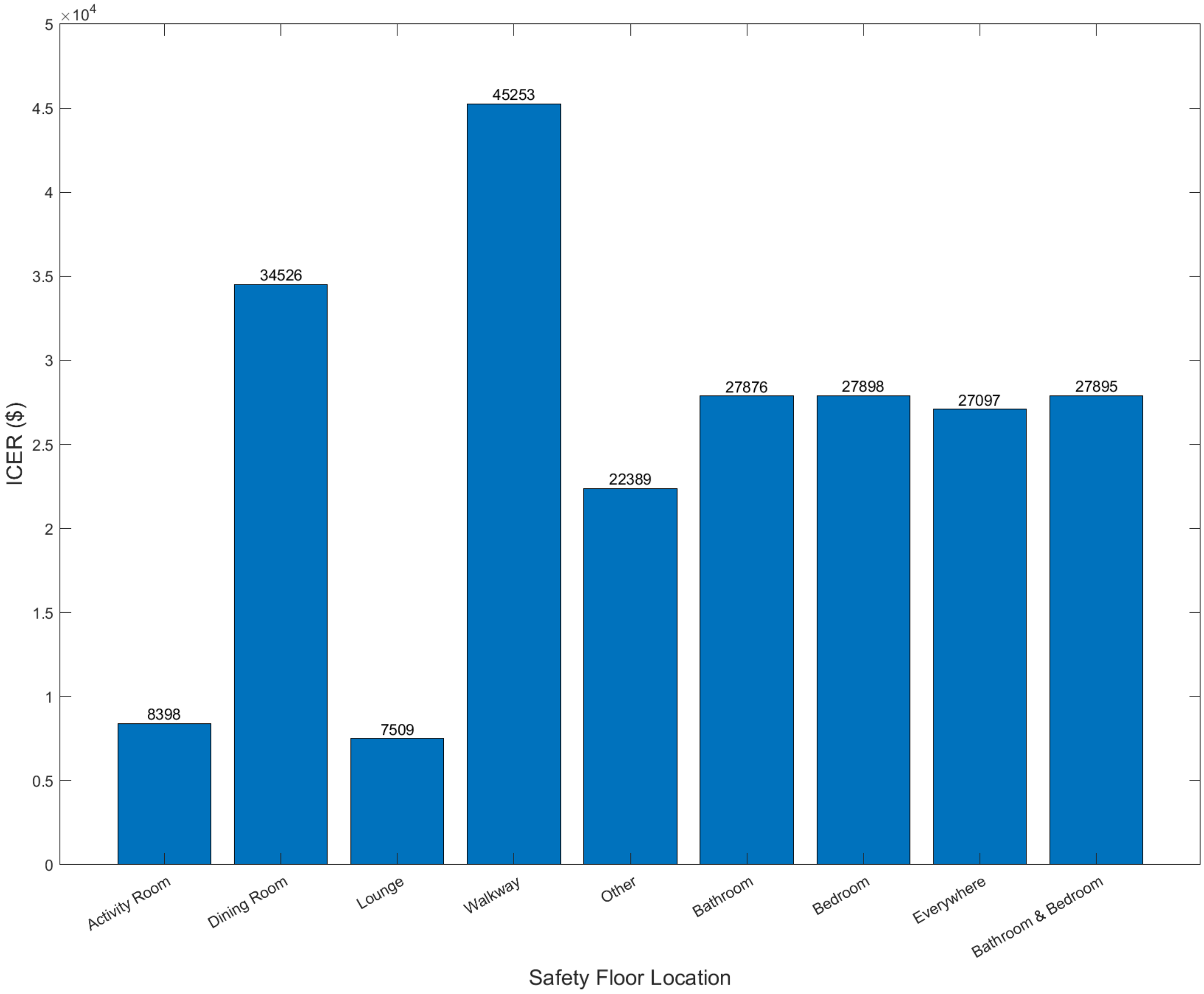


Figure 28: Location-specific incremental Cost Effectiveness ratios (ICERs) for selected locations of safety flooring within an Ontario retirement home.

Table 19: Savings for selected locations of safety flooring within an Ontario retirement home.

Location	Savings ($)	Difference ($) (raw)*	Difference (%) *
Bathroom and Bedroom	1195260987	N/A	N/A
Activity Room	6722697	-1188538290	-99.44
Dining Room	46905550	-1148355437	-96.08
Lounge	87894684	-1107366303	-92.65
Walkway	100308346	-1094952641	-91.61
Other	130000175	-1065260812	-89.12
Bathroom	206476696	-988784291	-82.73
Bedroom	988784291	-206476696	-17.27
Everywhere	1567092439	371831452	31.11

[*] Comparison is for locations relative to bedroom and bathroom estimated hip fractures, with + representing a higher location value

Table 20: Incremental Cost Effectiveness ratios (ICERs) for selected locations of safety flooring within an Ontario retirement home.

Location	ICER ($)	Difference ($) (raw)*	Difference (%) *
Bathroom and Bedroom	27895	N/A	N/A
Activity Room	8399	-19496	-69.89
Dining Room	34526	6631	23.77
Lounge	7510	-20385	-73.08
Walkway	45253	17358	62.23
Other	22390	-5505	-19.74
Bathroom	27877	-18	-0.07
Bedroom	27899	4	0.01
Everywhere	27098	-797	-2.86

[*] Comparison is for locations relative to bedroom and bathroom estimated hip fractures, with + representing a higher location value

Chapter 5: Discussion

This thesis was structured to provide insight into the following questions. Is the Canadian population representative of the retirement home population? Does the updated model exhibit the same directionality as the original model? Are there differential benefits on hip fracture outcomes when considering: a) Sex; b) Safety floor location? Are there differential benefits on economic outcomes when considering: a) Sex; b) Safety floor location? Results indicated that the Canadian population was different from the retirement home population. Similar behaviours were observed for the retirement home such as: a) a reduction in population hip fracture risk when the population was subjected to falls on safety flooring; b) a greater hip fracture risk for older adult females compared to older adult males for falls on standard flooring; c) a greater reduction in older adult male hip fractures compared to older adult female hip fractures for falls on safety flooring. Finally, there were differential benefits on hip fracture and economic outcomes when considering sex and safety flooring location. Specifically, male older adults had a lower hip fracture risk and increased savings due to safety floor mediated reductions in hip fractures than female older adults. This was observed for all placements of safety flooring considered. Also placing safety flooring in the bedroom and bathroom led to increased savings and a generally lower hip fracture risk than placing safety flooring in other locations.

5.1 Hypothesis 1

The retirement home older adult population was different from the larger Canadian population. This contradicted the first hypothesis which assumed that the retirement home population would statistically be the same as the Canadian population. On average the Canadian population had less females, was younger, heavier and had a higher body mass index (BMI) than the retirement home population. LaFleur (2016) estimated TSTT using sex and BMI values, showing that TSTT increased with increasing BMI. Therefore, using the soft-tissue attenuation equation of Robinovitch et al. (1995), the Canadian population would have benefitted from a higher soft tissue attenuation. Additionally, LaFleur (2016) estimated femoral neck bone mineral density to be dependent on age, sex, and mass. With BMD being greater for older adult males compared to older adult females, increasing with increasing mass and decreasing with increasing age. Therefore, the younger and heavier Canadian population would have benefitted from a higher bone strength. The combination of an increased soft tissue force attenuation and an increased bone strength relative to the Canadian population would theoretically cause the Canadian population to be less at risk of hip fractures relative to the retirement home population. These observations justified the decision to compare the Canadian population characteristics with the retirement home population characteristics. The observations also suggested that a population with Canadian characteristics is not sufficiently representative to make predictions about arbitrary subsets of the Canadian population and supports the idea that valid investigations into hip fractures need to consider the characteristics of the population of interest i.e., be population-specific. Finally, the observations indicated an opportunity for further studies to consider the differences between the Canadian and retirement home population e.g., differences in hip fracture risk, estimated hip fractures etc.

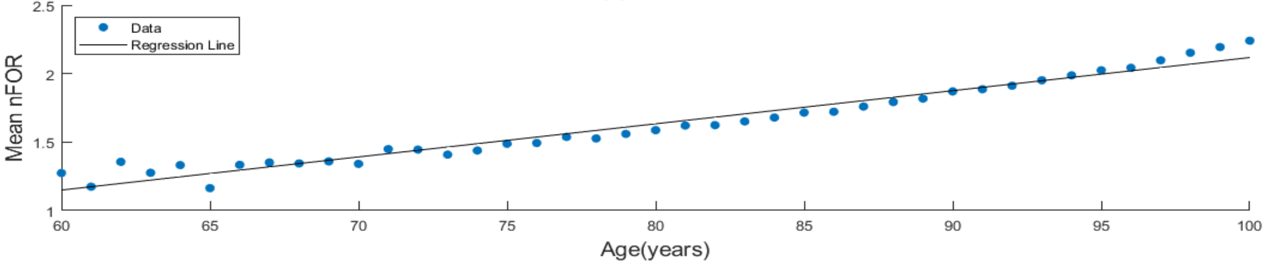
5.2 Hypothesis 2

Safety flooring reduced both the nFOR and the number of estimated hip fractures for the retirement home older adult population. This was true when considering both the main and simple main effects of safety floor location. These results agreed with the second hypothesis where a reduction in nFOR and consequently the number of hip fractures was expected when the population was simulated to fall on safety flooring relative to standard flooring. This indicated that the model exhibited directionality while being used on populations possessing different characteristics. Exhibiting directionality indicated that even though the model was generating a different population of older adults to those generated by Martel (2017) and Martel et al. (2020), the general patterns observed were the same. Therefore, the entire population as well as male and female VIs individually, all observed a reduction in hip fracture risk when falling on safety flooring relative to falling on standard flooring. However, when considering the mean normalized factor of risk (nFOR) at each age for falls on safety flooring an interesting observation was made. As older adult age increased there was a increase in mean nFOR corresponding to each age for falls on standard floors agreeing with epidemiological evidence (**Figure 29**), however, when the population was subjected to falls on safety flooring an increase in older adult age was associated with a decrease in mean nFOR (**Figure 30**). A sensitivity analysis performed on the safety floor attenuation module suggested that trochanteric soft tissue thickness (TSTT) and effective mass were responsible for the observation. Decreasing effective mass and TSTT both led to increases in the safety flooring attenuation output (**Table 21**). Therefore, the oldest adults who were lightest and possessed the least TSTT received the greatest attenuation from the safety flooring. This partially contradicted Martel (2017) which indicated a direct relationship between effective mass and safety flooring attenuation i.e., increases in effective mass occurring together with increases in safety flooring attenuation. This observation either indicated an elevated benefit of safety flooring for the oldest adults or it could be related to Martel (2017) and Martel et al. (2020) using different stiffness estimates to those used within this thesis. Finally, a 2008 estimate of the total number of hip fractures within Canada was set at approximately twenty-two thousand individuals over the age of fifty years (Hopkins et al., 2012). 73% of the hip fractures observed were female, while 64% of the hip fractures occurring in females occurred in females older than 80 (Hopkins et al., 2012). The model estimated 69% to 84% of hip fractures occurring in females for the cases where standard flooring was located everywhere, and safety flooring was located everywhere. It further estimated 90% of hip fractures occurring in females occurred in females older than 80 for falls on standard flooring, this figure decreased to 87% for falls on safety flooring. The percentage change in hip fractures in older adult females contradicted the increased proportion of females in the retirement home population. As the increased proportion of females in the retirement home relative to the Canadian population should lead to an increase in the percentage of hip fractures occurring in women (relative to total older adults). The expected behaviour was observed for falls on safety flooring; however, this increased percentage of female hip fractures was likely due to the greater reductive effect of safety flooring on older adult males. For falls on standard flooring the observed contradiction as predicted by the model could be due to actual population differences, where males in retirement homes are more likely to suffer from hip fractures than their community dwelling counterparts. This notion is supported by literature, Crilly et al. (2010) indicated that there was a 1.8 times greater risk of Canadian older adult hip fractures in Long-Term Care which when partitioned according to sex was 1.5 times greater for females and 4.3 times greater for males. However, unlike Crilly et al. (2010) the model did not indicate a reduced hip fracture risk for the oldest females relative to the older adult males. This indicates that more factors than the mechanistic ones used within this model are responsible for determining hip fracture risk within the older adult population.

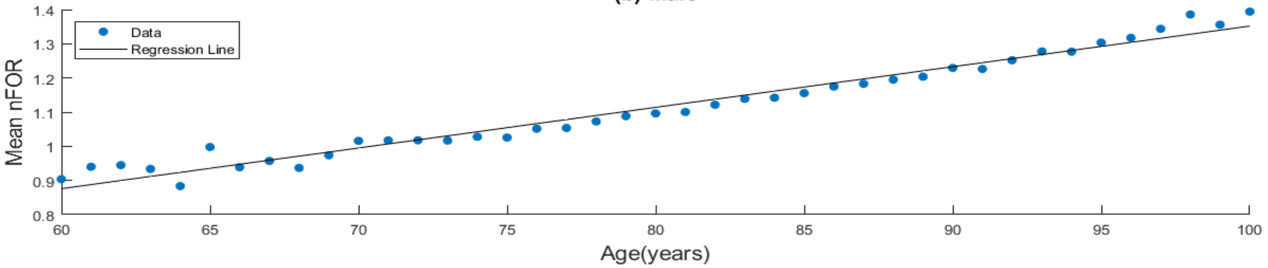
Table 21: Sensitivity of retirement home older adults' safety floor attenuation factor to effective mass and TSTT.

Variable	Standard Deviation	Female	Male
	0	0.0235	0.0663
Effective Mass	1	-0.0472	-0.0464
	2	-0.1178	-0.1591
	3	-0.1884	-0.2717
	-1	0.0941	0.1789
	-2	0.1647	0.2916
	-3	0.2354	0.4043
TSTT	1	-0.0188	0.0113
	2	-0.0610	-0.0436
	3	-0.1032	-0.0986
	-1	0.0657	0.1212
	-2	0.1079	0.1762
	-3	0.1501	0.2311

(a) Female



(b) Male



(c) All

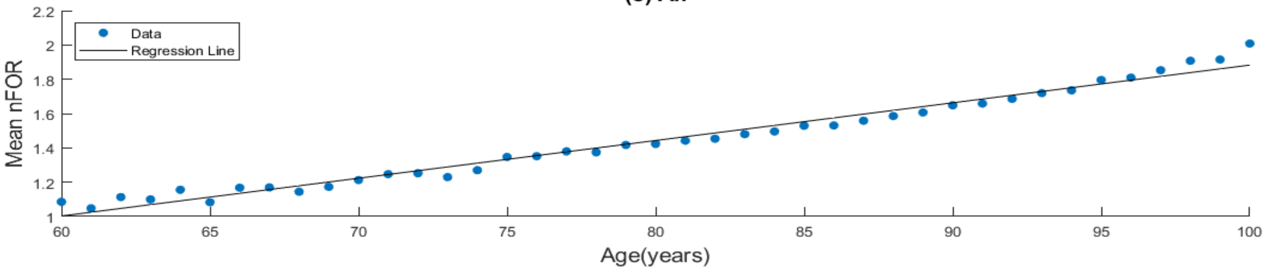


Figure 29: Mean nFOR at each age on standard flooring for: a) Females; b) Males; c) All older adults.

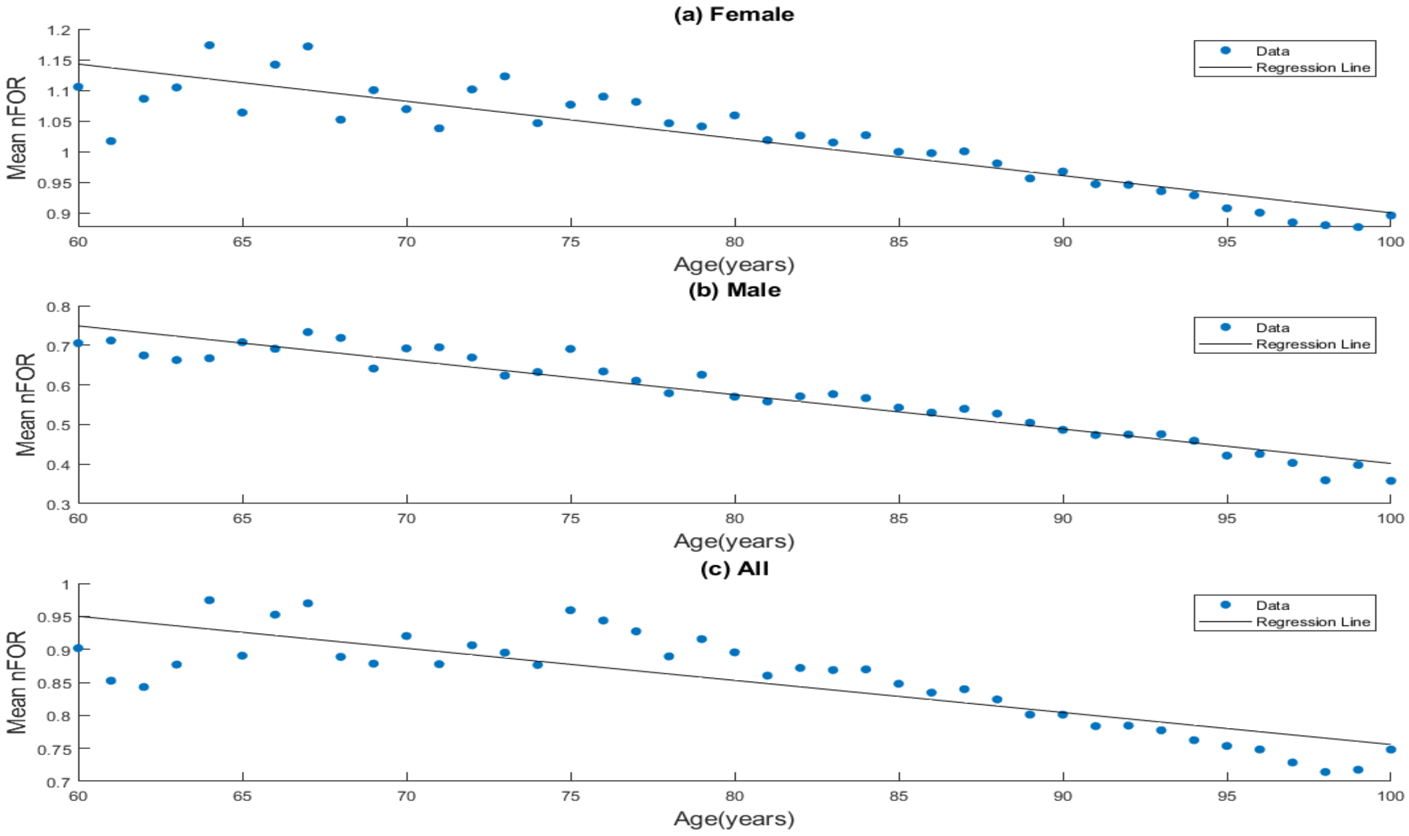


Figure 30: Mean nFOR at each age on safety flooring for: a) Females; b) Males; c) All older adults.

5.3 Hypothesis 3

Safety flooring had a greater reductive effect on older adult men when compared to older adult women. This was consistent with and extended the observations of Martel et al. (2020) and Martel (2017) who noted a greater benefit of safety flooring for older adult males. The reason for this observation was that the location of the injury criterion for older adult males is almost centred within the male FOR distribution, therefore any translation of the FOR distribution for older adult males should result in a larger change from fracture to non-fracture status when compared to older adult females. Older adult females in comparison have an injury criterion which is not as centred within the female FOR distribution, consequently, the translation of the FOR distribution results in a smaller change from fracture to non-fracture status. This trend remains consistent across all the locations of safety flooring. This is not surprising since increasing the number of virtual individuals falling on safety flooring within the simulation sequentially transformed the nFOR distribution from the standard flooring everywhere distribution to the safety flooring everywhere distribution. In both distributions older adult females were more likely to suffer from hip fractures, while older adult males were expected to benefit more from the provision of safety flooring. (Martel, 2017; Martel et al., 2020). Further this observed behaviour mimicked the clinical realities of hip fractures where older adult females were more likely to suffer from hip fractures than older adult males, Hopkins et al. (2012). The female nFOR at each age ranged from 16.63% to 61.79% greater than the male nFOR. Indicating an increased risk of hip fracture at each age for older adult females compared to older adult males. Additionally, a line of best fit which was determined from the data in MATLAB (MATLAB R2022a, MathWorks, Natick, Massachusetts, USA) indicated that the rate of increase of the mean nFOR with age was approximately twice as great in older adult females (0.024) compared to older adult males (0.012) (**Figure 29**). This agreed with the observation of Martel et al. (2020) which indicated a similar relationship between the rate of increase of the mean nFOR with age for older adult females (0.022) and older adult males (0.011). The difference in the increase of hip fracture risk between the Martel et al. (2020) population and the population used in this thesis could be random or indicate an increased risk of hip fracture for the retirement home population with age. When the mean nFOR was considered for falls on safety flooring the rate of decrease of the mean nFOR with age for older adult females (-0.006) was less than the rate of decrease for older adult males (-0.009) (**Figure 30**). The greater rate of decrease of mean nFOR for older adult males indicated an interesting relationship specifically that decreases in male TSTT had a greater influence on the magnitude of the safety flooring attenuation than the reductions in female effective mass (**Table 21**). This may partially be supported by observing that the mean TSTT of the over 90 males was approximately 88.15% of the mean TSTT of the under 90 males compared to 90.43% in females. Similarly, the mean effective mass of the over 90 males was approximately 92.55% of the mean effective mass of the under 90 males compared to 91.53% in females. According to LaFleur (2016) females possess higher levels of trochanteric soft tissue (TSTT) than males. Using equation (2.4), Robinovitch et al. (1995), it was expected that males would experience a smaller soft tissue force attenuation than females which would increase the safety floor mediated attenuation values, however, males were expected to be heavier than females which also reduced the safety floor mediated attenuation values. Noting that males benefitted from a greater rate of decline of hip fracture risk with age for falls on safety flooring suggested that their reduction in TSTT had a greater effect on safety flooring attenuation than the associated reduction in female effective mass.

