FORCASTING PROXIMAL FEMUR AND WRIST FRACTURE CAUSED BY A FALL TO THE SIDE DURING SPACE EXPLORATION MISSIONS TO THE MOON AND MARS

Paper ID: 1494
59th International Astronautical Congress 2008
SPACE LIFE SCIENCES SYMPOSIUM (A1.)

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ABSTRACT

The possibility of bone fracture in space is a concern due to the negative impact it could have on a mission. The Bone Fracture Risk Module (BFxRM) developed at the NASA Glenn Research Center is a statistical simulation that quantifies the probability of bone fracture at specific skeletal locations for particular activities or events during space exploration missions. This paper reports fracture probability predictions for the proximal femur and wrist resulting from a fall to the side during an extravehicular activity (EVA) on specific days of lunar and Martian exploration missions. The risk of fracture at the proximal femur on any given day of the mission is small and fairly constant, although it is slightly greater towards the end of the mission, due to a reduction in proximal femur bone mineral density (BMD). The risk of wrist fracture is greater than the risk of hip fracture and there is an increased risk on Mars since it has a higher gravitational environment than the moon. The BFxRM can be used to help manage the risk of bone fracture in space as an engineering tool that is used during mission operation and resource planning.

INTRODUCTION

It is widely accepted that mechanical strain of bone is a stimulus for bone growth [1-6]. Studies have shown a correlation between engaging in physical activities that result in bone strain and an increase in bone mineral density (BMD) [7-11]. Consequently, prevailing theory holds that bone is maintained as a result of the repetitive strain experienced over the course of daily activities in Earth's gravity [12-22]. A decrease in BMD results when the mechanical stimulus is absent due to inactivity or the reduction of gravity. This phenomenon has been observed in individuals with a sedentary lifestyle, as a result of prolonged bed rest, after spinal cord injury and after spaceflight [23-34]. On Earth, reduced BMD is one factor which indicates a risk of bone fracture during the activities of everyday living. [30;35-37].

A bone fracture can be considered a structural failure of the bone, which occurs when the load placed upon the bone exceeds its structural strength [38-41]. Apparent bone strength is dependent on several factors including mineral content, prior microdamage, geometry, architecture, age and the nature of the applied load [30;35-37;42-47]. Loading that exceeds the strength of the bone can occur during an accident, such as a fall, where a high impact load is experienced. Fracture is even more likely during a fall for bones with compromised bone strength. Bone fracture at certain locations, such as the proximal femur, are usually highly traumatic injuries, especially in damaged or osteoporotic bone [48-53]. Treatment of these injuries requires, at best, immobilization or, at worst, surgery, and often leave the patient temporarily disabled [54-60]. In falls to the side, the arm is often reflexively used to help absorb the impact, which can result in wrist fracture [61;62]. Treatment of wrist fracture requires immobilization of the arm, which limits a patient's ability to perform routine activities.

During the exploration missions to the moon and Mars the astronauts will be in a reduced gravity environment for a period of months to years. Studies that have measured pre- and post-flight BMD through dual energy X-ray absorptiometry (DXA) report that astronauts lose an average of 1 to 1.6% of their bone mass per month in the spine, femoral neck, throchanter and pelvis [24] and an average of 1.7% in the cancellous tibia after one month of space flight [25]. Success of future space exploration missions will depend on the astronauts' ability to perform physical activities, such as construction of a lunar or Martian base, with minimal threat of injury. However, there is a legitimate concern of fracture due to the occurrence of an unexpected event, such as tripping and falling, which is exacerbated by the state of their weakened bones. Space missions are severely constrained in resources, and by their very nature, provide limited access to medical care. This can have a serious impact on the necessary time for healing, and could even lead to permanent disability and/or loss of mission or crew member [63-66]. Since the possibility of fracture exists and the impact to the mission could be substantial, it is crucial to quantify the risk of bone fracture during space exploration missions so that mitigation strategies can be engineered.

This paper provides information about the Bone Fracture Risk Module (BFxRM), a mathematical model that has been constructed to calculate the probability of bone fracture during specific astronaut activities during space exploration missions. An overview is given of key elements of the model, including the mission parameters, the biomechanical loading models, the bone loss and ultimate strength models, the calculation of the fracture risk index (FRI), the incidence rates of the activities or events and the conversion of the FRI and incidence rates to a probability of fracture. Insight is given into the underlying uncertainties and assumptions of the model and the interaction of the key elements which ultimately produce predictions of fracture probability. Prior work examined the risk of fracture to the proximal femur and the lumbar spine resulting from falls [67]. In this study, BFxRM predictions of the probability of fracture are given for the proximal femur resulting from a fall to the side and the probability of wrist fracture when the arm is used to break the fall during an EVA on specific days for lunar and Mars space exploration mission scenarios. In addition, an analysis of the most sensitive parameters is given, exemplifying the value of the BFxRM for mission operation and resource planning.

METHODS

The BFxRM is a scenario-based model. It estimates the probability of fracture at a particular skeletal site during a mission by considering the key activities or events of a mission, the resultant skeletal loading, and the dynamically evolving bone strength. See Figure 1 for a block diagram of the model. The input of the model are the mission parameters and include gender, gravitational environment, the day of the mission the fall occurred, astronaut body mass, EVA suit mass and the pre-flight BMD level. The probability of proximal femur and wrist fracture were calculated on day 10 and day 150 of a lunar mission and day 10 and 500 of a Martian mission. The transit time to the moon was assumed to be 5 days and 189 days to Mars. At the core of the BFxRM is the calculation of a fracture risk index (FRI), which is the ratio of the skeletal load experienced during the fall to the maximal load (Ultimate Load) that the bone can sustain. FRI is also commonly referred to as factor of risk. An FRI substantially below one indicates that the bone is likely to be strong enough to support the load. Conversely, an FRI above one indicates that there is a significant risk of bone fracture [39;68;69]. The load experienced by proximal femur and the wrist during a fall were estimated using biomechanical models. Data from the literature on the ultimate strength of the distal radius were used to model the maximal load the wrist can withstand. Relationships between proximal femur BMD loss and time in space and between BMD and Ultimate Load (UL) were constructed from data reported in the literature and were used to determine the maximal load of the proximal femur. The likelihood of fracture on a particular day in the mission is made up of the combined probability of: 1) an EVA occurring on that mission day; 2) a fall occurring during the EVA; 3) endangerment of the hip or wrist due to the position of the body during the fall; and 4) the applied load at impact exceeding the Ultimate Load. Fracture probabilities were calculated with Crystal Ball software (Oracle, Denver, CO), using Monte Carlo and Latin Hypercube simulations. For each fracture location, at each mission location, on each particular mission day of interest, the fracture probability was calculated 100,000 times during the simulation trials. An estimate of the fracture probability was defined by the mean, standard deviation and 5% and 95% percentiles of the 100,000 fracture probability calculation trials.

Multiple trials were performed in order to account for uncertainty in the model parameters, which were defined as a distribution of values.

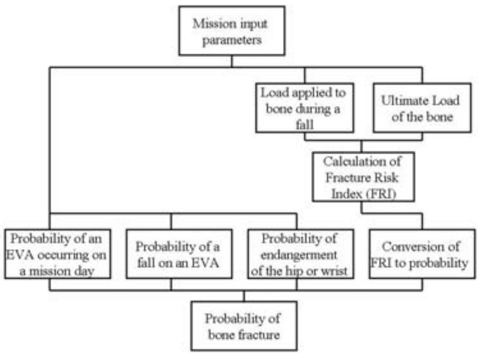

Figure 1. *Block diagram of the Bone Fracture Risk Module.*

Two biomechanical loading models were developed to estimate the loading experienced at the proximal femur and the wrist during a fall. The loading model for the hip during a fall to the side was based on a mass-spring-damper model developed by Robinovitch et al [70]. As shown in Figure 2A, the model uses one mass, the effective mass of the hip (H), one spring, representing the stiffness of the hip pad and one damper, representing the damping characteristics of the hip pad [70]. The effective mass of the hip was defined in the Robinovitch [71] model as the mass of the body from the under arms to the knees. A distribution of the percentage of body weight this represents was used as a multiplier to the total body weight within the model to determine the effective weight. The percentage was determined from sources with astronaut anthropometric data [72-74].