5.4 Hypothesis 4

Placing safety flooring in the bedroom and bathroom had a greater reductive effect on the population hip fracture risk than placing safety flooring in other locations, the only exception was the case where safety flooring was located everywhere. These estimations are consistent with the work of Cleworth et al. (2021), Martel (2017), and Martel et al. (2020). Martel (2017) and Martel et al. (2020) previously indicated a safety floor mediated reduction in the hip fracture risk, while Cleworth et al. (2021) indicated a high number of falls in the bedroom and bathrooms when compared to other locations within the retirement home. Fall frequency and location data from Cleworth et al. (2021) were fundamental to the underlying model assumptions, therefore more virtual individuals (VIs) were located within the bedroom and bathroom compared to any other location. Consequently, more VIs benefitted from the impact force attenuation provided by safety flooring. These results indicated that the attempt made within this thesis to capture and represent the spatial distribution and frequency of falls within the updated probabilistic model was successful. The model therefore is a promising tool to estimate population-level hip fracture risk in Canadian retirement home settings. However, without an opportunity to compare the simulation-based estimates with observational/clinical data it was difficult to validate the capability of the model.

5.5 Hypothesis 5

Savings were greater for older adult males compared to older adult females , when simulating equivalent numbers across both sexes (**Figure 25**, **Table 17**). From hypothesis 3, older adult males had a greater reduction in hip fracture risk than older adult females when safety flooring was used. Therefore, the increased number of hip fractures prevented, coupled with the greater one year directly attributable hip fracture costs for males led to larger savings for the older adult males. Additionally, the savings across locations showed similar percentage differences between older adult males and older adult females. With differences ranging from 23.44% to 35.50% greater savings for older adult males compared to older adult females. The differences in savings were mediated by the differential effectiveness of safety flooring on older adult hip fracture prevention. However, when a population containing retirement home sex proportions was simulated (which contained a greater proportion of females), older adult females' savings were larger compared to older adult males. Even though the males had a greater percentage reduction in hip fracture risk the absolute number of females had a greater influence on the savings than their percentage change in hip fracture risk.

Additionally, the ICER values were lower for older adult males compared to older adult females **(Figure 26**, **Table 18**). Using the population with equivalent numbers of older adults across both sexes more males moved from the hip fracture to non-hip fracture condition, therefore the same expenditure to place safety flooring within the retirement home resulted in more hip fractures prevented for males. This suggests that the sex composition of the retirement home could theoretically influence a decision to implement safety flooring as an alternative to standard flooring as a retirement home with more males would see more hip fractures prevented per dollar spent on safety flooring than a retirement home with more females. Additionally, the ICERS across locations showed similar percentage differences between older adult males and older adult females. With differences ranging from 18.72% to 25.94% smaller ICERs for older adult males compared to older adult females. As the ICERs have the same numerator the differences were mediated by the differential effectiveness of safety flooring on older adult hip fracture prevention. Decomposition of the number of hip fractures prevented indicated that older adult males had 48.54% to 56.82% more hip fractures prevented than older adult females. This explained the relatively constant relationship between the sex-specific savings and ICERs. These sex-specific findings support the suggestion of Nasiri and Luo (2016) for additional research exploring sex-specific strategies for reducing risk of hip fractures.

5.6 Hypothesis 6

Savings were greater when safety flooring was placed in the bedroom and bathroom when compared to all other locations except when safety flooring was located everywhere (**Figure 27**, **Table 19**). When safety flooring was located everywhere all older adults experienced the associated impact force attenuation provided by the safety flooring. Therefore, the overall hip fracture risk was lowest when safety flooring was located everywhere, followed by safety flooring being located within the bedroom and bathroom.

However, contradicting initial expectations the incremental cost effectiveness ration (ICER) was not lowest in the bedrooms and bathrooms (**Figure 28**, **Table 20**). The lowest ICERs were observed in the lounge followed by the activity rooms. This indicated that rooms with the lowest ICERs were not the same as rooms with the largest number of hip fractures prevented by safety flooring. The number of hip fractures prevented when safety flooring was located within the bedroom and bathroom was greater than the number of hip fractures prevented when safety flooring was located within the lounge. However, the increase in the number of hip fractures prevented was negated by the increased cost of laying safety flooring in the bedrooms and bathrooms of the retirement home due to the increased square footage accumulated across all 221 suites within the retirement home ((177545.38 square feet) compared to the Lounge (3515.18 square feet) and activity room (299.06 square feet)) **Table 4**. Appendix B presents a simple linear regression performed to determine the line of best fit in MATLAB (MATLAB R2022a, MathWorks, Natick, Massachusetts, USA) between surface area and the number of older adult falls. There was a strong positive linear relationship between the two variables, suggesting that the number of older adult falls occurring within locations was influenced by the surface area of the location. Any differences between the surface areas of locations in the care facilities used by Cleworth et al. (2021) and the surface area estimated using the Ontario retirement home could influence fall and concomitantly hip fracture estimates and subsequently the value of the ICER. As an example, if the surface area of the walkways was estimated to be greater in this thesis compared to the Cleworth et al. (2021) walkways, then the number of hip fractures estimated by the model would underestimate the number of hip fractures which would theoretically occur. This would lead to greater flooring costs to implement safety flooring, but a reduced number of hip fractures and hip fractures prevented. Consequently, the ICER calculated for the walkway would be consistently greater than reality. Therefore, the observation that the rooms with the lowest ICERS were not the same as rooms with the largest number of hip fractures prevented by safety flooring could be due to differences between the locations used in Cleworth et al. (2021) and the Ontario retirement home used to generate the ICERs.

In what follows costs were considered as positive values while savings are considered as negative values. Both Hypotheses 5 and 6 separated costs and savings into separate sub-hypotheses, this represented the distinctions between the costs to lay safety flooring which was borne by the retirement home and the estimated savings due to the predicted reduction in the number of hip fractures suffered. The savings are beneficial to the party/parties responsible for covering the cost of hip fractures which in Canada would be the various provincial governments. However, if these values were combined, i.e., costs subtract savings, as would be done when considering the societal perspective, then the value of the ICER would decrease (become less positive) i.e., making safety flooring a more favourable alternative. Additional ICER analyses are provided in Appendix C. The first row of **Table C 1** shows the updated ICER values for each location when estimated costs and savings were considered together within the economic evaluation. The most salient point was that placing compliant flooring within the walkways resulted in a positive ICER where the savings mediated by compliant flooring were less than the monetary cost to implement compliant flooring within the walkway. Therefore, this outcome relative to the others was not cost-saving. Furthermore, when the savings due to compliant flooring mediated hip fracture reductions were reduced to levels which represented more accurate incidence rate within the Canadian population (see section **5.7**) the ICERs for all locations were positive, indicating that the savings mediated by compliant flooring were less than the monetary costs to place compliant flooring (see the first rows in **Table C 2**, **Table C 3** and **Table C 4).**

Comparisons to the economic evaluation literature were challenging since the economic evaluation performed in this thesis was a cost-effectiveness analysis which valued the consequences of the safety flooring intervention in natural units i.e., hip fractures prevented. This choice should be better understood by administrators in retirement homes who may be a primary stakeholder for deciding whether to implement safety flooring within their facility. In comparison the literature valued the consequences in terms of dollars (Zacker & Shea, 1998), life-years saved (Zacker & Shea, 1998), and QALYs (Latimer et al., 2013; Ryen & Svensson, 2016). Additionally, the means of determining QALYs can vary depending on the method employed by the author (Gold et al., 2002). While all the existing economic evaluations demonstrated/projected safety flooring as cost effective when compared to standard flooring in the base case, these determinations were based on country-specific threshold values. When considering the model-predicted ICERs for placing safety flooring into the retirement home the worst value when considering only the costs expended to lay safety flooring was $45,253 (in the walkway). Therefore, placing safety flooring into the retirement home may be cost-effective but the decision to place safety flooring will be subject to certain questions and their answers i.e., Do the parties responsible for funding the safety flooring value the prevention of one hip fracture at $45,253? Are the parties capable of funding the safety flooring intervention? If the answers to both questions are yes, then the intervention of safety flooring is likely to be pursued. If one or more of the answers are no, then the intervention is unlikely to be pursued. Furthermore, when the savings were considered with the costs as would occur if the provincial government funded safety flooring in retirement homes the largest ICER value was $9222 dollars spent to prevent one hip fracture in the walkways (see Appendix C). However, when the savings were reduced to levels which represented their incidence rate within the Canadian population the worst ICER values exceeded $25,000,000 spent to prevent one hip fracture in the walkways (see Appendix C). The considerable variation in these figures indicate that ICERs are influenced by the underlying model assumptions i.e., the choice of costs and consequences also variables such as the social discount rate, time horizon, effectiveness of the intervention.

As safety flooring is only one of a multitude of interventions which could be considered to reduce hip fracture risk there is value in comparing the current economic evaluation outcomes to other intervention approaches. For example, a study by Visentin et al. (1997) estimated that using calcitonin to prevent one hip fracture in European women over 50 would cost 2,367,987 Italian Lira (1953 Canadian Dollars)[2]. However, if the women were screened using dual energy X-ray absorptiometry to determine the women in the lowest quartile of bone density, then using calcitonin to prevent one hip fracture would decrease to 838,120 Italian Lira (691 Canadian Dollars). In this study Visentin et al. (1997) used the sum of all direct medical and health-care costs, health care costs related to negative side effects of the calcitonin, savings in health care due to the prevention of a hip fracture and the cost of treating diseases that occurred because the patient had not died due to the hip fracture. This study indicated that screening to determine older adults who are at higher risk of falling and fracturing could reduce the ICER related to placing safety flooring in older adult care facilities. In contrast Scheckel et al. (2021) evaluated the cost-effectiveness of group-based exercise on fall prevention in community

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[2] Equivalent Canadian dollar values are determined according to historical exchange rates on the 31st of December of the year of publication of the original article. Figures are not adjusted.

dwelling older adults. They estimated ICERs of 52,864 and 169,805 Euros (76,6533 and 246,218 Canadian Dollars) per hip fracture avoided for women and men respectively. They determined that the group-based exercise intervention was not a cost-effective option. However, during a sensitivity analysis, the authors observed that inclusion of vertebral fractures which could be prevented by the group-based exercise intervention resulted in 12% and 54% reductions to the ICER. Therefore, if other types of fractures are reduced for falls onto safety flooring, then the ICER values calculated for safety flooring would become more cost-effective. However, in such a situation it may become necessary to change certain assumptions, i.e., cost per hip fracture prevented becomes cost per fracture prevented. Jonsson et al. (1995) estimated that the ICER for treating older adults with osteoporosis was equal to 350,000 Swedish Krona (71,400 Canadian Dollars) per hip fracture prevented if the treatment was given for 5 years and the yearly cost of the treatment was 6,000 Swedish Krona (1,224 Canadian Dollars). The authors observed increases in the ICER with increases in the cost of the treatment as well as increases in the ICER if the duration of the treatment was increased, finally there were increases in the ICER for reductions in the modelled effectiveness of the intervention. Increases in the duration of the treatment are equivalent to decreases in the lifetime of the safety flooring therefore in such a situation the ICER would be expected to increase. The largest ICER of $ 45,253 to prevent a hip fracture in the walkways compared favourably to the group-based exercise and the treatments for osteoporosis to reduce hip fractures. However, it compared less favourably to Calcitonin, it should be noted that the Calcitonin treatment study was done in a country (Italy) which had a very weak exchange rate to the Canadian dollar. This may negatively affect our ability to make comparisons between the ICERs.

5.7 Limitations

While the thesis provided novel insights into the potential of safety flooring to reduce older adult hip fracture risk within an older adult care setting, there were limitations which should be acknowledged. The mechanistic portion of the model assumed that the impact velocity was the same as the effective mass of the pelvis if it was dropped from the fall height with no resistance to its downward motion. Compensatory or reactionary balance mechanisms may provide resistance to the downward motion of an older adult leading to a reduction in their impact velocity during lateral falls onto the hip. A reduction in the impact velocity of older adults is responsible for a reduction in the impact force experienced at the hip. Therefore, the lack of attention to these responses which could reduce the magnitude of the impact velocity would lead to an overestimation of older adult hip fracture risk. Additionally, the model assumed that the loading is consistent with a lateral fall onto the hip, multiple factors may influence the orientation of a faller in real life which could lead to falls on the posterior or other aspects of the hip. This assumption also overestimates the population hip fracture risk, as the lateral fall orientation loads the hip in a manner which predisposes it to fracture. Also, this model assumed that all the simulated older adults fall, however, only about 20-30% of Canadian older adults fall each year, (Public Health Agency of Canada, 2014), therefore, of the 100,000 older adults generated by the model between twenty or thirty thousand of them will fall at least once. Further approximately 39% of fallers suffer from fractures of which approximately 8% of the fractures are hip fractures, (Public Health Agency of Canada, 2022). Therefore, a raw approximation of the number of hip fractures in a population of 100,000 would be slightly greater than 900 hip fractures within a year. According to Statistics Canada (2022) the older adult population is approximately 20% of the Canadian population or about seven million adults. Therefore, an approximation to the annual number of hip fractures in Canada would be 65,000 hip fractures. This figure is comparable to some of the hip fracture estimates provided within the model, however the Canadian older adult population is approximately 70 times greater than the simulated population. A lesser figure of 147 hip fractures per 100,000 adults was presented by the Public Health Agency of Canada (2020), however, this incidence rate included all adults older than 40. Even if a higher hip fracture rate of 3.2% (Berry et al., 1981) was chosen to represent the higher incidence of hip fractures in institutionalized adults, 3,200 hip fractures out of the simulated population is quite small compared to the model predictions. Therefore, the model overestimated actual hip fracture risk as well as potential savings for the simulated population. Considering more variables to predict fall risk within the model would be instructive and facilitate estimations of hip fracture risk which are better aligned with clinical observation. To accurately characterize the term ‘overestimation’ as used to describe the model estimations within the section, it is important to consider the model assumptions. The model simulates worst-case situations for older adults who fall from standing, the model does not assume reductions in impact velocity, or a redistribution of the impact load to other body parts. In such a situation the model provides a reasonable estimate of hip fracture risk. However, since most falls are not this severe, if fall severity were accounted for lower hip fracture rates than estimated within the model would occur. Still the model holds utility in the consideration of relative differences i.e., male vs female differences and location specific differences. Therefore, the information on relative differences and changes provided by these comparisons may facilitate additional analyses and insight.

When considering the savings, the one-year directly attributable hip fracture costs presented within Nikitovic (2013) may have underestimated the current costs of a hip fracture. Increases to the one-year directly attributable hip fracture costs may have occurred in the past decade, however, they were not considered. Indeed Hopkins et al. (2016) when estimating the economic burden of osteoporosis on Canada obtained a value that was double the similar estimate of Tarride et al. (2012). An increased cost of hip fracture would make safety flooring more cost effective, as it would increase the savings estimate for a given number of hip fractures. This model also ignored post hip fracture mortality which could reduce the magnitude of the savings estimated using the one-year directly attributable hip fracture costs since mortality should terminate any additional expenditure related to hip fracture. Additionally, the economic evaluation cannot be simply compared with other economic evaluations such as Latimer et al. (2013), Ryen and Svensson (2016), Zacker and Shea (1998). This model provided a dichotomous set of outcomes i.e., fracture and non-fracture, therefore the differential effect of falls were not considered extensively. In contrast Latimer et al. (2013) considered multiple outcomes of a fall i.e., no injury, minor injury, moderate injury, major injury. While the decision model used by Ryen and Svensson (2016) included three outcomes i.e., healthy, hip fracture or dead. Zacker and Shea (1998) considered morbidity (pain and suffering) in addition to mortality as part of their outcomes. Finally, this model does not account for temporally dependent characteristics such as the lifetime of safety flooring, mortality (lifetime of older adults), future benefits etc. Ryen and Svensson (2016) and Zacker and Shea (1998) both included mortality considerations, social discount rates and time horizons to consider the effect of safety flooring on hip fractures across multiple years. This model did not consider temporal characteristics as it aimed to use the factor of risk principle to classify older adults who were susceptible to hip fractures after a lateral fall onto the hip based on physical characteristics. Therefore, the model outputs cannot be simply compared to values presented within the literature. In conclusion the current model provides the most utility as a means of verifying the viability of the factor of risk (FOR) principle and comparing relative differences i.e., between sexes and safety flooring locations but caution should be exercised when interpreting its output i.e., estimated hip fractures, savings and ICERs.

5.8 Synthesis, Independent and Novel Contributions of Thesis

The goal of this thesis was to extend the capabilities of the probabilistic model presented by Martel (2017) and Martel et al. (2020), thereby increasing its real-world utility. All necessary modifications were completed and verified in a multi-stage process to ensure the correctness of the outputs. The modifications allowed the hip fracture model to generate a population of older adults with retirement home characteristics, quantify their hip fracture risk for situations where safety flooring was placed in specific locations within a simulated retirement home and consider the associated economic benefit of placing safety flooring in each location.

To facilitate the generation of a different population of older adults, the differences in the age and sex distributions for older adults within a retirement home were determined from a Microsoft Excel spreadsheet which contained the age, gender, height, and mass information for 2697 older adults in the retirement home and 1585 older adults who were previously within the retirement home. These differences were used to modify the way the population of older adults within the retirement home was generated. Additionally, two regression equations for the determination of older adult heights and masses (See Appendix D) were developed to account for the relationship between mass and height which was not present in the Martel et al. (2020) model. These regression equations addressed one limitation of the Martel et al. (2020) model where older adults could theoretically be simulated with incongruent characteristic i.e., a very tall older adult with a very low body weight. This limitation followed from the independent generation of mass and height variables. Therefore, the anthropometric characteristics of the older adults simulated in the updated model were similar to those of retirement home older adults, which were significantly different from those of the Canadian older adults. The anthropometric characteristics of the older adults simulated in the updated model were also dependent on each other as one would expect in reality.

To facilitate the consideration of safety flooring placement on hip fracture risk and potential economic benefit. A spatial dimension was imposed onto the model, where older adults were not only assigned variables which were fundamental to the mechanistic portion of the model. Therefore, older adults were assigned variables which served to locate them in space consistent with the room categorization of Cleworth et al. (2021). When combined with a decision module to compare the location of safety flooring and the location of the older adult, the updated model could determine how hip fracture risk was influenced by the absence or presence of safety flooring. Furthermore, with this information the model could additionally be used to consider the economic implications of safety flooring by estimating savings due to a safety flooring mediated reduction in the hip fractures.

Furthermore, the updated model could theoretically compare the effect of safety flooring on hip fracture risk in different older adult populations simulated to fall in a retirement home setting.

This thesis contributed important insight into the hip-fracture modelling literature. Initially, the importance of population-specific considerations of hip fractures was shown. Then a model which incorporated fall frequencies observed within Ontario older adult settings was completed. This model then integrated the individual location specific characteristics of one Ontario retirement home i.e., surface areas to estimate savings and ICERs related to safety-flooring mediated reductions in hip fractures for that location.

Though the Canadian population contained the retirement home population, the retirement home population was significantly different from the Canadian population. If the output of a model generating a population with Canadian characteristics was used to make estimates or predictions about a retirement home population then the output would underestimate the hip fracture risk, number of hip fracture and potential savings due to safety flooring while overestimating the ICERs. Estimated savings and ICERs are dependent on the number of hip fractures estimated within the model and these values may vary dependent on factors such as population age, population mass, population height, population bone mineral density, population TSTT, presence/absence of safety flooring or other impact force reduction interventions. The importance of hip fracture estimations tailored to the population of interest would be relevant to policy makers, as the accuracy of this information could influence their budgeting, fund allocation, and design decisions.

Through the incorporation of observed fall frequencies, the model was equipped with the ability to estimate hip fracture risk for specific combinations of safety flooring which was not previously possible. Coupled with the location specific characteristics of the Ontario retirement home, the model provided a simple tool for indicating the most appropriate locations to place safety flooring subject to desired goals and/or budgetary constraints. Additionally, the model could consider the sex-specific hip fracture risk for specific combinations of safety flooring. Though unlikely to influence decisions on implementation of safety flooring (due to ethical considerations), the model clearly indicates a greater (relative) benefit in savings and hip fracture reductions for older adult males. This would also be important to policy and decision makers, as this information could influence administrative decisions related to the placement of safety flooring. The model provides both costs and savings estimates for the placement of safety flooring therefore, optimal balance based on one or both variables could be determined and used to guide the spatial distribution of safety flooring.

5.9 Future Directions

Though the capabilities of the model were increased, there are still further changes which could be implemented to improve the validity of the model outputs. Initially factors responsible for determining fall risk should be integrated into the model. As stated within the limitations, this model subjects all older adults to a lateral fall onto the hip. Therefore, all older adults fall in a manner which maximally leads to hip fractures, this is not consistent with reality where only a subset of the older adult population falls at least once. Subsequently, variables associated with fall risk such as balance, vision challenges, drug use, history of previous falls, cognitive disability etc., as presented within Tinetti et al. (1988) and Li et al. (2023) could be integrated into the model towards providing a more accurate representation of older adult falls within a population.