The loading model for the wrist when it is used to break a fall was based on a mass-spring-damper model developed by Chiu et al [61]. As shown in Figure 2B, the model incorporated two masses (torso (T), and arm (A)), a spring and damper between the T and the A masses to represent the stiffness and damping characteristics of the shoulder [61;75], and a spring and damper between the A mass and ground to represent the stiffness and damping characteristics of the wrist [61;75-79]. For both the hip and the wrist, the load experienced by the bone due to a fall was calculated using a system of linear first order differential equations, with impact velocity as the initial condition.

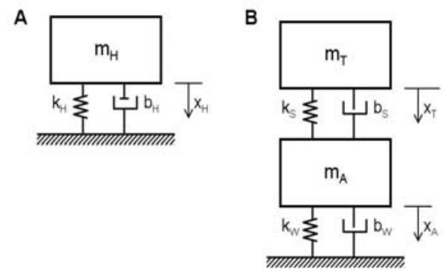

Figure 2. *Biomechanical mass-spring-damper models.* ***A.*** *The hip model. The effective mass of the hip (m_H); the stiffness (k_H) and damping characteristics (b_H) of the hip pad; and the displacement of m_H (x_H) are shown.* ***B.*** *The wrist model. The mass of the torso (m_T) and arm (m_A); the stiffness of the shoulder (k_S) and wrist (k_W); the damping characteristics of the shoulder (b_S) and wrist (b_W); and the displacement of m_T (x_T) and m_A (x_A) are shown.*

Bone-loss data resulting from space travel is sparse and does not clearly establish the time course that should be expected in long-duration spaceflight. In an attempt to bound the problem, the available data on astronaut femoral neck BMD [27] were fitted to define bone loss at that skeletal location as a function of time using a piece-wise linear approximation. This relationship was used to calculate the decrease in bone density as a function of mission elapsed time. A mathematical relationship between femoral neck BMD and its Ultimate Load, or the maximal loading above which fracture occurs, was found with data from cadaver studies [80]. The predicted femoral neck BMD at the time of fracture was then used with this relationship to determine femoral neck Ultimate Load. The BMD of the wrist does not significantly change over the course of a space mission [27]. Therefore, wrist BMD was assumed to remain constant over time and wrist Ultimate Load was not modeled as a function of BMD. Rather, the wrist Ultimate Load was specified with a mean and standard deviation, determined from two data sets. The first data set was the measured wrist Ultimate Strength of cadaver specimens with normal BMD levels [81] and the other data set was calculated Ultimate Strength using the measured BMD of healthy subjects between the ages of 20 and 59 years [82;83] and the relationship between wrist BMD and Ultimate Strength reported by Wu et al [84].

The rates of occurrence from past missions were used to calculate the probability of an EVA occurring on the mission day of interest. Using Apollo EVA films and astronaut reports, the rate of occurrence of a fall to the side was qualitatively estimated to be once per EVA and was converted to a probability assuming a Poisson distribution. The probability that the hip or wrist would be endangered during the fall was dependent on the distribution of energy absorption between the two locations. This probability was calculated based on the work of others [61;62]. The FRI was converted to a probability using the technique from [75], where a logistic regression was used to identify a mathematical relationship between FRI and fracture probability by comparing post incidence fractures to controls. For our model, the parameters of the equation used by Davidson et al. were modified to incorporate the findings of Kannus et al. The references therein utilize the relation that a fracture is most likely when the load applied to the bone is within one standard deviation of the Ultimate Load [85].

The model parameters contain aleatory uncertainty and epistemic uncertainty is illustrated in the assumptions made when structuring the model calculations. Aleatory uncertainty is the uncertainty associated with the natural variation in population. This type of uncertainty is present in the parameters of the model, such as body mass, body segment mass, preflight BMD levels, etc., due to the anatomical variation present among the astronaut corps. Assuming the use of accurate data for defining these parameters, the ability to reduce this uncertainty is minimal. To account for the variations, distributions of values were created for the model parameters. Epistemic uncertainty results from incomplete information about the parameters or the interaction of the parameters within the model, either because data is unavailable or because equally valid, competing assumptions exist. Examples of the epistemic uncertainty in our model include the method used to model the rate of bone loss in space and the analog force attenuation effect assumed for the spacesuit. To bound the epistemic uncertainty in the model, a range of possible values, based on the best available data, for the uncertain parameters were incorporated into a distribution of values. During each simulation trial, a different value from each parameter distribution was used in the calculation of fracture probability.

RESULTS

BFxRM predictions of fracture probability

Figure 3 provides an example of the output of the BFxRM. Figure 3A illustrates the distribution of the calculated probability of a proximal femur fracture due to a fall of a male astronaut during an EVA on day 500 on the surface of a Martian mission. Figure 3B illustrates the distribution of the calculated probability of a wrist fracture due to a fall of a male astronaut during an EVA on any discrete day of a Martian mission. The mean probability, standard deviation, 5th and 95th percentile probability for various mission scenarios are tabulated in Table 1 for the probability of proximal femur fracture and in Table 2 for the probability of wrist fracture. The risk of fracture at the proximal femur is small and fairly constant for any particular day during a mission, however it is slightly greater for missions of longer duration, due to the observed decrease in astronaut bone mineral density (BMD) during spaceflight induced by gravitational unloading, and the increased gravitational environment of Mars (roughly two-thirds of Earth gravity) compared to the moon (roughly one-sixth of Earth gravity). The risk of wrist fracture is greater than the risk of hip fracture. The risk of wrist fracture does not increase for a long duration mission because the BMD of the wrist does not vary much from pre-flight levels. There is an increased risk of wrist fracture on Mars since it has a higher gravitational environment than the moon.

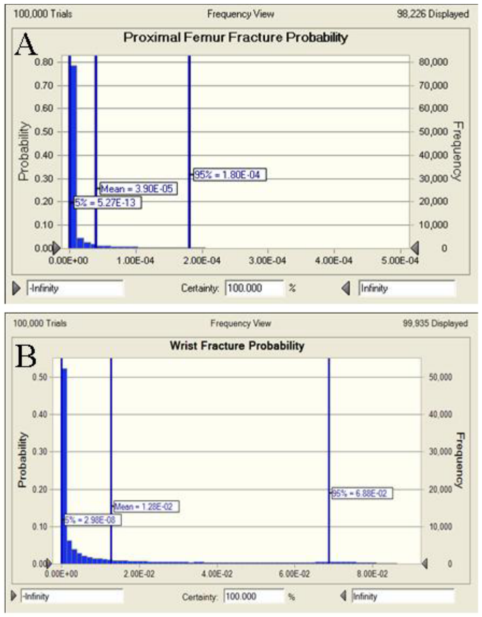

__Figure 3.__ BFxRM example output. The fracture probability distribution of ***A.*** *the proximal femur due to a fall to the side of a male astronaut on an EVA after 500 days of a Martian mission and* ***B.*** *the wrist when it is used to break the fall. Shown here is a screen shot from Crystal Ball software (Oracle, Denver, CO).*

Table 1. *Probability of proximal femur fracture resulting from a fall to the side during an EVA for various mission days of lunar and Martian missions for male and female astronauts.*

Day	Mean	Std	5%	95%
Male, Moon				
10	2.40E-05	1.10E-04	2.07E-13	1.16E-04
150	2.42E-05	1.11E-04	2.29E-13	1.17E-04
Male, Mars				
10	2.84E-05	1.31E-04	3.45E-13	1.39E-04
500	3.90E-05	2.06E-04	5.27E-13	1.80E-04
Female, Moon				
10	2.55E-05	1.17E-04	2.62E-13	1.22E-04
150	2.57E-05	1.16E-04	2.80E-13	1.26E-04
Female, Mars				
10	3.29E-05	1.57E-04	4.56E-13	1.57E-04
500	5.13E-05	3.20E-04	7.62E-13	2.23E-04

Table 2. *Probability of wrist fracture resulting from a fall to the side during an EVA for any mission day of lunar and Martian missions for male and female astronauts.*

Mean	Std	5%	95%
Male, Moon			
3.10E-03	9.18E-03	1.02E-09	1.83E-02
Male, Mars			
1.28E-02	2.21E-02	2.94E-08	6.93E-02
Female, Moon			
8.31E-03	1.76E-02	6.50E-09	5.60E-02
Female, Mars			
2.40E-02	2.94E-02	2.15E-07	7.82E-02

Sensitivity analysis

An analysis was performed in order to determine the most sensitive model parameters, where small changes to these parameters cause a large variance in the probability calculations. The two most sensitive parameters in the calculation of the proximal femur fracture probability are the parameters used to convert the FRI to a probability. This is followed by the angle at which the load is applied and the attenuation afforded by the EVA suit. For the wrist model the most sensitive parameters are also the parameters used to convert the FRI to a probability, followed by the parameters used to calculate the load on the wrist during a fall.