Within this model a lumped parameter (LP) mass-spring model was used to estimate the peak impact force experienced during a lateral fall onto the hip (Martel et al., 2020). According to Robinovitch et al. (1997b) this model was better at estimating the peak impact forces during simulated sideways falls when compared to the Voigt (spring-damper) model which is another LP model. Furthermore, Laing and Robinovitch (2010) indicated that the mass-spring model predicted peak impact forces to within 5% of observed values when human volunteers were subjected to sideway falls. In the future the estimation of peak impact forces may be replaced by sex-specific regression equations as introduced by Sarvi and Luo (2019). Attempts to integrate sex-specific differences within this model can only improve the accuracy of the model outputs. Another potential change to enhance the accuracy of the model output would include the integration of contact mechanics equations as suggested by Levine (2017).

The role of trochanteric soft tissue thickness (TSTT) in reducing hip fracture risk has been presented by both Robinovitch et al. (1995) and Levine et al. (2013). Further, the importance of TSTT in energy absorption Fleps et al. (2018) and influencing impact loads during sideways falls Majumder et al. (2013) encouraged Martel et al. (2020) to include TSTT effects within the probabilistic mechanistic model. TSTT effects were modelled according to the equations presented by Robinovitch (1995) for the attenuation of impact force by TSTT. However, there are potential limitations to these equations including the lack of age and sex-specific considerations. As further research is conducted into the relationship between TSTT and impact force attenuation the model can be updated to reflect new information further enhancing the accuracy of the model outputs.

Finally, the force attenuation estimates provided within the probabilistic mechanistic model based on in-vitro approaches presented in Martel (2017) could be replaced with regression equations based on in-vivo approaches. The current regression equations presented issues for generating force attenuation estimates for a large proportion of the simulated populations, specifically indicating minimal or no attenuation for falls onto safety flooring. Therefore, more accurate regression equations could facilitate better estimates of the effect of safety flooring on hip fracture risk during lateral falls onto the hip.

The type of economic evaluation which was performed within this thesis was a cost-effectiveness analysis. Though simpler to understand by non-technical audiences i.e., non-economists, the economic evaluation could be changed to a cost-utility analysis, which would bring the conclusions into agreement with the published literature. This agreement should facilitate much simpler comparisons particularly between different types of interventions i.e., fall prevention program, dietary changes etc.

Each of the changes suggested within this section should ultimately lead to better estimations of the number of hip fractures with and without safety flooring i.e., hip fracture estimates which are close to the frequency observed clinically. Better estimations will then facilitate more accurate estimations of safety flooring mediated savings and ICERs relative to other hip fracture prevention interventions. These accurate estimates will then provide an improved understanding of the relationships (including sex-specific relationships) between the location of safety flooring within older adult care settings and potential savings and ICERs.

5.10 Significance

Hip fractures are a serious public health issue in Canadian older adults. Their negative post fracture outcomes continually indicate that there is still potential to increase our understanding of the injury mechanisms and potential mitigating factors. This thesis continued the work of Martel (2017) and Martel et al. (2020) by quantifying hip fracture risk at the population level, however, unlike Martel it considered intermediate situations which were challenging to replicate experimentally and/or observationally due to the high costs of safety flooring. The ability to model a population of old adults and quantify their hip fracture risk is a step towards removing some of the challenges associated with age related physical and mental decline which makes specific experimental paradigms unrealistic. The ability to estimate savings and incremental cost-effectiveness ratios due to safety flooring could provide federal, provincial, and regional policy makers and stakeholders as well as administrators with evidence to support or oppose the implementation of safety flooring in older adult care facilities. In addition to the evidence on the feasibility of safety flooring in older adult care settings the information provided by this model could even guide optimal safety flooring placement based on observed fall location data. These quantifiable metrics should remove guesswork and provide decision makers with actionable insight into the potential benefits of safety flooring within older adult care facilities.

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Appendix A: Model Modifications

A few modifications were performed to generate the final model whose output was presented within this thesis. Some of these were omitted from the Methods and/or Discussion section due to having minimal relevance to the hypotheses. These modifications are presented within the appendix for interested readers.

Two of the major modifications to the model were: a) the addition of the fall location variable to each virtual individual and, b) the creation of a safety floor location variable. The first modification allowed the model to simulate falls within a retirement home by recreating the observed fall proportion of older adults in specified locations. The second modification allowed for modelling the effect of placing safety flooring within specific retirement home locations on the population hip fracture risk. (Table A 1) highlights the effort to recreate the fall proportions within retirement home locations. There was a high level of agreement between the simulated percentages and the observed percentages presented by Cleworth et al. (2021). Specifically, the difference between the simulated and observed percentages was always less than 1%.

Two other major modifications to the model were changes to the method in which virtual individual heights and masses were simulated. From the original probabilistic model presented in Martel (2017) and Martel et al. (2020) both variables were simulated using a cumulative distribution function (CDF) method. An issue with the CDF method was the potential to assign unlikely values to a virtual individual, such as a virtual individual with an above average height but below average mass. To reduce the likelihood of such an occurrence both modules responsible for generating mass and height were replaced with new modules which used regression equations. These regression equations were developed from the retirement home older adult data set using the R statistical programming language (R Core Team, 2022) and are:

$$h = 1.6675 + 0.1409s - 0.0026a \qquad (\boldsymbol{A.1})$$

$$m = 25.4907 + 7.3115s - 0.4653a + 45.0504h \qquad (\boldsymbol{A.2})$$

Where 'h' represents the height of the virtual individual, 'm' represents the mass of the virtual individual, 's' is a dichotomous variable which represents the sex of the virtual individual, and 'a' is the age of the virtual individual. All the coefficients and intercepts were significant ($p < .001$).

Another major modification to the model was the change to the age module, though the CDF method was retained. The age distribution and the Male/Female proportions observed at each age were changed to represent the retirement home older adult population (**Figure A 1**). These proportions were averaged across five-year bins to account for an anomaly where there were no female older adults at one age value. Also due to the completeness of the age data there was no need to fit a polynomial function to the datapoints for the purposes of interpolation. Therefore, the age distribution function was replaced with 41 separate age frequency bins representing ages from 60-100. The age distribution function was exactly the age distribution of the retirement home population presented in (**Figure 18**).

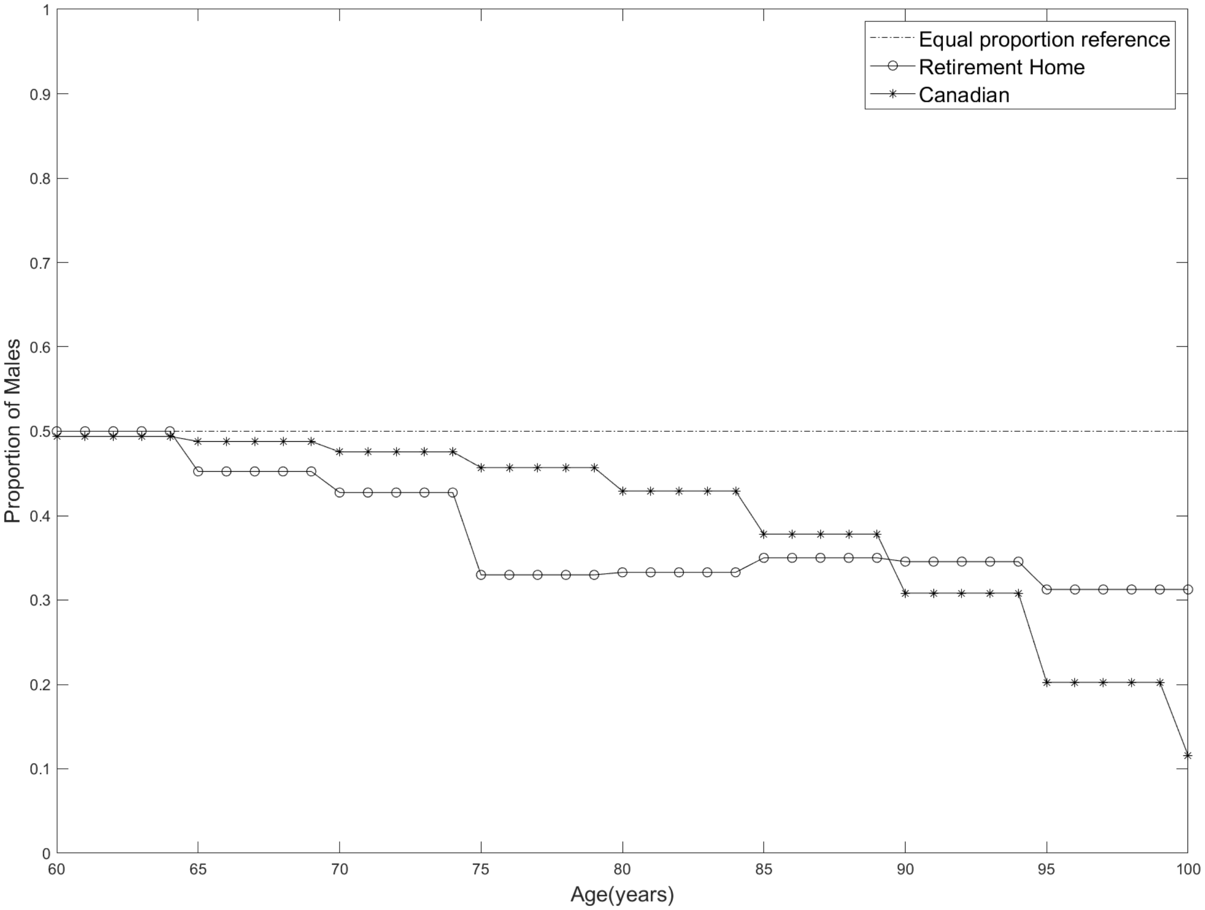

Figure A 1: Male age proportions at each age for retirement home and Canadian older adults.

Table A 1: Table of simulated and observed fall locations within the Retirement Home simulation.

Fall Location	Male	Female	Simulated (n (%))	Observed (n (%))	Difference (n (%))
Activity Room	129	287	416 (0.416)	400 (0.4)	16 (< 1%)
Dining Room	1017	1959	2976(2.976)	3000 (3.0)	24 (< 1%)
Lounge	1969	3744	5713 (5.713)	5800 (5.8)	87 (< 1%)
Walkway	2209	4106	6315 (6.315)	6300 (6.3)	15 (< 1%)
Other	2797	5366	8163 (8.163)	8200 (8.2)	37 (< 1%)
Bathroom	4632	8886	13518 (13.518)	13500 (13.5)	18 (< 1%)
Bedroom	21601	41298	62899 (62.899)	62800 (62.8)	99 (< 1%)

Appendix B: Linear Regression

Linear Regression was performed on the observed number of falls in each location (per 1000 falls) presented within Cleworth et al. (2021) and the surface area of each location within the retirement home as estimated from the floor plans. The linear regression model **(Figure B 1**) indicated a very strong relationship between the two variables, ($R = 0.9935$, $p < .001$). This suggested that the number of falls observed in a particular location are strongly related to the surface area of the location.

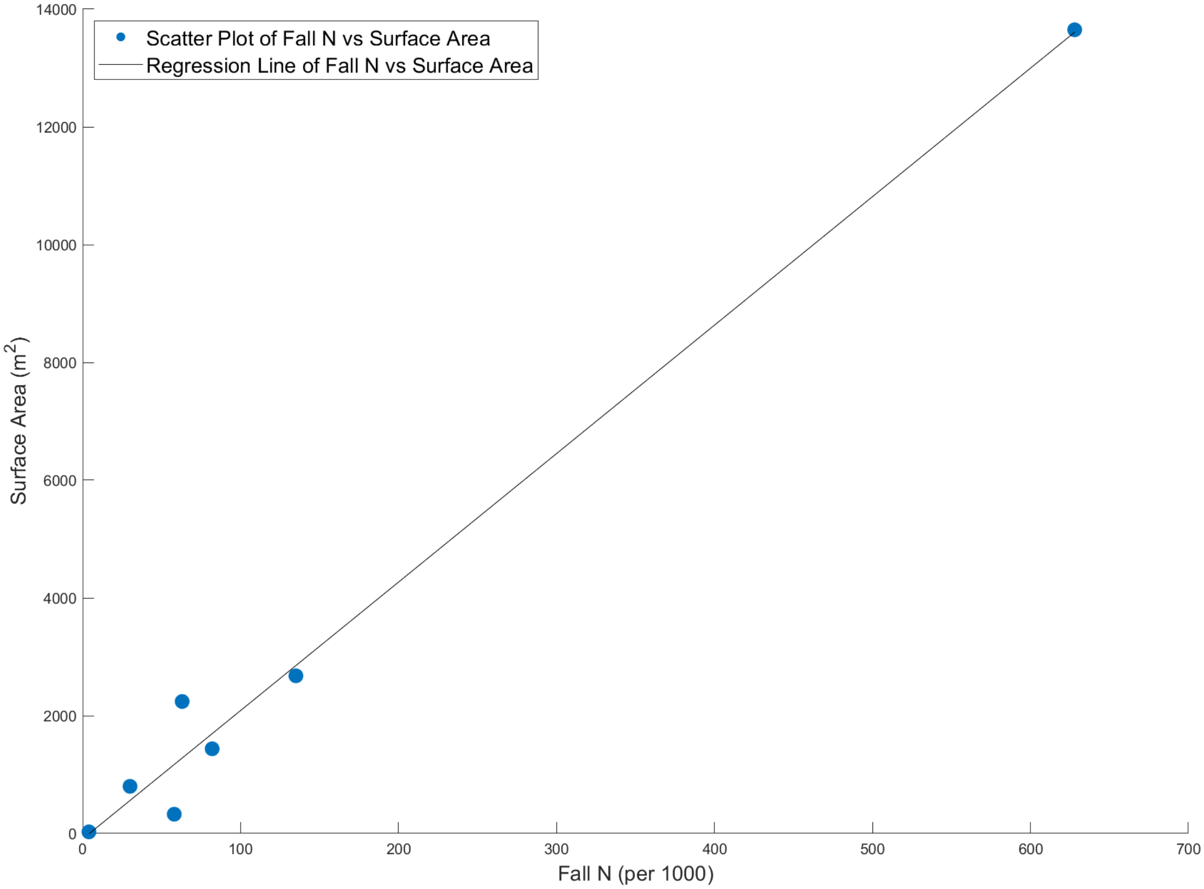

Figure B 1: Scatterplot and line of best fit for observed fall frequency and estimated surface area data.

Appendix C: Economic Evaluation

The ICER values for safety flooring relative to standard flooring which were presented within the results and discussion were difficult to interpret relative to other economic evaluations. Two of the reasons were a lack of temporal considerations i.e., no consideration of mortality or morbidity, added years of life etc., and the overestimation of hip fractures relative to falls as observed within the Canadian older adult population (See section **5.7** for an explanation). It should be noted that the hip fractures predictions of the mechanistic model are worst-case estimates for falls from standing height. The impact velocity, orientation of the faller and transfer of energy to other body segments may reduce the impact forces experienced at the hip but are not considered within the model. Therefore, the number of hip fractures estimated are not congruent with real-life observations, though they are representative of the worst-case scenario they are overstated relative to observational data. Consequently, the ICER values have savings and hip fractures prevented estimates which are both greater than observed. An attempt was made to determine more representative ICER values by reducing the number of hip fractures occurring in the simulated population to levels like those observed within a) the general Canadian older adult population, and b) the institutionalized Canadian older adult population. To achieve this all the estimated number of hip fractures and their savings were divided (multiplied) by a) 70.00 (0.0143), b) 25.93 (0.0386) and c) 565.99 (0.0018) (See section **5.7** for an explanation). The number of hip fractures observed in the standard flooring only condition was used as a reference to determine the appropriate division (multiplication) factor. Additionally, to account for the lack of temporal considerations, time horizons from the 1st year up to the 40th year were considered. The related assumptions were that a) the same number of hip fractures occurred each year, b) the retirement home was always fully populated, c) the safety flooring did not have any maintenance costs once laid, d) savings for a year occurred at the beginning of the year. A social discount rate of 1.5% as suggested by Canada's Drug and Health Technology Agency (2023) was used to determine how future savings due to hip fracture would be calculated within the model. The appropriate equations C.1 and C.2 obtained from Hurley (2010) to calculate present costs are shown where *P* = present cost, *F* = future cost, *T* = the sum of present costs.

$$P = \frac{F}{(1 + 0.015)^{t-1}} \qquad (\boldsymbol{C.1})$$

$$T = \sum_{1}^{t} \frac{F}{(1 + 0.015)^{t-1}} \qquad (\boldsymbol{C}.\mathbf{2})$$

The following tables and figures show how the ICER for safety flooring relative to standard flooring changed using the assumptions above over a 40-year period. In each table the hip fracture rates within the population were different, in **Table C 1** the hip fracture rates were exactly as estimated by the hip fracture model. In **Table C 2** the hip fracture rates were the estimated rate of hip fractures within the general Canadian older adult population (900 per 100,000). In **Table C 3** the hip fracture rates were the estimated rate of hip fractures within the Canadian institutionalized older adult population (3200 per 100,000). In **Table C 4** the hip fracture estimates are the observed rates for adults 40 years and older as presented by the Public Health Agency of Canada (2020), (147 per 100,000). The discussion and the literature consider the ICER numerator i.e., net costs as costs subtract savings for the situations when savings were considered, the tables and figures in this section employ the same convention i.e., the ICER's numerator is costs subtract savings. With this convention negative values are cost-saving i.e., the cost to implement safety flooring is less than the savings due to the hip fractures prevented/avoided by the implementation of safety flooring. As the effectiveness of the safety flooring increases, i.e., the number of hip fractures prevented increases the ICER becomes more cost-effective. Additionally, increasing the social discount rate has the opposite effect i.e., the ICER becomes less cost-effective. Since the present value of future costs is the future value divided by an increasing denominator the present value of the savings decreases leading to a less cost-effective ICER. **Table C 5, Table C 6, Table C 7** and **Table C 8** have similar hip fracture rates to the tables above, however they used a social discount rate of 3.0%. **Table C 9**, **Table C 10**, **Table C 11** and **Table C 12** also have similar fracture rates to the tables above, however they used a social discount rate of 4.5%. The general trend is for the ICER to become more cost effective as the estimated lifetime of the safety flooring increases.

Table C 1: Safety Flooring ICER changes over a 40-year period model predicted number of hip fractures per year estimate. The ICER numerator is Costs subtract Savings, therefore positive values indicate costs exceeding savings. The social discount rate is equal to 1.5%.

Year	Activity Room	Dining Room	Lounge	Walkway	Other	Bathroom	Bedroom	Everywhere	Bathroom & Bedroom
1	-27745	-1472	-28439	9222	-13612	-8108	-8048	-8867	-8058
2	-31677	-18469	-31928	-13138	-24541	-21780	-21732	-22150	-21740
3	-32813	-23960	-32917	-20416	-28009	-26163	-26119	-26403	-26126
4	-33251	-26577	-33282	-23926	-29614	-28225	-28183	-28400	-28190
5	-33411	-28045	-33400	-25930	-30475	-29361	-29320	-29497	-29327
6	-33434	-28940	-33395	-27183	-30965	-30034	-29995	-30145	-30002
7	-33380	-29509	-33321	-28007	-31245	-30445	-30406	-30537	-30413
8	-33279	-29874	-33205	-28564	-31394	-30692	-30654	-30771	-30661
9	-33146	-30106	-33061	-28944	-31457	-30831	-30794	-30899	-30800
10	-32992	-30244	-32899	-29201	-31460	-30895	-30858	-30954	-30865
11	-32824	-30314	-32724	-29369	-31420	-30905	-30869	-30958	-30875
12	-32646	-30334	-32540	-29470	-31349	-30876	-30839	-30922	-30846

13	-32460	-30317	-32350	-29521	-31253	-30816	-30780	-30857	-30786
14	-32269	-30270	-32155	-29533	-31140	-30733	-30697	-30770	-30703
15	-32074	-30201	-31957	-29515	-31013	-30631	-30596	-30665	-30602
16	-31876	-30113	-31757	-29471	-30874	-30516	-30481	-30546	-30487
17	-31676	-30010	-31555	-29408	-30727	-30389	-30354	-30417	-30360
18	-31476	-29896	-31353	-29328	-30572	-30253	-30218	-30278	-30224
19	-31274	-29771	-31150	-29235	-30413	-30109	-30075	-30132	-30081
20	-31072	-29639	-30947	-29131	-30249	-29959	-29926	-29981	-29932
21	-30871	-29501	-30744	-29018	-30081	-29805	-29772	-29825	-29777
22	-30669	-29357	-30542	-28897	-29911	-29647	-29614	-29665	-29619
23	-30468	-29208	-30341	-28769	-29738	-29485	-29452	-29502	-29458
24	-30268	-29056	-30140	-28636	-29564	-29321	-29289	-29337	-29294
25	-30069	-28901	-29940	-28499	-29389	-29155	-29123	-29170	-29129
26	-29870	-28744	-29742	-28358	-29213	-28988	-28956	-29001	-28961
27	-29673	-28585	-29544	-28214	-29037	-28819	-28787	-28831	-28793
28	-29477	-28424	-29348	-28067	-28860	-28650	-28618	-28661	-28623

29	-29282	-28262	-29153	-27918	-28683	-28480	-28448	-28490	-28454
30	-29088	-28099	-28959	-27767	-28506	-28309	-28278	-28319	-28283
31	-28896	-27935	-28767	-27615	-28329	-28139	-28108	-28147	-28113
32	-28705	-27771	-28576	-27462	-28153	-27968	-27937	-27976	-27943
33	-28515	-27607	-28387	-27308	-27978	-27798	-27767	-27805	-27772
34	-28327	-27443	-28199	-27153	-27802	-27628	-27597	-27635	-27603
35	-28140	-27279	-28012	-26998	-27628	-27458	-27428	-27464	-27433
36	-27954	-27115	-27827	-26842	-27455	-27289	-27259	-27295	-27264
37	-27770	-26951	-27643	-26686	-27282	-27120	-27091	-27126	-27096
38	-27588	-26788	-27461	-26531	-27110	-26953	-26923	-26957	-26928
39	-27407	-26626	-27281	-26375	-26939	-26785	-26756	-26790	-26761
40	-27227	-26464	-27101	-26220	-26769	-26619	-26590	-26623	-26595

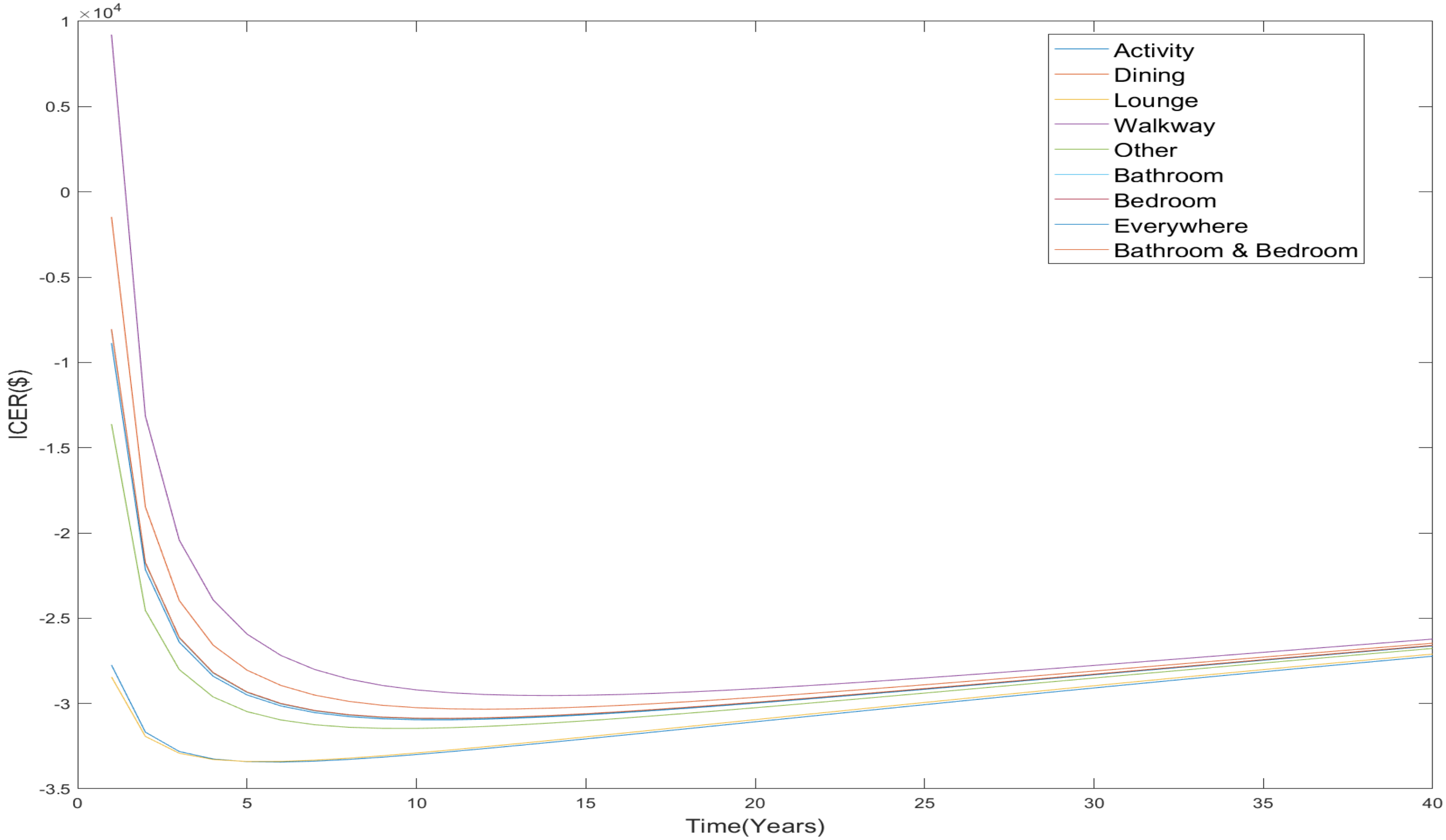

Figure C 1: Retirement home safety floor ICER changes over a 40-year period using the model predicted number of hip fractures per year. The social discount rate is equal to 1.5%.

Table C 2: Safety Flooring ICER changes over a 40-year period 900 hip fractures per year estimate. The ICER numerator is Costs subtract Savings, therefore positive values indicate costs exceeding savings. The social discount rate is equal to 1.5%.

Year	Activity Room	Dining Room	Lounge	Walkway	Other	Bathroom	Bedroom	Everywhere	Bathroom & Bedroom
1	551736	2380808	489710	3131647	1531244	1915352	1916948	1860846	1916672
2	258063	1172671	227146	1548074	747888	939950	940766	912707	940625
3	160348	770133	139800	1020392	486943	614991	615547	596835	615451
4	111620	568994	96255	756680	356600	452640	453066	439028	452992
5	82485	448412	70230	598554	278496	355331	355679	344446	355619
6	63146	368107	52963	493221	226511	290542	290838	281474	290787
7	49403	310817	40701	418054	189448	244335	244593	236565	244549
8	39157	267911	31564	361739	161713	209740	209970	202944	209931
9	31241	234592	24511	317992	140194	182886	183095	176847	183059
10	24956	207985	18916	283041	123026	161451	161642	156017	161609
11	19856	186257	14380	254488	109021	143955	144131	139016	144101
12	15644	168189	10639	230732	97389	129413	129577	124887	129549

13	12115	152935	7508	210665	87582	117143	117297	112967	117270
14	9123	139893	4855	193497	79207	106657	106803	102781	106778
15	6558	128618	2586	178647	71978	97599	97737	93982	97713
16	4342	118780	627	165680	65680	89701	89831	86311	89809
17	2411	110124	-1076	154264	60147	82756	82881	79567	82859
18	718	102453	-2567	144140	55253	76606	76726	73595	76705
19	-775	95612	-3879	135103	50895	71126	71241	68274	71221
20	-2098	89475	-5039	126990	46994	66214	66324	63505	66305
21	-3276	83941	-6071	119669	43483	61788	61895	59209	61876
22	-4329	78929	-6990	113032	40310	57783	57886	55322	57868
23	-5273	74369	-7812	106988	37429	54143	54243	51790	54226
24	-6123	70206	-8550	101465	34805	50823	50920	48568	50903
25	-6889	66390	-9214	96398	32405	47783	47877	45619	47861
26	-7582	62882	-9813	91735	30204	44991	45083	42911	45067
27	-8211	59648	-10353	87431	28180	42420	42509	40417	42494
28	-8781	56658	-10843	83448	26314	40045	40132	38115	40117

29	-9300	53886	-11286	79752	24588	37847	37931	35983	37916
30	-9772	51310	-11688	76313	22989	35806	35889	34005	35874
31	-10203	48912	-12053	73108	21505	33909	33989	32166	33975
32	-10596	46675	-12384	70114	20124	32140	32219	30452	32205
33	-10955	44583	-12685	67311	18836	30489	30566	28853	30553
34	-11283	42624	-12959	64683	17634	28945	29020	27357	29007
35	-11583	40786	-13208	62214	16511	27498	27572	25956	27559
36	-11858	39059	-13434	59892	15458	26141	26213	24642	26201
37	-12109	37434	-13639	57703	14471	24865	24936	23407	24924
38	-12338	35903	-13826	55638	13544	23665	23735	22245	23723
39	-12548	34458	-13995	53687	12673	22534	22603	21151	22591
40	-12740	33093	-14148	51841	11852	21467	21535	20120	21523

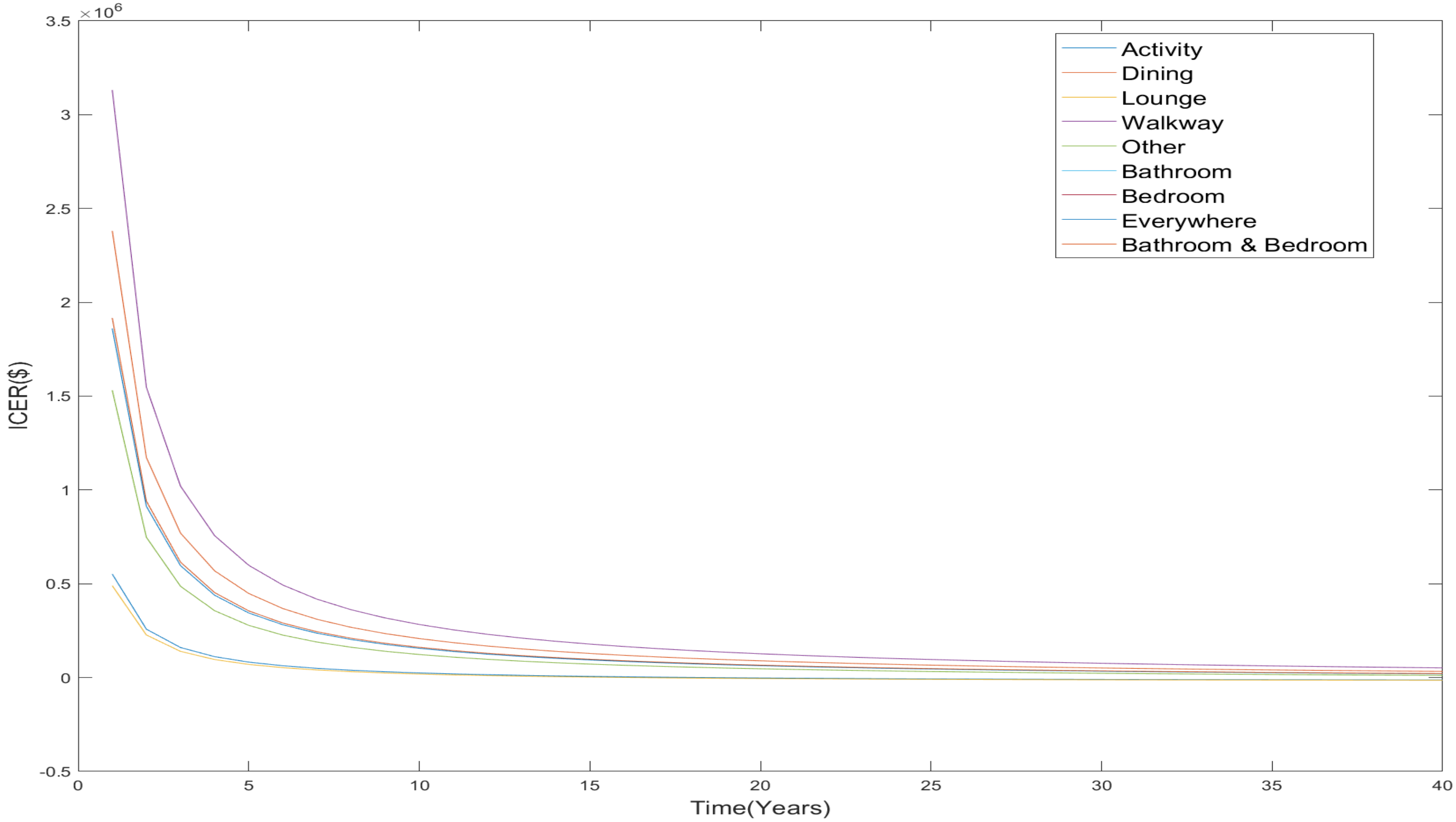

Figure C 2: Retirement home safety floor ICER changes over a 40-year period 900 hip fractures per year. The social discount rate is equal to 1.5%.

Table C 3: Safety Flooring ICER changes over a 40-year period 3200 hip fractures per year estimate. The ICER numerator is Costs subtract Savings, therefore positive values indicate costs exceeding savings. The social discount rate is equal to 1.5%.

Year	Activity Room	Dining Room	Lounge	Walkway	Other	Bathroom	Bedroom	Everywhere	Bathroom & Bedroom
1	181618	859235	158766	1137339	544537	686829	687444	666652	687338
2	73005	411884	61674	550921	254534	325689	326014	315610	325958
3	36975	262942	29485	355623	158041	205483	205712	198770	205673
4	19090	188600	13519	258103	109924	145509	145690	140479	145659
5	8461	144097	4041	199693	81155	109627	109778	105607	109752
6	1459	114511	-2194	160837	62059	85788	85921	82442	85898
7	-3471	93449	-6577	133153	48490	68832	68950	65966	68929
8	-7108	77714	-9804	112450	38374	56175	56283	53669	56264
9	-9883	65528	-12260	96402	30559	46384	46483	44159	46466
10	-12056	55827	-14178	83611	24355	38598	38691	36597	38675
11	-13791	47932	-15705	73187	19321	32271	32358	30453	32343
12	-15199	41391	-16940	64540	15164	27036	27118	25371	27104

13	-16355	35891	-17950	57257	11681	22641	22720	21106	22706
14	-17314	31209	-18783	51046	8728	18906	18981	17481	18968
15	-18116	27180	-19477	45693	6197	15698	15770	14370	15758
16	-18791	23681	-20057	41036	4010	12918	12987	11674	12975
17	-19361	20620	-20543	36952	2106	10490	10557	9320	10546
18	-19844	17922	-20953	33345	436	8355	8420	7251	8409
19	-20255	15529	-21297	30140	-1036	6467	6530	5421	6519
20	-20604	13396	-21587	27275	-2341	4787	4849	3795	4838
21	-20901	11486	-21830	24702	-3503	3287	3347	2343	3337
22	-21153	9767	-22033	22381	-4540	1941	2000	1041	1990
23	-21365	8214	-22201	20279	-5471	729	786	-132	777
24	-21544	6807	-22340	18368	-6308	-366	-310	-1190	-319
25	-21694	5527	-22452	16626	-7063	-1358	-1303	-2149	-1313
26	-21818	4360	-22541	15031	-7746	-2260	-2206	-3019	-2215
27	-21919	3293	-22611	13568	-8364	-3081	-3028	-3812	-3037
28	-21999	2316	-22662	12223	-8926	-3830	-3779	-4535	-3788

29	-22062	1418	-22698	10982	-9436	-4516	-4466	-5196	-4474
30	-22109	591	-22719	9836	-9901	-5145	-5095	-5801	-5103
31	-22142	-171	-22728	8776	-10325	-5721	-5672	-6357	-5681
32	-22162	-874	-22726	7792	-10711	-6251	-6203	-6866	-6211
33	-22170	-1525	-22714	6877	-11064	-6739	-6692	-7335	-6700
34	-22169	-2128	-22693	6027	-11386	-7188	-7142	-7766	-7150
35	-22158	-2687	-22663	5234	-11681	-7603	-7557	-8164	-7565
36	-22139	-3207	-22627	4494	-11950	-7985	-7940	-8530	-7948
37	-22112	-3689	-22584	3803	-12197	-8338	-8294	-8869	-8301
38	-22078	-4138	-22535	3157	-12422	-8665	-8621	-9181	-8628
39	-22038	-4556	-22481	2551	-12628	-8967	-8923	-9469	-8931
40	-21993	-4946	-22421	1983	-12816	-9246	-9203	-9735	-9210

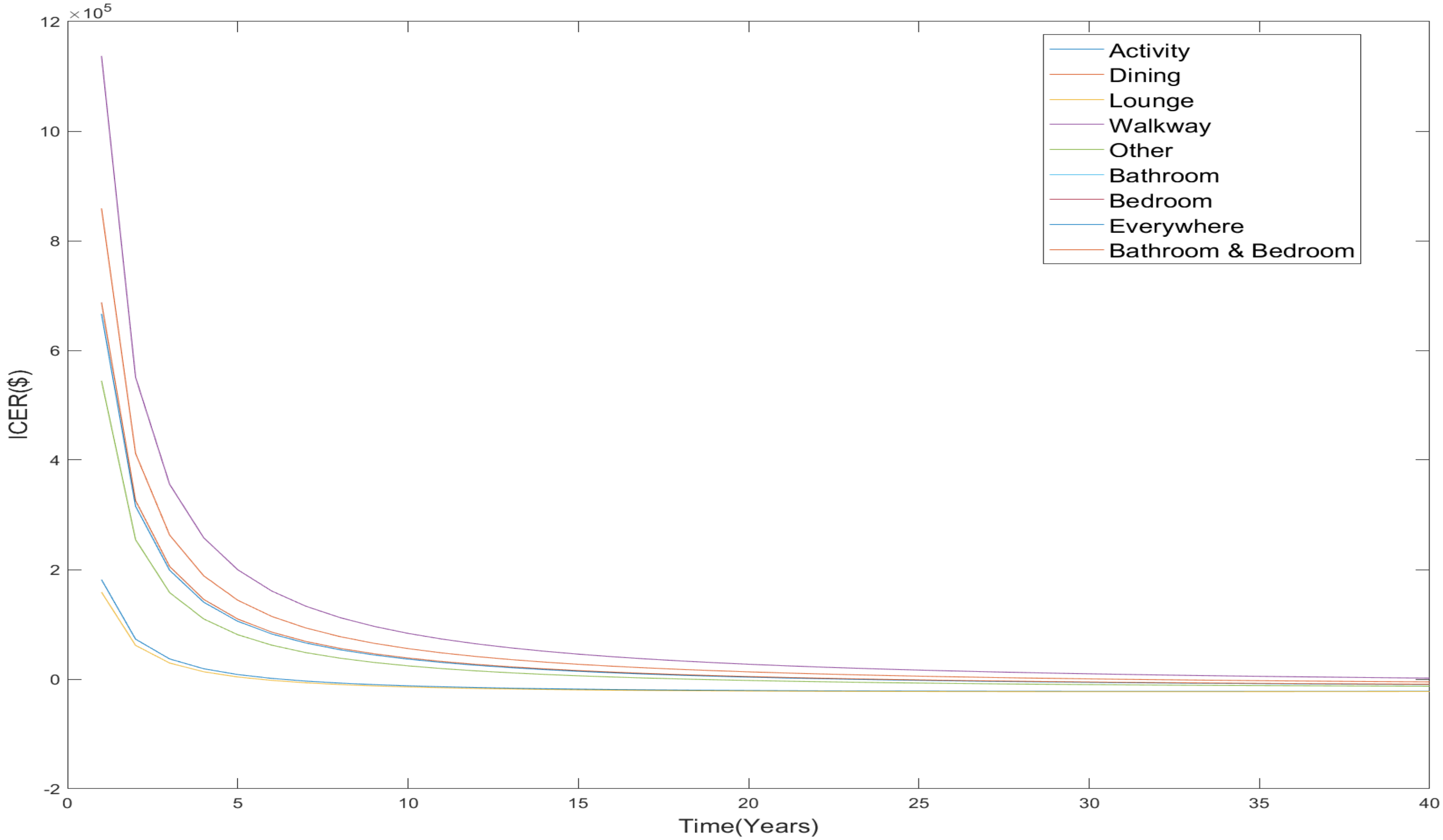

Figure C 3: Retirement home safety floor ICER changes over a 40-year period 3200 hip fractures per year. The social discount rate is equal to 1.5%.

Table C 4: Safety Flooring ICER changes over a 40-year period 147 hip fractures per year estimate. The ICER numerator is Costs subtract Savings, therefore positive values indicate costs exceeding savings. Social discount rate equal to 1.5%.