DISCUSSION

A model that quantifies the risk of a bone fracture during space exploration missions has been developed. The uncertainties associated with the conditions that are necessary for a fracture to occur have been bounded in the model. The risk of fracture at the proximal femur is small and fairly constant for any particular day during a mission. However, it is slightly greater for missions of longer duration and of higher gravitational environment. The risk of wrist fracture is greater than the risk of hip fracture and is greater in a higher gravitational environment. The resulting probability predictions and sensitivity analyses of the BFxRM can be used as an engineering tool for mission operation and resource planning in order to mitigate the risk of bone fracture in space.

The large uncertainty bands illustrate the need for additional relevant data. As it becomes available it can be incorporated into the model to increase fidelity and to reduce epistemic uncertainty surrounding the risk of bone fracture during space exploration missions. The sensitivity analysis provides guidance on the key factors controlling fracture risk. This insight can be used to most efficiently mitigate risk through, e.g., potential modifications to the astronaut's habitat, equipment, training, and operations plan.

Simplifications were made during model development, particularly in the biomechanical loading models. Quantification of loading forces is not easily achieved. *In vivo* measurements require invasive implantation of strain gauges or pressure sensors. Therefore, instead of direct measurements, the loads on the bone were found indirectly, through mathematical estimation with biomechanical models. Skeletal loading results from a complex interaction between external objects, skeletal muscles, tendons, ligaments, other tissues and bones. Simplifications of these interactions were essential to produce a practical, useful biomechanical model. Examples of the simplifications used in our biomechanical models are lumped masses and the assumption that the stiffness and damping characteristics are linear.

Our models of Ultimate Load were built from the best available data in the literature. However, there are limitations in the model due to the fact that it was not possible to completely match our demographics and loading situations of interest. For example, studies of bone strength tend to have a preponderance of elderly subjects, as opposed to athletic, middle-aged astronauts. Aging imposes a loss in the mineral content of bone as well as a modification of the bone microarchitecture, both of which contribute to fracture susceptibility. From the standpoint of the microarchitecture, it is unclear whether “space aging” of bone is comparable to aging bone on earth. These types of factors may have led to conservative model predictions.

This model has applications as an engineering tool. For example, it could be used to determine whether or not padding should be added to the hip area of the EVA suit. It can be used to determine the optimal type and amount of medical resources that should be taken on the mission and it can be used to determine the most beneficial medical training for the crew.

CONCLUSION

A model has been developed that bounds the uncertainty associated with the risk of bone fracture of the proximal femur and the wrist due to a fall to the side in space. Fractures of the proximal femur are of particular interest since this region is sensitive to bone loss and fracture could lead to catastrophic consequences for the crew and/or mission. While the impact of wrist fracture to the mission may not be as great as a hip fracture, its probability of occurrence is greater. Biomechanical models of a fall to the side were developed to determine the applied loads at the specific skeletal sites. Bone fracture models were created for both the proximal femur and the wrist, based on data from terrestrial populations subjected to comparable loading conditions. Several mission scenarios were examined, resulting in fracture probabilities, as well as sensitivity analyses. This model shows great promise as an engineering and planning tool for managing the risk of bone fracture during space missions.

ACKNOWLEDGEMENTS

The BFxRM is a component of the NASA Integrated Medical Model Task, under the NASA Exploration Medicine Capabilities Element and was funded by the NASA Human Research Program, which is managed at the Johnson Space Center.

Special thanks to Shreyasee Amin who provided wrist BMD data obtained from NIH funded study R01 AR 27065, PI: Dr. Sundeep Khosla.

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