Year	Activity Room	Dining Room	Lounge	Walkway	Other	Bathroom	Bedroom	Everywhere	Bathroom & Bedroom
1	4717188	19505233	4214298	25576406	12636054	15741662	15754294	15300806	15752114
2	2340789	9734883	2089440	12770454	6300292	7853105	7859439	7632687	7858346
3	1548832	6478275	1381329	8501978	4188546	5223760	5227995	5076822	5227264
4	1152983	4850100	1027402	6367870	3132803	3909217	3912402	3799018	3911853
5	915575	3873296	815148	5087506	2499458	3120593	3123148	3032438	3122707
6	757388	3222178	673728	4234014	2077312	2594927	2597062	2521467	2596694
7	644467	2757164	572785	3624448	1775850	2219522	2221357	2156559	2221040
8	559838	2408464	497138	3167334	1549814	1938029	1939639	1882939	1939361
9	494069	2137306	438354	2811854	1374061	1719143	1720578	1670176	1720330
10	441501	1920427	391375	2527517	1233507	1544082	1545376	1500013	1545153
11	398533	1743023	352979	2294921	1118549	1400892	1402072	1360831	1401868
12	362765	1595224	321021	2101128	1022790	1281605	1282689	1244884	1282502

13	332535	1470199	294014	1937185	941798	1180705	1181708	1146810	1181535
14	306655	1363066	270897	1796694	872407	1094251	1095185	1062778	1095023
15	284255	1270246	250892	1674964	812298	1019353	1020227	989980	1020076
16	264682	1189056	233414	1568478	759730	953845	954666	926308	954524
17	247437	1117443	218017	1474544	713371	896068	896842	870152	896709
18	232132	1053810	204355	1391071	672187	844735	845467	820259	845341
19	218459	996897	192152	1316406	635359	798826	799522	775640	799402
20	206174	945696	181190	1249228	602235	757529	758191	735503	758077
21	195079	899390	171291	1188467	572284	720184	720816	699207	720707
22	185010	857312	162310	1133248	545074	686252	686857	666229	686752
23	175833	818909	154126	1082847	520247	655287	655867	636136	655767
24	167438	783723	146641	1036663	497505	626919	627476	608566	627380
25	159729	751367	139769	994188	476597	600835	601371	583217	601278
26	152627	721514	133441	954995	457312	576773	577288	559833	577199
27	146065	693886	127594	918719	439470	554506	555003	538194	554917
28	139985	668244	122178	885047	422914	533842	534323	518113	534240

29	134337	644383	117148	853709	407513	514616	515081	499430	515001
30	129076	622125	112465	824472	393150	496683	497133	482004	497056
31	124167	601313	108095	797133	379724	479919	480355	465713	480280
32	119575	581813	104009	771512	367149	464212	464636	450451	464563
33	115271	563505	100181	747455	355346	449468	449880	436124	449809
34	111230	546284	96588	724823	344247	435601	436001	422650	435932
35	107430	530055	93209	703493	333791	422535	422925	409955	422858
36	103849	514738	90027	683357	323925	410205	410584	397974	410518
37	100471	500257	87025	664318	314601	398549	398919	386649	398855
38	97279	486546	84190	646290	305776	387515	387875	375929	387813
39	94258	473546	81508	629194	297411	377055	377406	365766	377346
40	91396	461204	78967	612960	289472	367125	367468	356119	367409

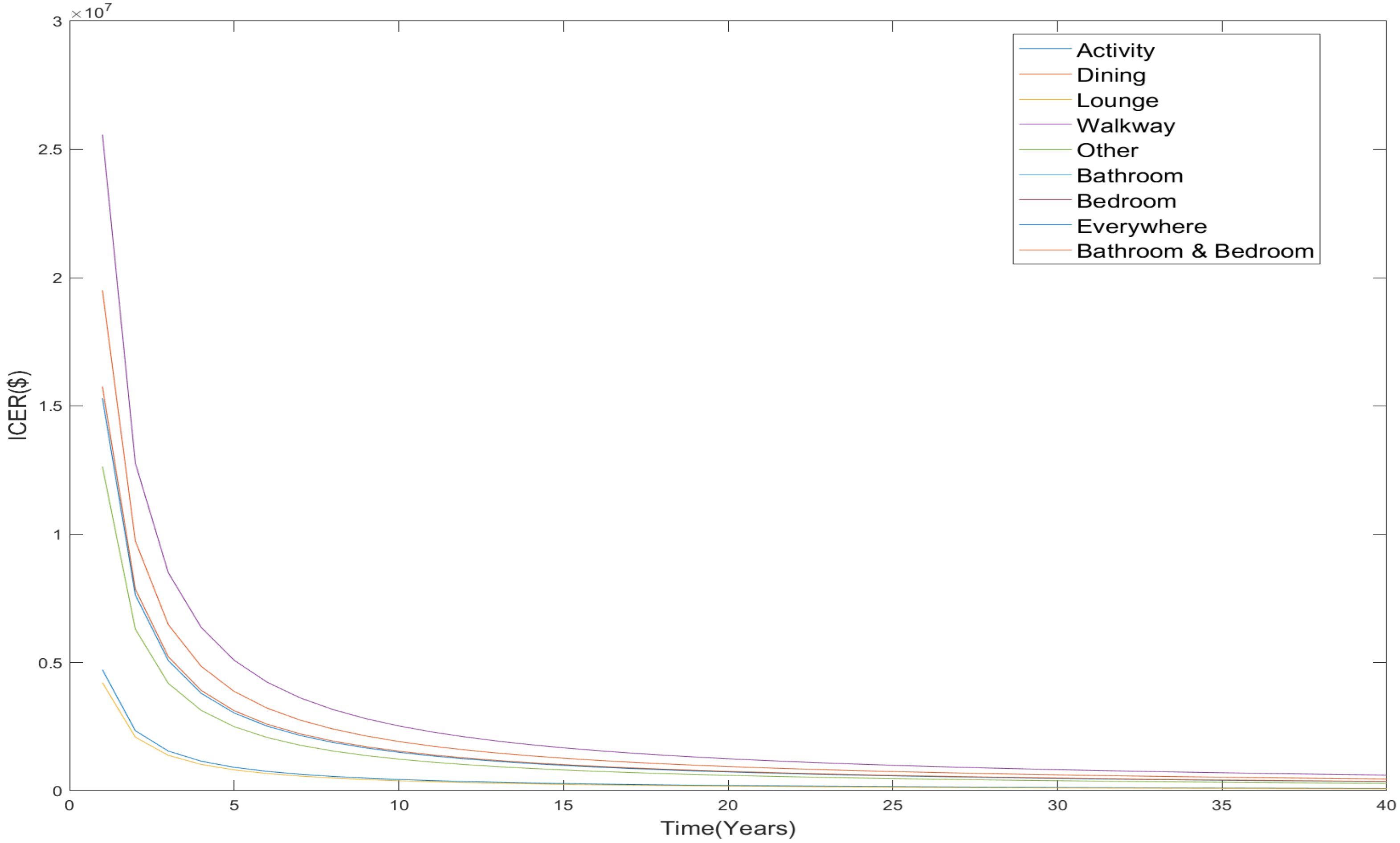

Figure C 4: Retirement home safety floor ICER changes over a 40-year period 147 hip fractures per year. The social discount rate is equal to 1.5%.

Table C 5: Safety Flooring ICER changes over a 40-year period model predicted number of hip fractures per year estimate. The ICER numerator is Costs subtract Savings, therefore positive values indicate costs exceeding savings. The social discount rate is equal to 3.0%.

Year	Activity Room	Dining Room	Lounge	Walkway	Other	Bathroom	Bedroom	Everywhere	Bathroom & Bedroom
1	-27745	-1472	-28439	9222	-13612	-8108	-8048	-8867	-8058
2	-31418	-18211	-31671	-12879	-24282	-21522	-21474	-21892	-21482
3	-32302	-23451	-32409	-19907	-27500	-25654	-25610	-25894	-25618
4	-32495	-25824	-32531	-23173	-28861	-27473	-27432	-27649	-27439
5	-32419	-27056	-32413	-24941	-29486	-28373	-28333	-28510	-28340
6	-32212	-27722	-32179	-25964	-29748	-28817	-28779	-28928	-28786
7	-31935	-28069	-31883	-26566	-29805	-29006	-28968	-29099	-28975
8	-31616	-28219	-31551	-26907	-29739	-29037	-29001	-29117	-29007
9	-31274	-28241	-31199	-27078	-29592	-28967	-28931	-29036	-28938
10	-30916	-28176	-30834	-27131	-29392	-28828	-28793	-28889	-28799
11	-30551	-28049	-30463	-27102	-29155	-28642	-28607	-28695	-28613
12	-30181	-27879	-30088	-27013	-28893	-28421	-28387	-28469	-28393

13	-29809	-27677	-29713	-26879	-28613	-28176	-28143	-28219	-28149
14	-29438	-27451	-29339	-26711	-28320	-27914	-27881	-27953	-27887
15	-29068	-27207	-28968	-26519	-28019	-27639	-27607	-27675	-27612
16	-28702	-26951	-28600	-26307	-27712	-27355	-27324	-27388	-27329
17	-28338	-26685	-28235	-26080	-27402	-27065	-27034	-27095	-27039
18	-27979	-26413	-27875	-25842	-27089	-26771	-26740	-26798	-26746
19	-27623	-26135	-27519	-25596	-26777	-26474	-26444	-26500	-26449
20	-27273	-25855	-27168	-25343	-26464	-26177	-26147	-26200	-26152
21	-26927	-25573	-26822	-25087	-26153	-25879	-25850	-25901	-25855
22	-26586	-25290	-26481	-24827	-25844	-25582	-25553	-25602	-25558
23	-26251	-25007	-26146	-24565	-25537	-25286	-25258	-25305	-25263
24	-25920	-24725	-25815	-24302	-25233	-24992	-24964	-25010	-24969
25	-25594	-24445	-25490	-24039	-24932	-24701	-24673	-24717	-24678
26	-25274	-24166	-25170	-23776	-24635	-24412	-24384	-24427	-24389
27	-24958	-23889	-24855	-23514	-24341	-24126	-24099	-24140	-24103
28	-24648	-23615	-24545	-23254	-24050	-23842	-23816	-23856	-23820

29	-24343	-23343	-24241	-22995	-23764	-23563	-23536	-23576	-23541
30	-24043	-23074	-23941	-22738	-23481	-23286	-23260	-23299	-23265
31	-23748	-22808	-23647	-22483	-23202	-23013	-22988	-23025	-22992
32	-23457	-22545	-23357	-22231	-22927	-22744	-22719	-22755	-22723
33	-23172	-22286	-23072	-21982	-22655	-22478	-22453	-22489	-22458
34	-22891	-22029	-22792	-21735	-22388	-22216	-22191	-22226	-22196
35	-22615	-21777	-22517	-21490	-22125	-21958	-21933	-21967	-21938
36	-22344	-21527	-22247	-21249	-21866	-21703	-21679	-21712	-21683
37	-22077	-21281	-21981	-21011	-21611	-21452	-21428	-21461	-21432
38	-21814	-21038	-21719	-20776	-21359	-21205	-21181	-21213	-21185
39	-21556	-20799	-21462	-20543	-21112	-20961	-20938	-20969	-20942
40	-21303	-20563	-21209	-20314	-20868	-20721	-20698	-20728	-20702

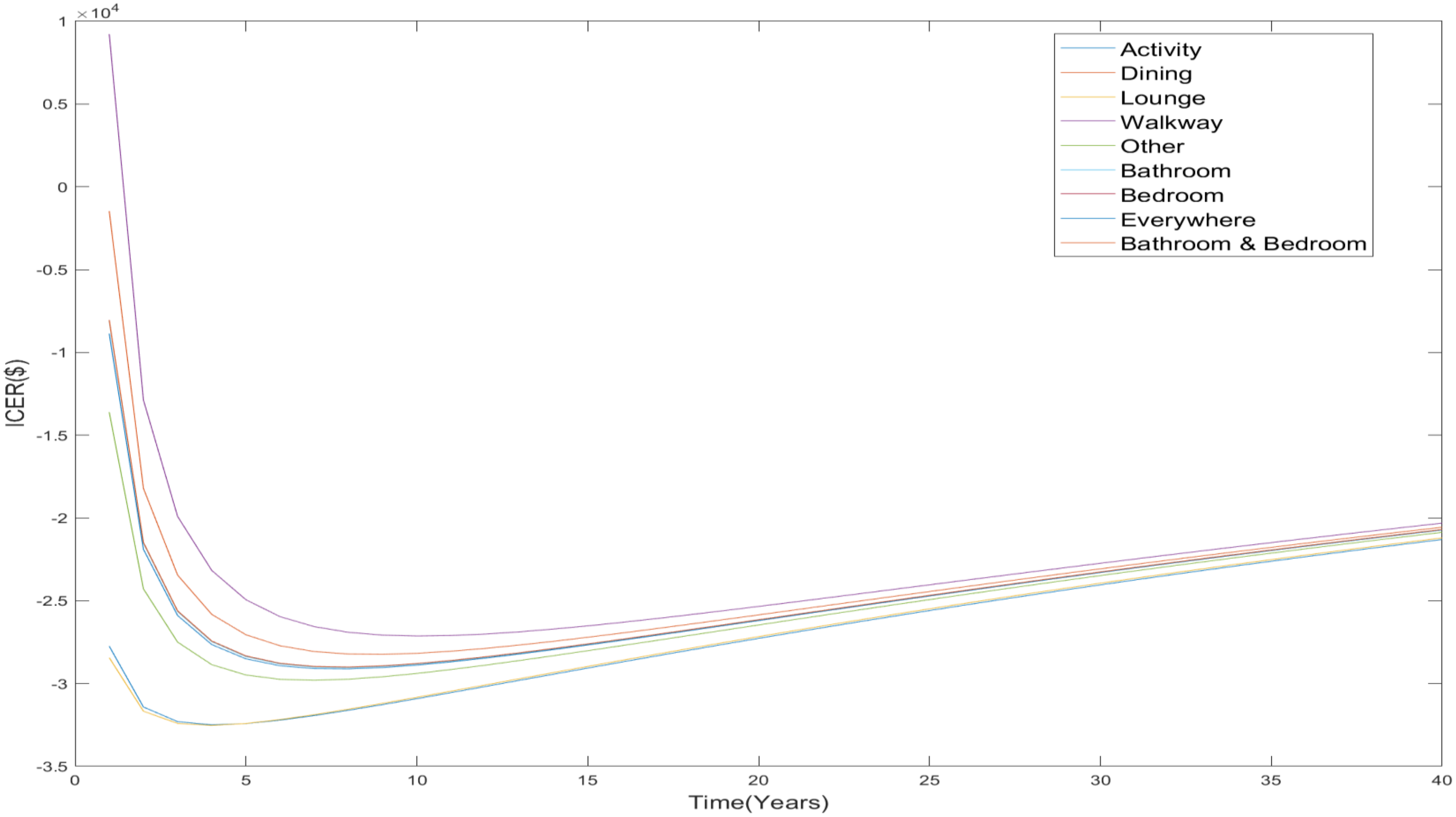

Figure C 5: Retirement home safety floor ICER changes over a 40-year period model predicted number of hip fractures per year. The social discount rate is equal to 3.0%.

Table C 6: Safety Flooring ICER changes over a 40-year period 900 hip fractures per year estimate. The ICER numerator is Costs subtract Savings, therefore positive values indicate costs exceeding savings. The social discount rate is equal to 3.0%.

Year	Activity Room	Dining Room	Lounge	Walkway	Other	Bathroom	Bedroom	Everywhere	Bathroom & Bedroom
1	551736	2380808	489710	3131647	1531244	1915352	1916948	1860846	1916672
2	258322	1172929	227404	1548333	748146	940208	941024	912965	940883
3	160859	770642	140308	1020901	487452	615499	616055	597343	615959
4	112375	569746	97006	757433	357353	453392	453817	439780	453744
5	83477	449400	71217	599544	279485	356319	356666	345433	356606
6	64368	369325	54179	494440	227728	291759	292054	282690	292003
7	50848	312257	42138	419495	190888	245774	246031	238003	245987
8	40819	269566	33217	363396	163368	211395	211624	204598	211584
9	33113	236457	26373	319858	142059	184751	184957	178710	184921
10	27032	210052	20981	285111	125094	163518	163706	158083	163674
11	22129	188522	16642	256755	111286	146218	146392	141279	146362
12	18109	170644	13091	233189	99845	131867	132029	127340	132001

13	14766	155576	10144	213308	90222	119782	119933	115605	119907
14	11954	142712	7671	196319	82027	109476	109618	105598	109594
15	9564	131611	5575	181643	74972	100592	100726	96973	100703
16	7516	121942	3785	168845	68842	92861	92989	89469	92967
17	5749	113449	2244	157592	63472	86080	86201	82888	86180
18	4215	105936	911	147626	58736	80088	80204	77074	80184
19	2876	99248	-248	138742	54532	74760	74871	71906	74852
20	1701	93259	-1261	130778	50779	69996	70103	67285	70084
21	667	87869	-2148	123600	47411	65714	65817	63133	65799
22	-246	82995	-2929	117102	44377	61848	61947	59385	61930
23	-1056	78570	-3617	111193	41630	58342	58438	55987	58421
24	-1775	74536	-4226	105799	39136	55152	55244	52895	55228
25	-2415	70846	-4764	100858	36862	52238	52327	50071	52311
26	-2986	67460	-5241	96317	34783	49568	49654	47485	49639
27	-3496	64344	-5664	92131	32876	47114	47198	45108	47183
28	-3952	61467	-6040	88261	31123	44853	44934	42919	44920

29	-4361	58805	-6374	84675	29507	42764	42843	40897	42829
30	-4727	56335	-6670	81343	28015	40829	40906	39025	40893
31	-5055	54040	-6932	78240	26632	39034	39109	37288	39096
32	-5348	51901	-7165	75345	25350	37364	37437	35674	37425
33	-5612	49905	-7371	72637	24158	35809	35880	34169	35868
34	-5847	48038	-7553	70101	23049	34356	34426	32765	34414
35	-6058	46289	-7713	67722	22014	32998	33067	31453	33055
36	-6247	44647	-7854	65485	21047	31727	31793	30224	31782
37	-6415	43105	-7977	63379	20142	30533	30599	29072	30587
38	-6565	41653	-8084	61394	19295	29413	29477	27990	29466
39	-6698	40285	-8176	59519	18500	28359	28421	26973	28410
40	-6816	38994	-8255	57746	17753	27365	27427	26014	27416

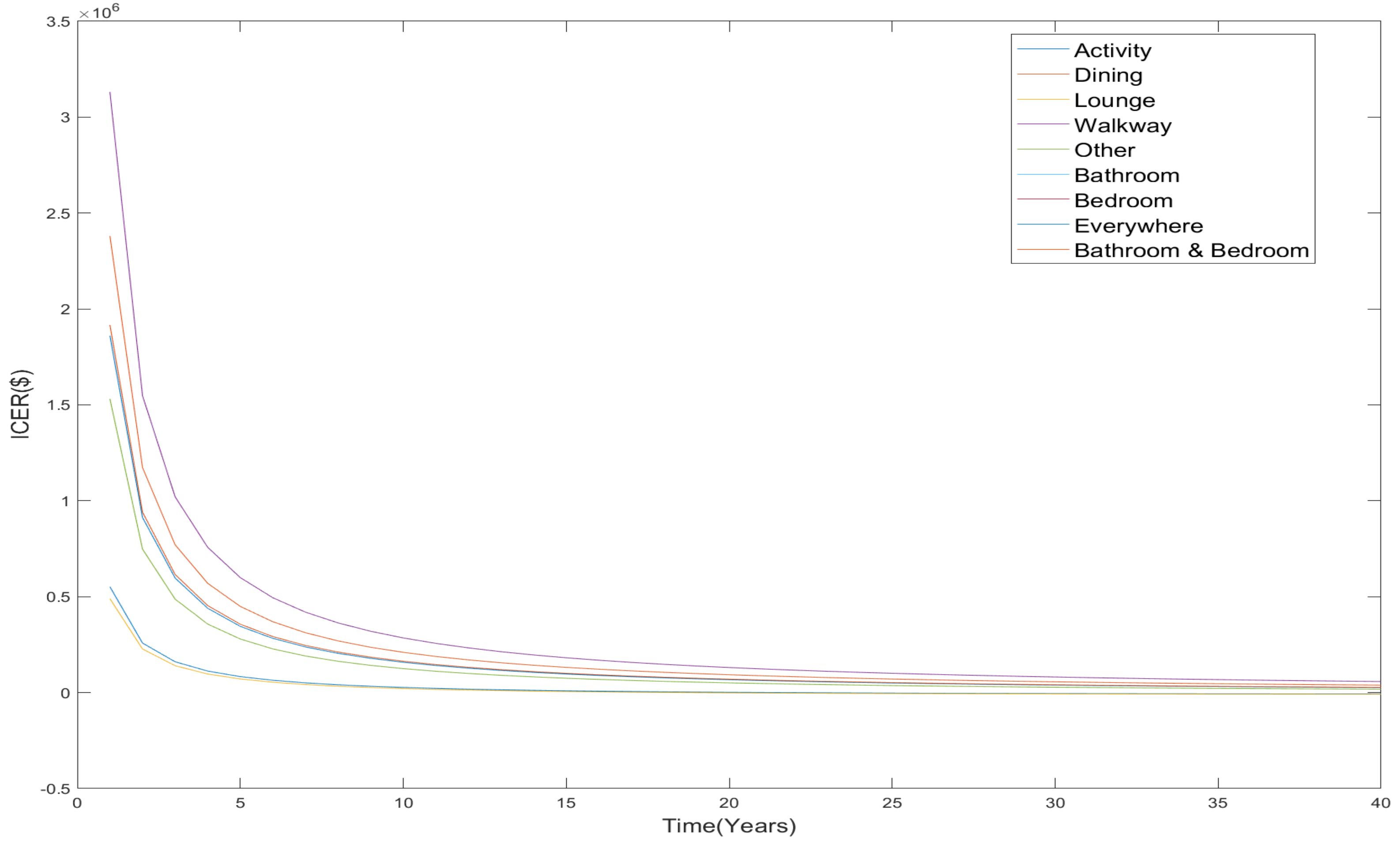

Figure C 6: Retirement home safety floor ICER changes over a 40-year period 900 hip fractures per year. The social discount rate is equal to 3.0%.

Table C 7: Safety Flooring ICER changes over a 40-year period 3200 hip fractures per year estimate. The ICER numerator is Costs subtract Savings, therefore positive values indicate costs exceeding savings. The social discount rate is equal to 3.0%.

Year	Activity Room	Dining Room	Lounge	Walkway	Other	Bathroom	Bedroom	Everywhere	Bathroom & Bedroom
1	181618	859235	158766	1137339	544537	686829	687444	666652	687338
2	73264	412142	61932	551179	254792	325947	326272	315868	326216
3	37486	263451	29993	356132	158550	205992	206220	199279	206181
4	19846	189352	14270	258856	110676	146261	146441	141231	146410
5	9454	145085	5028	200682	82144	110615	110765	106594	110739
6	2682	115729	-978	162055	63277	87005	87136	83658	87114
7	-2025	94889	-5139	134594	49930	70271	70388	67404	70368
8	-5446	79370	-8151	114108	40030	57830	57936	55323	57917
9	-8011	67393	-10398	98269	32424	48248	48345	46022	48329
10	-9980	57895	-12114	85680	26423	40665	40756	38663	40740
11	-11518	50197	-13444	75454	21585	34534	34619	32716	34605
12	-12734	43846	-14488	66997	17619	29490	29570	27824	29556

13	-13704	38531	-15313	59900	14322	25280	25356	23744	25343
14	-14483	34028	-15968	53868	11548	21724	21797	20298	21784
15	-15111	30173	-16488	48689	9191	18690	18759	17360	18747
16	-15616	26843	-16899	44201	7172	16078	16145	14832	16133
17	-16023	23945	-17223	40280	5431	13814	13877	12641	13866
18	-16347	21404	-17474	36831	3919	11837	11898	10730	11887
19	-16604	19165	-17666	33779	2600	10101	10161	9054	10150
20	-16805	17180	-17808	31062	1443	8570	8628	7576	8618
21	-16957	15413	-17908	28633	425	7213	7269	6267	7259
22	-17070	13833	-17972	26451	-474	6006	6060	5103	6051
23	-17148	12415	-18006	24484	-1270	4928	4981	4065	4972
24	-17196	11137	-18015	22703	-1977	3963	4015	3136	4006
25	-17220	9983	-18002	21086	-2606	3097	3147	2303	3138
26	-17221	8938	-17970	19613	-3168	2317	2365	1554	2357
27	-17204	7989	-17922	18268	-3669	1613	1660	879	1652
28	-17171	7125	-17860	17036	-4116	977	1023	269	1015

29	-17124	6337	-17786	15906	-4517	401	446	-282	438
30	-17064	5616	-17701	14866	-4876	-122	-77	-781	-85
31	-16994	4957	-17608	13907	-5197	-596	-552	-1234	-560
32	-16915	4352	-17507	13022	-5484	-1027	-985	-1645	-992
33	-16827	3796	-17400	12204	-5742	-1419	-1378	-2018	-1385
34	-16733	3285	-17286	11445	-5972	-1777	-1736	-2358	-1743
35	-16633	2815	-17168	10742	-6178	-2102	-2062	-2667	-2069
36	-16528	2382	-17046	10087	-6362	-2399	-2360	-2948	-2367
37	-16418	1981	-16921	9479	-6526	-2670	-2631	-3203	-2638
38	-16305	1612	-16793	8912	-6671	-2917	-2879	-3436	-2885
39	-16188	1270	-16662	8383	-6800	-3142	-3105	-3648	-3111
40	-16069	955	-16529	7889	-6915	-3348	-3311	-3841	-3317

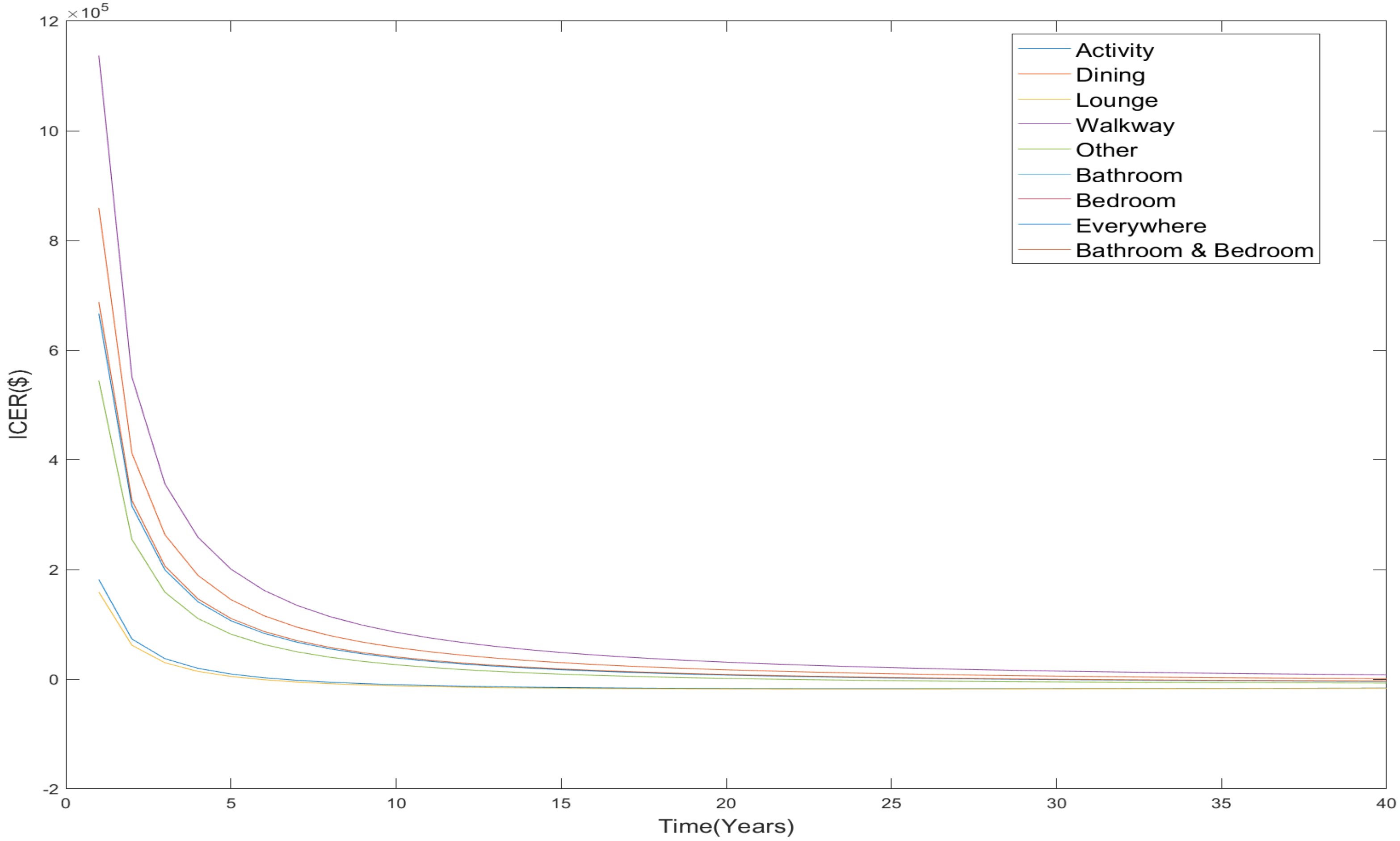

Figure C 7: Retirement home safety floor ICER changes over a 40-year period 3200 hip fractures per year. The social discount rate is equal to 3.0%.

Table C 8: Safety Flooring ICER changes over a 40-year period 147 hip fractures per year estimate. The ICER numerator is Costs subtract Savings, therefore positive values indicate costs exceeding savings. The social discount rate is equal to 3.0%.

Year	Activity Room	Dining Room	Lounge	Walkway	Other	Bathroom	Bedroom	Everywhere	Bathroom & Bedroom
1	4717188	19505233	4214298	25576406	12636054	15741662	15754294	15300806	15752114
2	2341049	9735142	2089698	12770713	6300550	7853363	7859697	7632945	7858604
3	1549343	6478784	1381837	8502488	4189055	5224269	5228504	5077330	5227773
4	1153738	4850852	1028153	6368623	3133555	3909969	3913154	3799770	3912604
5	916568	3874285	816135	5088496	2500447	3121581	3124135	3033425	3123694
6	758610	3223395	674944	4235233	2078530	2596144	2598278	2522684	2597910
7	645913	2758603	574222	3625889	1777290	2220961	2222795	2157998	2222478
8	561500	2410119	498791	3168991	1551470	1939684	1941292	1884593	1941014
9	495941	2139171	440217	2813720	1375926	1721007	1722440	1672039	1722193
10	443577	1922495	393440	2529587	1235574	1546149	1547441	1502079	1547218
11	400807	1745287	355241	2297187	1120814	1403155	1404333	1363093	1404130
12	365230	1597680	323473	2103586	1025246	1284060	1285141	1247337	1284954

13	335186	1472839	296651	1939828	944438	1183344	1184345	1149448	1184172
14	309486	1365885	273713	1799516	875227	1097069	1098000	1065595	1097840
15	287261	1273240	253881	1677960	815292	1022346	1023216	992970	1023066
16	267857	1192218	236572	1571642	762892	957005	957823	929467	957682
17	250776	1120768	221338	1477872	716696	899392	900163	873474	900030
18	235629	1057293	207833	1394557	675670	848216	848945	823739	848819
19	222110	1000533	195783	1320045	638995	802461	803153	779272	803033
20	209974	949480	184969	1253016	606019	761312	761970	739283	761856
21	199022	903318	175213	1192398	576212	724110	724738	703131	724630
22	189092	861378	166370	1137318	549141	690317	690917	670292	690813
23	180051	823110	158321	1087052	524448	659486	660062	640333	659962
24	171786	788054	150965	1040997	501836	631248	631800	612893	631705
25	164203	755823	144219	998649	481054	605290	605821	587670	605729
26	157224	726092	138012	959577	461891	581349	581860	564406	581771
27	150780	698581	132283	923418	444165	559199	559692	542885	559607
28	144814	673053	126981	889860	427724	538649	539125	522918	539043

29	139275	649302	122060	858632	412432	519533	519993	504344	519913
30	134122	627149	117483	829501	398175	501706	502151	487024	502074
31	129315	606440	113216	802264	384852	485044	485475	470835	485401
32	124822	587039	109228	776743	372375	469436	469855	455672	469782
33	120614	568827	105495	752782	360668	454788	455194	441441	455123
34	116666	551697	101994	730241	349661	441012	441407	428058	441339
35	112955	535558	98704	709001	339294	428036	428419	415452	428353
36	109460	520326	95607	688950	329514	415791	416164	403557	416099
37	106165	505927	92688	669994	320272	404218	404581	392314	404518
38	103052	492296	89932	652045	311527	393263	393617	381673	393556
39	100108	479373	87326	635026	303238	382879	383225	371587	383165
40	97320	467104	84859	618865	295373	373023	373360	362013	373302

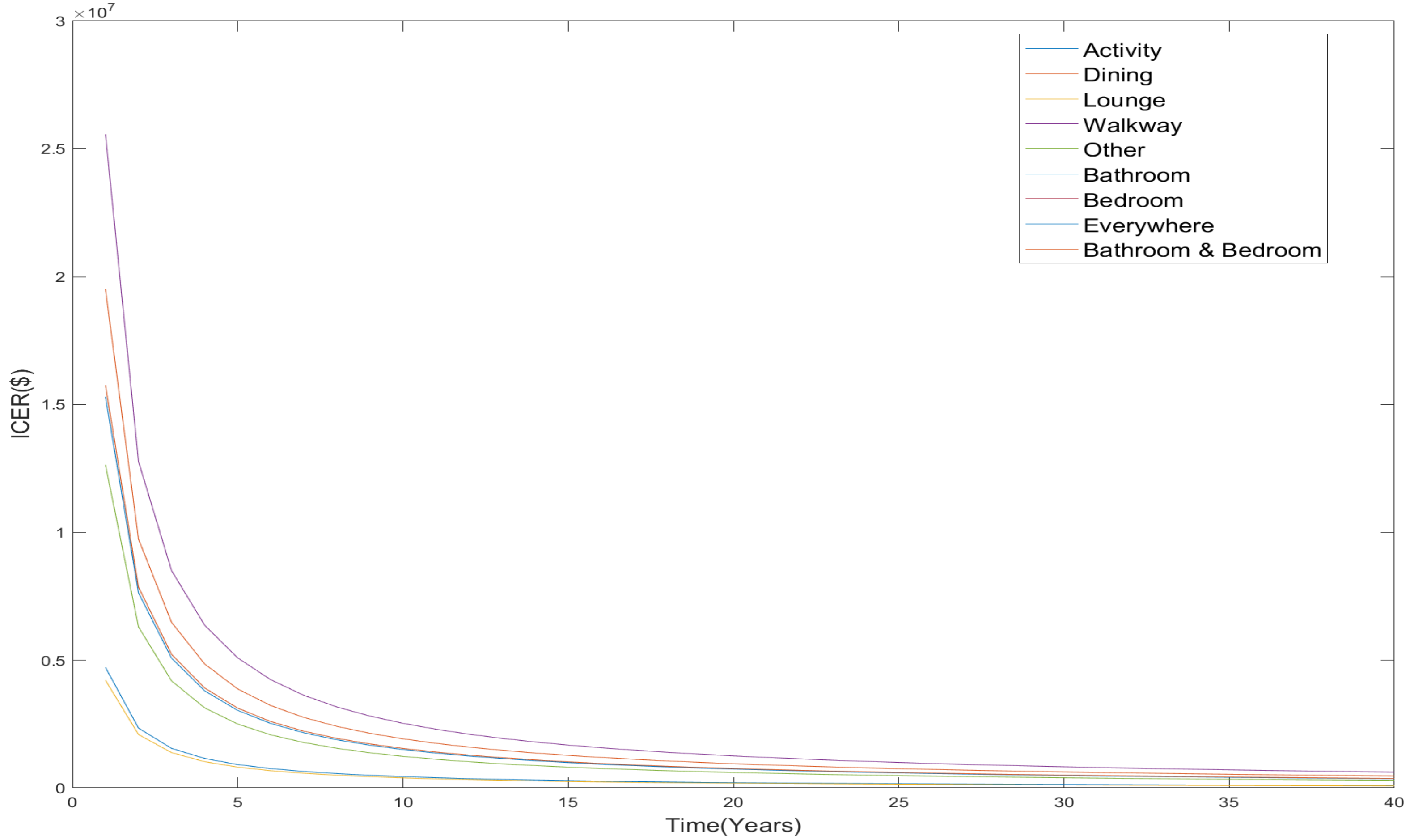

Figure C 8: Retirement home safety floor ICER changes over a 40-year period 147 hip fractures per year. The social discount rate is equal to 3.0%.

Table C 9: Safety Flooring ICER changes over a 40-year period model generated number of hip fractures per year estimate. The ICER numerator is Costs subtract Savings, therefore positive values indicate costs exceeding savings. The social discount rate is equal to 4.5%.

Year	Activity Room	Dining Room	Lounge	Walkway	Other	Bathroom	Bedroom	Everywhere	Bathroom & Bedroom
1	-27745	-1472	-28439	9222	-13612	-8108	-8048	-8867	-8058
2	-31166	-17960	-31420	-12628	-24031	-21271	-21223	-21641	-21232
3	-31810	-22962	-31920	-19417	-27010	-25165	-25121	-25405	-25129
4	-31776	-25107	-31815	-22456	-28144	-26757	-26716	-26933	-26723
5	-31482	-26123	-31481	-24007	-28553	-27440	-27402	-27578	-27408
6	-31069	-26584	-31042	-24825	-28609	-27680	-27642	-27791	-27649
7	-30596	-26735	-30551	-25231	-28472	-27673	-27637	-27766	-27643
8	-30091	-26700	-30034	-25387	-28219	-27519	-27484	-27599	-27490
9	-29572	-26546	-29506	-25381	-27897	-27273	-27239	-27342	-27245
10	-29047	-26314	-28974	-25267	-27530	-26967	-26934	-27028	-26939
11	-28522	-26029	-28445	-25080	-27134	-26622	-26589	-26676	-26595
12	-28001	-25708	-27920	-24840	-26722	-26251	-26220	-26300	-26225

13	-27486	-25363	-27403	-24563	-26299	-25864	-25833	-25908	-25838
14	-26980	-25003	-26895	-24261	-25872	-25467	-25437	-25507	-25442
15	-26482	-24632	-26396	-23941	-25443	-25064	-25035	-25101	-25040
16	-25994	-24255	-25907	-23608	-25015	-24660	-24631	-24694	-24636
17	-25517	-23875	-25429	-23267	-24591	-24256	-24228	-24287	-24233
18	-25049	-23495	-24961	-22922	-24171	-23854	-23827	-23884	-23832
19	-24592	-23116	-24504	-22574	-23757	-23457	-23429	-23484	-23434
20	-24146	-22740	-24058	-22226	-23349	-23063	-23037	-23089	-23041
21	-23709	-22368	-23622	-21879	-22948	-22676	-22650	-22699	-22654
22	-23284	-22001	-23196	-21534	-22554	-22294	-22268	-22316	-22273
23	-22868	-21639	-22781	-21193	-22168	-21919	-21894	-21940	-21898
24	-22462	-21282	-22376	-20855	-21790	-21550	-21526	-21570	-21530
25	-22067	-20931	-21981	-20522	-21419	-21189	-21164	-21207	-21169
26	-21680	-20587	-21596	-20194	-21056	-20834	-20810	-20852	-20815
27	-21304	-20249	-21220	-19871	-20700	-20487	-20464	-20504	-20468
28	-20936	-19918	-20853	-19553	-20353	-20147	-20124	-20163	-20128

29	-20578	-19593	-20496	-19241	-20013	-19814	-19791	-19829	-19795
30	-20228	-19274	-20147	-18935	-19681	-19488	-19466	-19503	-19470
31	-19887	-18963	-19807	-18635	-19356	-19169	-19148	-19183	-19151
32	-19554	-18657	-19475	-18340	-19038	-18858	-18836	-18871	-18840
33	-19229	-18359	-19151	-18051	-18728	-18553	-18532	-18565	-18535
34	-18912	-18067	-18835	-17768	-18425	-18255	-18234	-18267	-18238
35	-18603	-17781	-18527	-17491	-18129	-17963	-17943	-17975	-17947
36	-18301	-17501	-18226	-17220	-17840	-17679	-17659	-17690	-17662
37	-18007	-17227	-17933	-16954	-17557	-17400	-17381	-17411	-17384
38	-17720	-16960	-17646	-16694	-17281	-17128	-17109	-17139	-17112
39	-17439	-16698	-17367	-16439	-17011	-16862	-16843	-16872	-16846
40	-17166	-16443	-17094	-16190	-16748	-16602	-16584	-16612	-16587

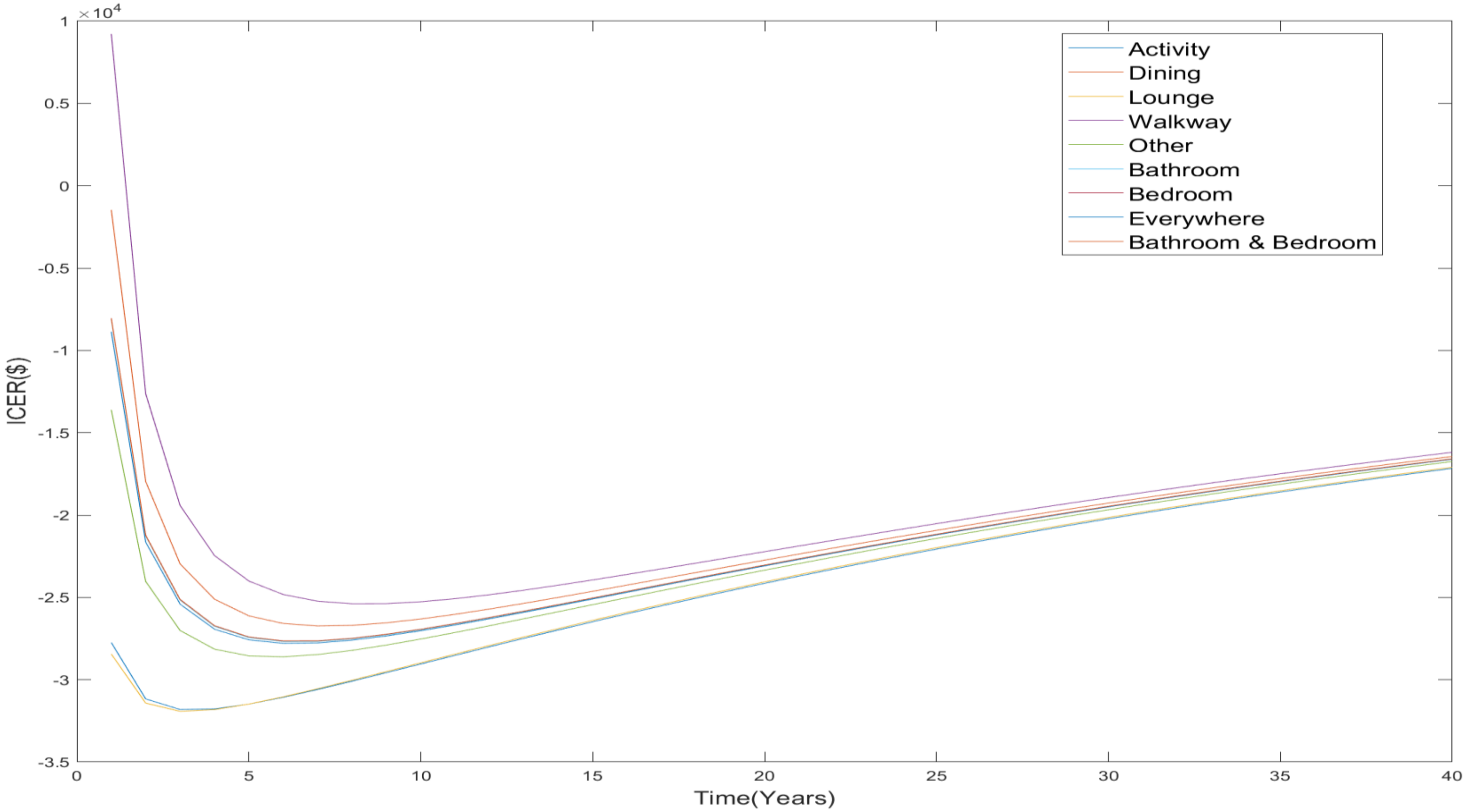

Figure C 9: Retirement home safety floor ICER changes over a 40-year period model estimated number of hip fractures per year. The social discount rate is equal to 4.5%.

Table C 10: Safety Flooring ICER changes over a 40-year period 900 hip fractures per year estimate. The ICER numerator is Costs subtract Savings, therefore positive values indicate costs exceeding savings. The social discount rate is equal to 4.5%.

Year	Activity Room	Dining Room	Lounge	Walkway	Other	Bathroom	Bedroom	Everywhere	Bathroom & Bedroom
1	551736	2380808	489710	3131647	1531244	1915352	1916948	1860846	1916672
2	258574	1173180	227655	1548584	748397	940459	941274	913216	941134
3	161350	771132	140797	1021391	487942	615989	616544	597833	616448
4	113095	570463	97722	758150	358070	454108	454533	440496	454460
5	84414	450333	72149	600477	280418	357252	357598	346365	357538
6	65511	370463	55316	495579	228867	292897	293190	283828	293140
7	52187	313591	43470	420830	192222	247107	247363	239336	247319
8	42344	271085	34734	364916	164888	212914	213141	206115	213101
9	34815	238152	28066	321555	143754	186445	186650	180404	186614
10	28902	211915	22841	286975	126956	165379	165566	159943	165534
11	24158	190542	18660	258777	113307	148238	148410	143298	148381
12	20289	172815	15259	235362	102016	134037	134197	129509	134169

13	17089	157889	12455	215623	92536	122095	122243	117916	122218
14	14412	145160	10116	198769	84475	111923	112063	108044	112039
15	12150	134187	8148	184221	77547	103166	103298	99546	103275
16	10223	124638	6477	171544	71538	95556	95681	92163	95660
17	8571	116259	5051	160405	66283	88889	89007	85696	88987
18	7144	108854	3825	150546	61654	83004	83117	79989	83098
19	5907	102267	2767	141764	57551	77778	77886	74922	77868
20	4828	96374	1850	133895	53894	73110	73213	70397	73195
21	3885	91074	1052	126808	50616	68918	69017	66335	69000
22	3056	86285	356	120394	47666	65136	65231	62671	65215
23	2327	81939	-253	114565	45000	61710	61802	59352	61786
24	1683	77980	-787	109246	42580	58594	58683	56335	58667
25	1113	74360	-1255	104375	40376	55750	55835	53581	55821
26	607	71039	-1667	99899	38362	53145	53228	51060	53214
27	159	67984	-2029	95774	36517	50752	50833	48745	50819
28	-240	65164	-2348	91962	34821	48548	48626	46613	48612

29	-595	62555	-2628	88428	33258	46512	46588	44644	46575
30	-912	60135	-2875	85146	31815	44627	44700	42821	44688
31	-1194	57885	-3092	82089	30478	42878	42949	41130	42937
32	-1445	55789	-3282	79236	29238	41251	41320	39558	41308
33	-1669	53832	-3449	76568	28086	39734	39801	38092	39790
34	-1869	52001	-3595	74068	27012	38318	38383	36725	38372
35	-2046	50285	-3723	71721	26010	36993	37057	35445	37046
36	-2205	48673	-3833	69514	25073	35751	35813	34247	35803
37	-2345	47158	-3929	67436	24196	34585	34646	33122	34636
38	-2470	45732	-4011	65475	23373	33489	33549	32064	33539
39	-2581	44386	-4081	63623	22601	32457	32516	31069	32506
40	-2679	43114	-4141	61871	21874	31484	31541	30131	31531

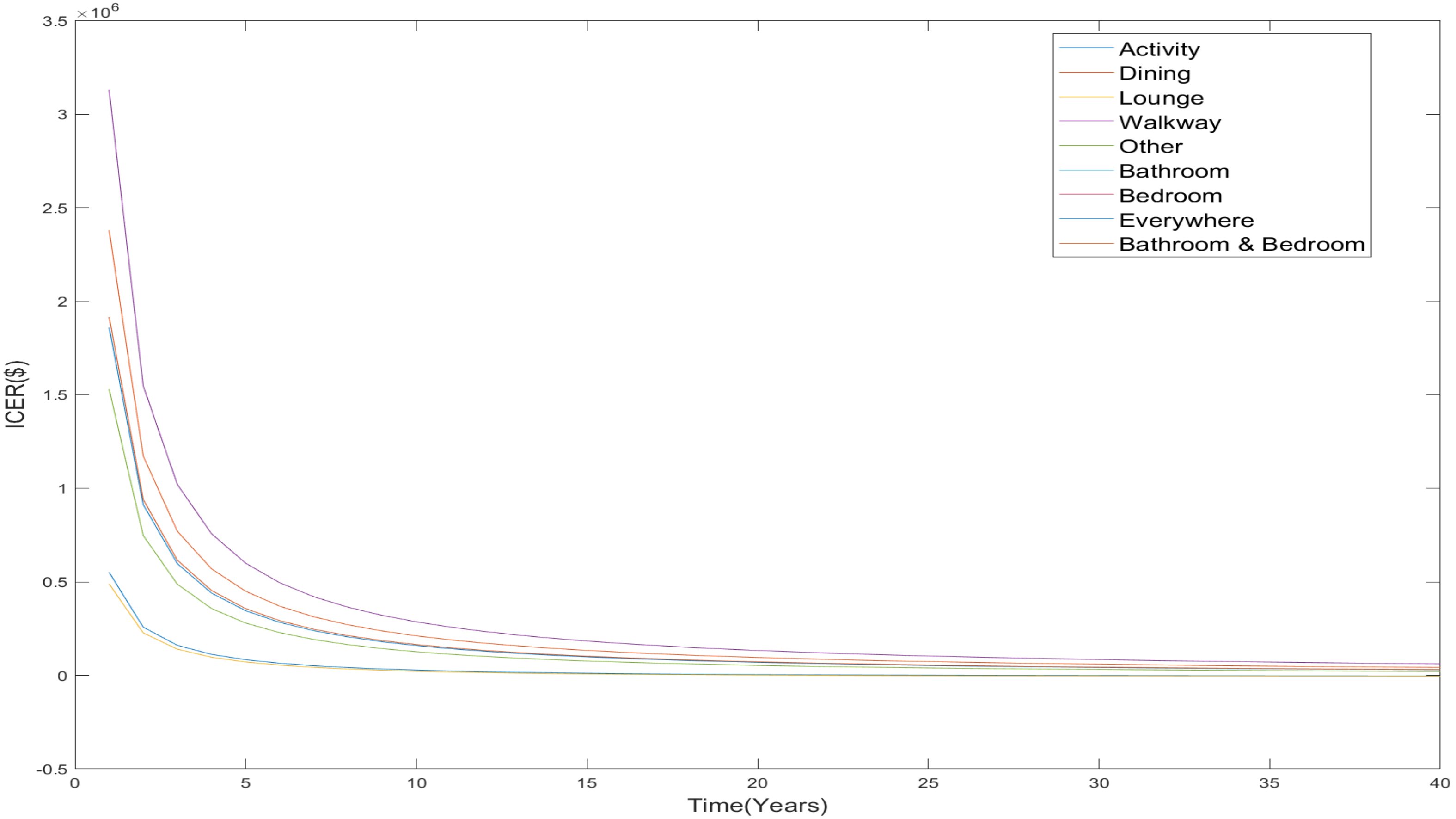

Figure C 10: Retirement home safety floor ICER changes over a 40-year period 900 hip fractures per year. The social discount rate is equal to 4.5%.

Table C 11: Safety Flooring ICER changes over a 40-year period 3200 hip fractures per year estimate. The ICER numerator is Costs subtract Savings, therefore positive values indicate costs exceeding savings. The social discount rate is equal to 4.5%.

Year	Activity Room	Dining Room	Lounge	Walkway	Other	Bathroom	Bedroom	Everywhere	Bathroom & Bedroom
1	181618	859235	158766	1137339	544537	686829	687444	666652	687338
2	73516	412393	62182	551430	255043	326197	326523	316118	326466
3	37978	263941	30482	356622	159040	206481	206709	199768	206670
4	20565	190069	14986	259573	111393	146978	147157	141947	147126
5	10391	146018	5960	201616	83076	111547	111697	107526	111671
6	3825	116867	159	163195	64416	88143	88273	84795	88251
7	-686	96223	-3808	135929	51264	71604	71719	68736	71699
8	-3921	80889	-6634	115628	41549	59348	59453	56841	59435
9	-6309	69088	-8705	99965	34120	49942	50038	47715	50022
10	-8110	59757	-10254	87544	28285	42527	42616	40524	42600
11	-9489	52217	-11426	77477	23606	36554	36637	34734	36623
12	-10554	46017	-12320	69170	19791	31660	31738	29993	31725

13	-11381	40845	-13003	62215	16635	27593	27666	26055	27654
14	-12025	36476	-13523	56319	13996	24171	24241	22744	24229
15	-12525	32749	-13915	51267	11767	21265	21331	19933	21320
16	-12909	29539	-14207	46899	9869	18774	18837	17526	18826
17	-13201	26755	-14417	43093	8241	16623	16683	15449	16673
18	-13418	24322	-14561	39751	6837	14753	14812	13645	14802
19	-13573	22184	-14651	36801	5619	13119	13175	12070	13166
20	-13677	20295	-14697	34180	4558	11684	11738	10687	11728
21	-13740	18618	-14707	31841	3630	10417	10469	9468	10460
22	-13767	17122	-14687	29744	2816	9294	9345	8389	9336
23	-13765	15784	-14642	27856	2099	8296	8345	7431	8337
24	-13739	14581	-14576	26150	1467	7406	7453	6577	7445
25	-13692	13497	-14493	24603	907	6609	6655	5813	6647
26	-13628	12517	-14396	23195	412	5894	5939	5130	5931
27	-13549	11629	-14287	21911	-28	5252	5295	4516	5288
28	-13459	10822	-14167	20737	-419	4672	4715	3963	4708

29	-13358	10087	-14040	19659	-766	4150	4191	3465	4184
30	-13249	9416	-13907	18669	-1076	3677	3717	3015	3710
31	-13133	8802	-13768	17756	-1351	3248	3288	2608	3281
32	-13011	8240	-13625	16914	-1596	2859	2898	2239	2891
33	-12885	7723	-13478	16134	-1815	2506	2544	1905	2537
34	-12754	7248	-13329	15412	-2009	2185	2221	1601	2215
35	-12621	6811	-13178	14741	-2182	1892	1928	1325	1922
36	-12486	6408	-13026	14117	-2336	1625	1661	1075	1654
37	-12349	6035	-12873	13536	-2472	1382	1416	846	1411
38	-12210	5690	-12720	12994	-2593	1160	1194	638	1188
39	-12071	5371	-12567	12487	-2700	957	990	449	984
40	-11932	5075	-12414	12013	-2794	771	804	276	798

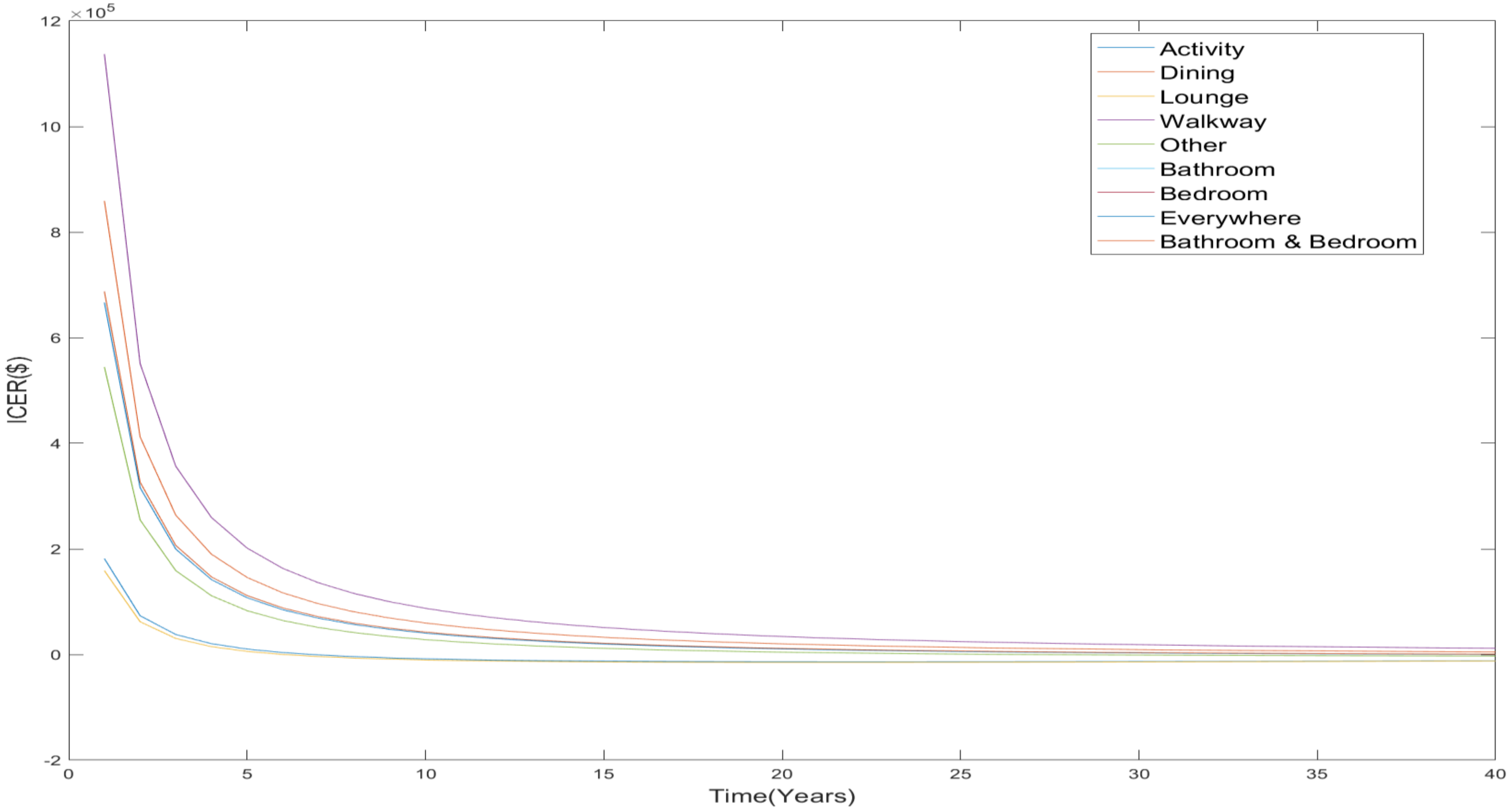

Figure C 11: Retirement home safety floor ICER changes over a 40-year period 3200 hip fractures per year. The social discount rate is equal to 4.5%.

Table C 12: Safety Flooring ICER changes over a 40-year period 147 hip fractures per year estimate. The ICER numerator is Costs subtract Savings, therefore positive values indicate costs exceeding savings. The social discount rate is equal to 4.5%.

Year	Activity Room	Dining Room	Lounge	Walkway	Other	Bathroom	Bedroom	Everywhere	Bathroom & Bedroom
1	4717188	19505233	4214298	25576406	12636054	15741662	15754294	15300806	15752114
2	2341301	9735392	2089949	12770964	6300801	7853614	7859948	7633196	7858854
3	1549835	6479273	1382326	8502978	4189545	5224758	5228993	5077819	5228262
4	1154458	4851569	1028869	6369340	3134272	3910686	3913869	3800486	3913320
5	917505	3875218	817066	5089429	2501380	3122514	3125067	3034357	3124626
6	759753	3224534	676081	4236372	2079668	2597282	2599415	2523821	2599047
7	647252	2759937	575554	3627224	1778623	2222294	2224127	2159330	2223810
8	563026	2411638	500308	3170511	1552989	1941202	1942809	1886110	1942532
9	497643	2140866	441909	2815417	1377622	1722702	1724133	1673732	1723886
10	445447	1924357	395299	2531451	1237437	1548010	1549301	1503939	1549078
11	402836	1747308	357259	2299210	1122835	1405175	1406351	1365112	1406148
12	367410	1599851	325641	2105759	1027417	1286230	1287309	1249506	1287123

13	337509	1475152	298961	1942143	946752	1185657	1186655	1151759	1186482
14	311944	1368333	276158	1801966	877676	1099517	1100445	1068041	1100285
15	289847	1275815	256453	1680538	817868	1024920	1025788	995544	1025638
16	270564	1194914	239264	1574341	765589	959701	960515	932161	960375
17	253597	1123578	224144	1480685	719507	902201	902969	876282	902836
18	238558	1060211	210747	1397477	678588	851133	851859	826654	851734
19	225141	1003552	198798	1323067	642015	805479	806168	782289	806049
20	213101	952595	188079	1256133	609134	764425	765080	742395	764967
21	202240	906522	178413	1195606	579417	727313	727938	706333	727830
22	192395	864668	169655	1140610	552430	693605	694202	673578	694099
23	183434	826479	161685	1090424	527817	662854	663426	643698	663327
24	175243	791497	154404	1044444	505280	634690	635239	616333	635144
25	167731	759337	147728	1002165	484568	608802	609329	591180	609238
26	160817	729671	141586	963159	465470	584926	585433	567982	585346
27	154435	702222	135918	927062	447806	562838	563327	546521	563242
28	148526	676751	130673	893560	431421	542345	542817	526611	542735

29	143041	653052	125806	862386	416182	523282	523738	508091	523659
30	137937	630949	121278	833304	401975	505504	505945	490820	505869
31	133176	610286	117056	806113	388698	488888	489315	474677	489241
32	128725	590927	113111	780635	376264	473323	473737	459556	473665
33	124557	572753	109417	756712	364595	458713	459115	445364	459045
34	120645	555660	105951	734208	353624	444974	445364	432018	445297
35	116967	539554	102694	713000	343290	432030	432409	419444	432344
36	113502	524352	99628	692980	333540	419815	420184	407579	420120
37	110234	509981	96736	674051	324326	408269	408629	396364	408567
38	107147	496374	94005	656127	315605	397340	397690	385748	397629
39	104226	483474	91421	639130	307339	386978	387319	375684	387261
40	101458	471225	88974	622990	299494	377142	377475	366130	377418

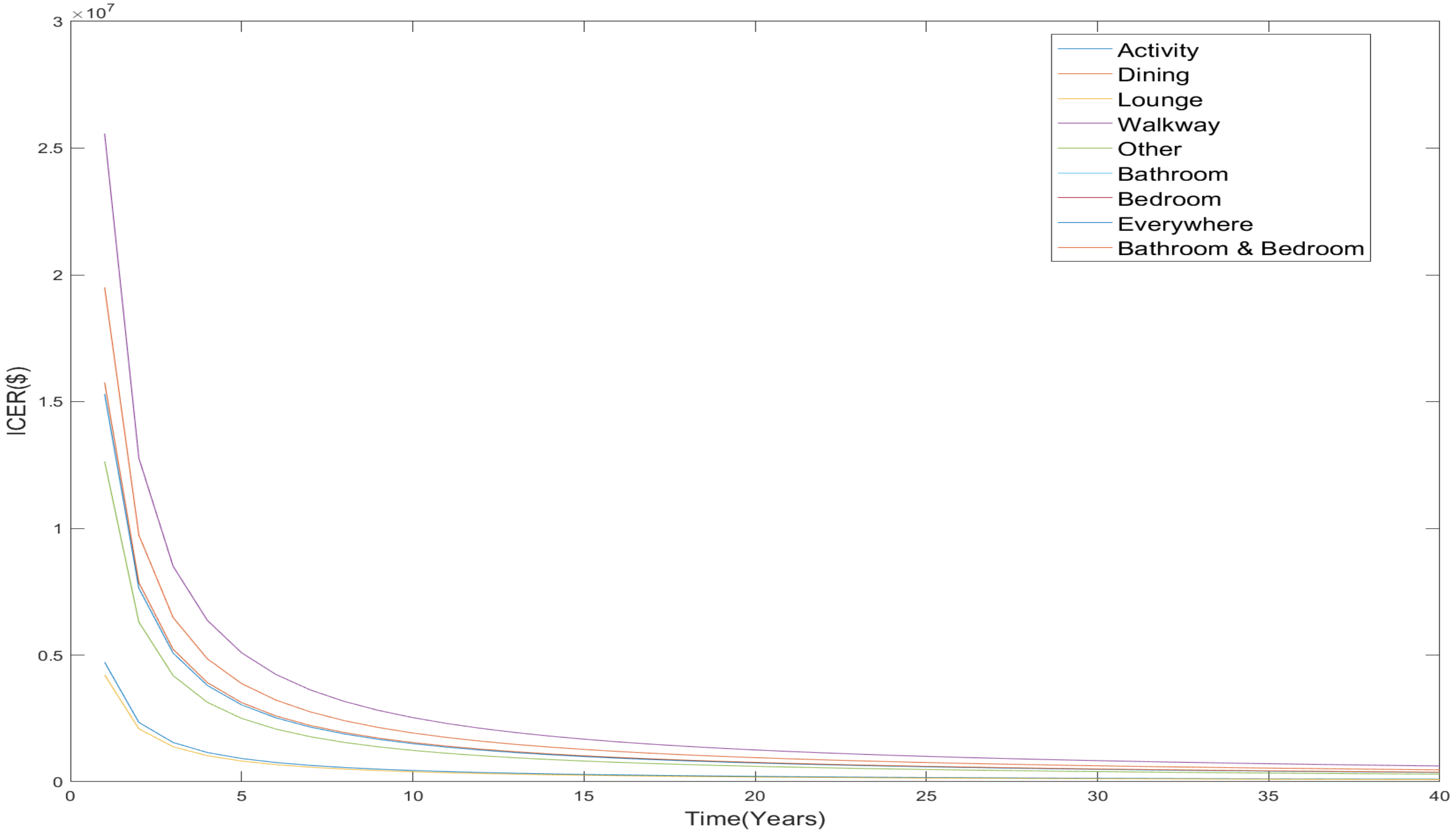

Figure C 12: Retirement home safety floor ICER changes over a 40-year period 147 hip fractures per year. The social discount rate is equal to 4.5%.

Appendix D: Height and Mass Linear Regression Equations

To address a previously identified limitation of the Martel (2017) and Martel et al. (2020) model where older adults could be simulated with incongruent/unrealistic masses and heights (i.e., a tall adult with uncharacteristically low mass) linear regression modules were added to the updated model. The purpose of implementing the regression equation was to capture the relationship which existed between both mass and height for the retirement home older adults. Though these modifications were highlighted in Appendix A, a thorough re-examination of the linear regressions is performed here.

Equation (A.1) and Equation (A.2) were determined by performing multiple linear regression in the R statistical programming language (R Core Team, 2022). Equation (A.1) related height (the criterion/response variable) to age and sex (the predictor variables). The intercept was 1.6674954 ± (0.0514581), the coefficients for sex and age were 0.1408746 ± (0.0070617) and -0.0026294 ± (0.0005685) all their associated p values were $< .001$. The residual standard error for height was 0.0864 on 667 degrees of freedom, while the multiple and adjusted R^2 values were 0.3921 and 0.3902. Finally, the F-statistic for the regression was 215.1 on 2 and 667 degrees of freedom ($p < .001$).

Equation (A.2) related mass (the criterion/response variable) to age, sex, and height (the predictor variables). The intercept was 25.49074 ± (12.22600), the coefficients for sex, age and height were 7.31147 ± (1.32134), -0.46532 ± (0.08553), and 45.05038 ± (5.73371) all associated p values were $< .001$ except the intercept which had a p value of 0.0375. The residual standard error for mass was 12.79 on 666 degrees of freedom, while the multiple and adjusted R^2 values were 0.3037 and 0.3006. Finally, the F-statistic for the regression was 96.83 on 3 and 666 degrees of freedom ($p < .001$).

Within the model to capture the natural variability which is present within all populations additional error terms (E1 and E2) were added to each value of height and mass generated within the model. Therefore, the final equations used to determine an older adult's height and mass were as follows: where 'h' = height, 'm' = mass, s = 'sex' (s = 1 for females and 2 for males), a = 'age'.

$$h = 1.6675 + 0.1409s - 0.0026a + E1 \qquad (\boldsymbol{D.1})$$

$$m = 25.4907 + 7.3115s - 0.4653a + 45.0504h + E2 \qquad (\boldsymbol{D.2})$$

Specifically, E1 was based on the residual standard error determined for the height variable, a random normal variable was generated for each older adult distributed according to the following (0, 0.0864), where (0 = mean, 0.0864 = standard deviation). This random variable was then added to the height regression equation output to determine the height of the older adult. E2 was based on the residual standard error determined for the mass variable, a random normal variable was generated for each older adult distributed according to the following (0, 12.79), where (0 = mean, 12.79 = standard deviation). This random variable was then added to the mass regression equation output to determine the mass of the older adult.

The following were the processes followed to determine the regression equations for mass and height. A Microsoft Excel spreadsheet was obtained from Schlegel Villages, which contained the age, gender, height, and mass information for 2697 older adults in the retirement home and 1585 older adults who were previously within the retirement home. Ethics approval was obtained from the Office of Research Ethics at the University of Waterloo, Waterloo, Ontario (ORE # 43852 Correlating Physical and Environmental Factors to Body Mass Index in Older Adults) to access this spreadsheet for a secondary analysis of data.

The spreadsheet was transferred into MATLAB (MATLAB R2022a, MathWorks, Natick, Massachusetts, USA) for further data processing. If either the height or the mass of the older adult was equal to zero (0), then both the height and mass values were set to NaN (Not a Number) otherwise the height and mass values remained unchanged. Next all entries with NaN, NaT (Not a Time) and empty strings contained within them were deleted. Therefore, all entries with any type of missing value were removed from the storage data structure. Due to the peculiarities of the dataset for older adults who were no longer at the retirement home it was necessary to calculate the ages of older adults at the time they moved out. Therefore, ages were obtained for both the older adults who had moved out and who were still within the retirement home. Once ages were obtained for all older adults BMI values were determined according to equation 2.2. The two separate data structures for the older adults who had moved out of the retirement home and who were still within the retirement home were unified into one data structure. Next all older adults with ages from 60 to 100 years inclusive were retained (N = 3813), all others were excluded from the data structure. Next the data structure was partitioned according to sex generating two sex-specific structures (F = 2484, M = 1329). These sex-specific data structure were then filtered in the order height, mass, and BMI. This process obtained the means and standard deviations of the heights of the male and female older adults. All entries which had heights which were outside of the range [mean ± 3SD] were excluded. The new data structures were considered to be height filtered data structures. The height filtered data structures were then filtered by obtaining the means and standard deviations of the masses of the male and female older adults. All entries in this data structure which had masses which were outside of the range [mean ± 3SD] were excluded. Finally, these mass filtered structures were filtered according to BMI by obtaining the means and standard deviations of the BMIs of the male and female older adults. All entries in the mass filtered data structures which had BMI values outside of the range [mean ± 3SD] were excluded.

The final data structure obtained from the above filtering process had 671 older adults (F = 443, M = 228) and was then used in the development of the linear regression equations for height and mass. The mean age of the older adults was (F = 88.1332 ± (5.7922) years, M = 87.4737 ± (6.0362) years), the mean height of the older adults was (F = 1.5766 ± (0.0815) m, M = 1.7191 ± (0.0986) m), the mean mass of the older adults was (F = 62.8203 ± (13.2297) kg, M = 76.9443 ± (14.8440) kg), the mean BMI of the older adults was (F = 25.3277 ± (5.2675) kgm^2, M = 26.0815 ± (4.8310) kgm^2).

Appendix E: Model Flow

In the updated model presented within this thesis, the age distribution of the retirement home older adults was determined from the age distribution mentioned in section 3.1. In what follows the process for generating one older adult is described.

FLV: Generating a FLV for the older adult was achieved with a uniform (0,1) random variable, a location was assigned to the older adult dependent on the value of the uniform (0,1) random variable (Table 1). The decision criteria for choosing a fall location were determined from the proportion of older adults falls as obtained from the Cleworth et al. (2021) paper. This variable was probabilistic.

Age: Determining the age of the older adult was achieved with a uniform (0,1) random variable, an age was chosen dependent on the value of the uniform (0,1) random variable. The decision criteria for choosing an age were determined from the proportion of older adults at each age as obtained from the age distributions derived from the retirement home data see (Table E 2). This variable was probabilistic.

Sex: Once an age was assigned, the sex-proportions mentioned in section 3.1 were used to assign a sex to the older adult. Again, the sex was determined using another uniform (0,1) random variable, the sex was assigned based on an age-dependent male/female sex ratio. Specifically, a decision criterion value was determined if the random variable was less than the decision criterion then the sex was assigned to be male otherwise female. The sex-ratio differed by age subsequently the criterion for determining male or female differed depending on the age assigned in the first step see (Table E 2). This variable was probabilistic.

Height: Using the regression equation (D.1) the height of the older adult was determined by the age and a numerical 'dummy' value corresponding to sex (1 = Female, 2 = Male) finally a random E1 obtained from a normal distribution was attached to complete the assignment of a height. Therefore, height was a probabilistic variable.

Mass: With height determined equation (D.2) was used to generate the mass of the older adult using their age, a numerical value corresponding to sex (1 = Female, 2 = Male) and the value of height determined through equation (D1). Finally, a random E2 obtained from a normal distribution was attached to complete the assignment of mass. Therefore, mass was a probabilistic variable.

BMI: BMI was determined using equation (2.2) and was a deterministic variable.

TSTT: TSTT of the older adult was determined from the regression equation (2.3) developed by LaFleur (2016) as presented. Once age, sex, mass, height, and BMI were determined for the older adult they were used in equation (E.1) which is just equation (2.3) with an error term added Specifically, the error term E3 was distributed according to (0, 1.12015) (mean, standard deviation). This variable was probabilistic.

$$TSTT = -2.22(s) + 0.33(BMI) - 3.31 + E3 \qquad \textbf{(E.1)}$$

Fall height: Fall height was determined using a fall height ratio from Chandler et al. (1975) by multiplying the heights obtained for the older adult using equation (D1). The fall height ratio was a non-sex-specific scaling factor i.e., same for males and females. The fall height ratio was a random variable distributed according to (0.586,0.0079) (mean, standard deviation) for both males and females. This variable was probabilistic.

Effective Mass: Effective mass was determined separately depending on whether the older adult was male or female. For both male and females the effective mass distribution was obtained by multiplying the mass obtained using the equation (D2) by a scaling factor. This scaling factor was sex-specific, i.e., different for males and females and presented within Martel (2017). The scaling factor was a random variable distributed according to (0.467, 0.043) (mean, standard deviation) for males and (0.553, 0.029) (mean, standard deviation) for females. This variable was probabilistic.

Pelvic Stiffness: Pelvic stiffness was determined separately for males and females; these values were obtained from Robinovitch et al. (1991) and were 90440 N/m and 71060 N/m for males and females respectively. Pelvic stiffness was a random variable distributed according to (90,440, 9464) (mean, standard deviation) for males and (71060, 6126) (mean, standard deviation) for females. This variable was probabilistic.

Soft Tissue Attenuation: The trochanteric soft tissue thickness was determined by the value of BMI generated above due to the work of Robinovitch (1995) and is given by equation (2.4). This variable was deterministic.

Impact Force: The peak impact force experienced at the hip was determined by the values of effective mass, fall height, and pelvic stiffness using equation (2.1) from Robinovitch (1991). This variable was deterministic.

Bone Mineral Density: Bone mineral density was determined using the age, sex, and mass of the older adult according to regression equations developed by LaFleur (2016). Equation (E.2) is a restatement of equation (2.6) with an additional error term E4 added. Specifically, this error term was distributed according to the following (0, 0.13438). It should be noted that the dummy variable used to represent sex in this equation is (0 = female, 1 = male). This variable was probabilistic. Note: The specific simulation which was used did not include Bone Mineral Density as a probabilistic variable. The error term led to some low and negative values of BMD which resulted in some anomalies. Therefore, the regression without the error was used. (FN BMD = Femoral neck bone mineral density.)

$$FN\ BMD\ (g/cm^2) = -0.006(a) + 0.058(s) + 0.005(m) + 0.818 + E4 \qquad (\boldsymbol{E.2})$$

Net Force/Net Impact Force: The net force experienced at the proximal femur of the older adult was determined from the peak force estimated for a lateral fall onto the hip and the trochanteric soft tissue mediated force absorption equation (2.8). This variable was deterministic.

Fall Velocity: This is the actual peak velocity determined by an older adult's fall height and the acceleration due to gravity (g). It was determined from energy conservation considerations and is equal to (E.3).

$$v = \sqrt{gh} \qquad (\boldsymbol{E.3})$$

Safety Flooring Force Attenuation Percentage: The force attenuation due to safety flooring (represented as a percentage of the net force) was determined from experimental work performed by Martel (2017) equation (E.4). The inputs to this nonlinear multiple regression equation were the older adult's height to calculate a fall velocity, the older adult's effective mass, the older adult's pelvic stiffness and the older adult's TSTT. This equation includes an additional error term E5, which is distributed according to the following (0, 2.561). Therefore, the safety flooring attenuation module generated a probabilistic measurement of the force attenuation (as a percentage) experienced at the proximal femur of the older adult due to a fall on safety flooring. (SFFP = Safety Flooring Force Attenuation Percentage, v = peak impact velocity, em = effective mass, k = stiffness, t = TSTT).

$$\begin{aligned} SFFP\ (\%) = {} & \\ & 296.810 - 109.2(v) - 5.772(em) - 3.8(t) - 0.007968(k) + 0.003393(vk) + 2.544\big(v(em)\big) \\ & + 0.7787\ (vt) + 0.000178\ \big((em)k\big) + 0.000073(tk) + 0.01359\ \big((em)t\big) \\ & - 0.000078(v(em)k) - 0.00002105(vtk) + E5 \end{aligned} \qquad (\boldsymbol{E.4})$$

Safety Flooring Force Attenuation: This is the actual force attenuation determined at the proximal femur of the older adult. It is determined from the safety flooring force attenuation percentage and the net impact force experienced at the proximal femur equation (E.5). (SFFA = Safety Flooring Force Attenuation)

$$SFFA\ (N) = (SFFP)x(NIF) \qquad (\boldsymbol{E.5})$$

Intervened Net Force: The intervened force experienced at the proximal femur of the older adult was determined from the peak force estimated for a lateral fall onto the hip, the trochanteric soft tissue mediated force absorption and the safety flooring mediated force absorption equation (E.6). This variable was deterministic. (INF = Intervened Impact Force, PIF = Peak Impact Force, STFA = Soft Tissue Force Attenuation, SFFA = Safety Flooring Force Attenuation.)

$$Intervened\ Net\ Force\ (N) = Impact\ Force\ - STFA - SFFA \qquad (\boldsymbol{E.6})$$

Femoral/Bone Strength: The bone strength was derived dependent on the equation (2.7) of Robinson et al. (2010). The value of bone strength depended on the bone density which itself depended on the age, sex, and mass of the older adult. There was a direct relationship between bone mineral density and bone strength, and the variable was deterministic.

Factor of Risk: The factor of risk Hayes (1991) which quantified hip fracture risk of the older adult was determined from the net force experienced at the proximal femur and the estimated bone strength according to equation (2.5). This variable was deterministic.

Intervened Factor of Risk: The intervened factor of risk is just a different presentation of the factor of risk Hayes (1991) which quantified hip fracture risk of the older adult (for falls onto safety flooring) and was determined from the intervened force experienced at the proximal femur and the estimated bone strength according to equation (2.5). This variable was deterministic.

In most of the previous steps, probabilities were incorporated into the assignment and generation of variables. Further in the generation of the final mass, height, bone mineral density and TSTT variables, variability was introduced using the normal distribution, it is this which then leads to the term probabilistic model as variability is an integral aspect in the generation of most variables.

In the original model of Martel (2017) and Martel et al. (2020) the sex of an older adult was determined in the same manner, except that the decision criteria for determining sex at each age were different. However due to the complexity of the data Martel (2017) fit polynomial functions to Statistics Canada data on age, height, and mass percentiles. The methods section of Martel (2017), Martel (2020) or Section (2.7) of this thesis provide more information on the polynomial functions used to represent the respective distributions. An important note is that in the original Martel (2017) model, the order in which the variables for mass and height were generated were irrelevant as the processes were independent of each other. Within the updated model the implementation of regression equations requires height to be determined before mass as the height variable was one of the inputs into the regression equation for mass.

Table E 1: Summary table of all equations contained within the probabilistic hip fracture model.

Variable of Interest	Determining Equation	Contributing Variables	Equation Type $^{\#}$	Reference
FLV	**N/A**	**N/A**	**P**	**Shade (2023)**
Age	**N/A**	**N/A**	**P**	**Shade (2023)**
Sex	**N/A**	**N/A**	**P**	**Shade (2023)**
Height	$h = 1.6675 + 0.1409s - 0.0026a + E1 \quad (\boldsymbol{D.1})$	**Age (a), Sex (s)**	**P**	**Shade (2023)**
Mass	$m = 25.4907 + 7.3115s - 0.4653a + 45.0504h + E2 \quad (\boldsymbol{D.2})$	**Age (a), Sex (s), Height (h)**	**P**	**Shade (2023)**
BMI	$BMI = \frac{Mass}{Height^2} \quad (\mathbf{2.2})$	**Height (h), Mass (m)**	**D**	**N/A**

TSTT	$TSTT = -2.22(s) + 0.33(BMI) - 3.31 + E3$ $(\boldsymbol{E.1})$	**Sex (s), BMI**	**P**	**LaFleur (2016)**
Fall Height (FH)*	$HR \sim N(0.5857, 6.24e^{-5})$ $(\mathbf{2.16})$ $FH = (h)x(HR)$ $(\mathbf{E.6})$	**Height (h), Fall Height Ratio (HR)**	**P**	**Chandler et al. (1975)** **Martel (2017)**
Effective Mass (EM)	$Male: EM \sim N(0.467, 0.043)$ $(\mathbf{2.17})$ $Female: EM \sim N(0.553, 0.029)$ $(\mathbf{2.18})$ $EM = (m)x(EMR)$ $(\mathbf{E.7})$	**Mass (m), Effective Mass Ratio (EMR)**	**P**	**Martel (2017)**
Pelvic Stiffness (K)	$Males: K \sim N(90{,}440, 9464^2)$ $(\mathbf{E.8})$ $Females: K \sim N(71060, 6126^2)$ $(\mathbf{E.9})$	**N/A**	**P**	**Robinovitch et al. (1991)**
Soft Tissue Force Attenuation (STFA)	$STFA\ (N) = 71\ (N/mm)\ x\ TSTT\ (mm)$ $(\mathbf{2.4})$	**TSTT**	**D**	**Robinovitch (1995)**

Impact Force (IF)	$IF\ (N) = \sqrt{2ghmk}$ $\quad(\mathbf{2.1})$	**Acceleration due to Gravity (g), Fall Height (h), Effective Mass (m), Pelvic Stiffness (k)**	**D**	**Robinovitch et al. (1997 b)** **Robinovitch et al. (2009)** **Dufour et al. (2012)**
Femoral Neck Bone Mineral Density (FN BMD)	$FN\ BMD\ (g/cm^2) = -0.006(a) + 0.058(s) + 0.005(m) + 0.818 + E4$ $\quad(\boldsymbol{E}.\mathbf{2})$	**Age (a), Sex (s), Mass (m)**	**P**	**LaFleur (2016)**
Net Impact Force (NIF)	$Net\ Impact\ Force\ (N) = Impact\ Force - STFA$ $\quad(\mathbf{2.5})$	**Impact Force, Soft Tissue Force Attenuation**	**D**	**Robinovitch et al. (1995)** **Dufour et al. (2012)** **Martel (2017)**

Impact Velocity	$v = \sqrt{gh}$ $(\boldsymbol{E.3})$	**Acceleration due to Gravity (g), Fall Height (h)**	**D**	**Robinovitch et al. (1991)**
Safety Flooring Force Attenuation Percentage (SFFP)	$SFFP\ (\%) =$ $296.810 - 109.2(v) - 5.772(em) - 3.8(t) - 0.007968(k) + 0.003393(vk) + 2.544\big(v(em)\big) + 0.7787\ (vt) + 0.000178\ \big((em)k\big) + 0.000073(tk) + 0.01359\ \big((em)t\big) - 0.000078(v(em)k) - 0.00002105(vtk) + E5$ $(\boldsymbol{E.4})$	**Effective Mass (em), Pelvic Stiffness (k), Impact Velocity (v), TSTT (t)**	**P**	**Martel (2017)** **Martel et al. (2020)**
Safety Flooring Force Attenuation (SFFA)	$SFFA\ (N) = (SFFP)x(NIF)$ $(\boldsymbol{E.5})$	**Safety Flooring Force Attenuation Percentage (SFFP), Net**	**D**	**Martel (2017)** **Martel et al. (2020)**

		Impact Force (NIF)		
Intervened Net Force (INF)	$Intervened\ Net\ Force\ (N) = Impact\ Force\ - STFA - SFFA \qquad (\boldsymbol{E.6})$	**Impact Force, Soft Tissue Force Attenuation, Safety Flooring Force Attenuation**	**D**	**Robinovitch et al. (1995)** **Martel (2017)**
Femoral/Bone Strength (FS)	$Femoral\ Strength\ (N) = 8207 * \left(FN\ BMD\ (g/cm^2)\right) - 568.62 \qquad (\mathbf{2.7})$	**Femoral Neck/Bone Mineral Density (FN BMD)**	**D**	**Robinson et al. (2010)**
Factor of Risk (FOR)	$FOR = \frac{Net\ Impact\ Force\ (N)}{Femoral\ Strength\ (N)} \qquad (\mathbf{2.8})$	**Net Impact Force, Bone Strength**	**D**	**Hayes (1991)** **Dufour et al. (2012)**

				Martel (2017) **Martel et al. (2020)**
Intervened Factor of Risk (IFOR)	$IFOR = \frac{Intervened\ Net\ Force\ (N)}{Femoral\ Strength\ (N)}$ $(\mathbf{2.8})$	**Intervened Net Force, Femoral Strength**	**D**	**Hayes (1991)** **Martel (2017)** **Martel et al. (2020)**

[#] Equation Type indicates whether the equation is probabilistic (P) or deterministic (D).

Table E 2: Retirement home age densities and male/female probability ratio.

Age	Population Density	Male/Female Ratio
60	5.2452E-04	0.500
61	7.8678E-04	0.500
62	7.8678E-04	0.500
63	1.3113E-03	0.500
64	1.3113E-03	0.500
65	7.8678E-04	0.452
66	1.8358E-03	0.452
67	2.3603E-03	0.452
68	1.5736E-03	0.452
69	3.1471E-03	0.452
70	4.7207E-03	0.427
71	4.1962E-03	0.427
72	6.0320E-03	0.427
73	7.3433E-03	0.427
74	8.3923E-03	0.427
75	7.6056E-03	0.330
76	1.1802E-02	0.330
77	1.7309E-02	0.330
78	1.8883E-02	0.330
79	1.8358E-02	0.330
80	2.2030E-02	0.333

81	2.4915E-02	0.333
82	3.6716E-02	0.333
83	3.0947E-02	0.333
84	4.5371E-02	0.333
85	5.4026E-02	0.350
86	5.5599E-02	0.350
87	6.4778E-02	0.350
88	6.9499E-02	0.350
89	6.0320E-02	0.350
90	6.1369E-02	0.346
91	6.7926E-02	0.346
92	5.9533E-02	0.346
93	5.7173E-02	0.346
94	4.8518E-02	0.346
95	3.8290E-02	0.313
96	2.5702E-02	0.313
97	2.7275E-02	0.313
98	1.4162E-02	0.313
99	1.1539E-02	0.313
100	5.2452E-03	0.313