Background

A previous study [1] reported that the instantaneous risk of developing a Herniated Nucleus Pulposus (HNP) was higher in astronauts who had flown at least one mission, as compared with those in the corps who had not yet flown. However, the study only analyzed time to HNP after the first mission (if any) and did not account for the possible effects of multiple missions. While many HNPs occurred well into astronauts’ careers or in some cases years after retirement, the higher incidence of HNPs relatively soon after completion of space missions appears to indicate that spaceflight may lead to an increased risk of HNP. In addition, when an HNP occurs after spaceflight, is it related to previous spaceflight exposure? The purpose of this study was to investigate whether multiple missions, sex, age, vehicle landing dynamics, and flight duration affect the risk of developing an HNP using a competing risks model. The outcome of the study will inform the Human System Risk Board assessment of back pain, inform the risk of injury due to dynamic loads, and update the previous dataset, which contained events up to December 31, 2008.

Methods

The study was done using data queried by an epidemiologist from the electronic medical record and provided by the Lifetime Surveillance of Astronaut Health. The data included all 330 United States Astronauts beginning at selection and continuing throughout their life from 1959 through February 2014. HNP diagnoses were confirmed by Magnetic Resonance Imaging, Computed Tomography, Myelography, operative findings, or through clinical correlation by a neurosurgeon. In this analysis, cases of HNP diagnosed at or before an astronaut was selected into the astronaut corps were ignored.

Survival Model. We modeled the distribution of \( T \), the time from selection to the astronaut corps until first diagnosis of HNP. Explanatory variables fall into two categories:

- Flight-related explanatory variables: number and timing of missions, mission duration, type of landing vehicle(s), experience as pilot of a high-performance jet aircraft. For purposes of this study, "long-duration" missions were those flown on Skylon, MIR, or ISS. Others were considered "short-duration" missions. Landing vehicles were classified into "STS" (Space Shuttle) or "capsule" (all others).

- Demographic explanatory variables: age, gender, weight, height, and BMI.

An important component of the model allows for the possibility that only some astronauts are susceptible to developing a HNP during their active careers or after retirement. For astronauts in the "susceptible" (S) category, if a HNP had not been reported by the time of their last physical exam, \( T \), was treated as censored at that time, meaning that these astronauts would have eventually developed a HNP had they been observed longer. On the other hand, non-susceptible astronauts (M) are those who would never develop a HNP no matter how long they were observed. In practice, susceptibility is treated probabilistically, i.e., we cannot tell on an individual basis whether or not a particular astronaut who did not develop a HNP during the study period is in the Sus or M category, but we were able to estimate the proportion of susceptible astronauts as a function of how many missions they flew (0 – 7).

Analysis goals. The main analysis goal was to separate effects of spaceflight from those of just being in the astronaut corps on the distribution of \( T \).

Secondary goals were to investigate the degree to which numbers of missions, age, gender, etc. also had an effect on \( T \).

Survival Model Details. Multiple stochastic processes take place for each astronaut: \( T \) is time from selection to HNP (influenced by astronaut training and lifestyle) and \( t \) is time from selection to first HNP after the \( i \)th mission flight \((i = 1, 2, n)\).

Hazard Functions. The distributions of \( T \) and \( T_i \), as well as \( P(M) \), the probability that an astronaut is in the M category are modeled through their hazard functions. A hazard function \( h(t) \) is a measure of instantaneous risk of HNP at time \( t \) given that one has not occurred previously. For example, in Figure 1, the probability of a first HNP occurring in the small time window shown is approximately the value of the hazard function times the width of the window, \( \Delta t \), defined as elapsed time from the date of selection.

In this application, hazard functions are modeled as proportional to Weibull density functions:

Weibull Density Function

\[
W(t;p, \theta) = \frac{p}{\theta} \left( \frac{t}{\theta} \right)^{p-1} e^{-(t/\theta)^p}
\]

Hazard Function Components.

Astronaut training and lifestyle:

\[
A_i(t) = 4p_i \left( \frac{t}{\theta_i} \right)^{p_i-1} \left( \frac{t}{\theta_i} \right) \quad (i = 1)
\]

After each spaceflight mission:

\[
h_i(t) = A_i(t) - t \quad (i > 1)
\]

where \( p_i \), \( \theta_i \), are \( P(M) \), and if there are variables that generally depend on the explanatory variables. The effect of the explanatory variables on the hazard function parameters is estimated by the method of maximum likelihood. Figure 2 illustrates how the component hazard functions reflect differences in the explanatory variables.

Survival Function for \( T \): \( S(T) = e^{-\int_0^T h(t)dt} \)

Probability of non-susceptibility. The proportion of astronauts that would never develop HNP’s no matter how long they were observed is given by \( P(M) = e^{-\int_0^\infty \ h(t)dt} \).

where \( n \) is the number of space missions. Reflecting the increased cumulative risk as more flights are undertaken, Figure 3 shows how the \( P(M) \) would decrease if everyone had equally spaced missions 3 years apart. This calculation was made with model parameters estimated from the study data.

Probability that an HNP at time \( t \) was caused by Spaceflight:

\[
P(F(t)) = \int_0^t h(t)dt
\]

(Density functions \( f(t) \) and \( f^*(t) \) are obtained from hazard functions).

Figure 4 illustrates how this probability changes with respect to the number and spacing and of missions, as well mission duration and landing vehicle type.

Results

Survival Model. Figure 5 shows the probability of an HNP occurring as a function of years after astronaut selection \( a \) without any distributional assumptions (solid line), and b) with our survival model (red dots). The overall trends agree well. Deviations of the dots from the solid line reflect how our model accounts for variation in HNP risk due to differing numbers and spacing of missions for the 330 astronauts.

Figure 6 shows how the probability of an HNP within one year of a mission landing was estimated to increase with the number of missions. However because of the lower numbers of astronauts with many missions, the accuracy of this estimated probability becomes worse (increased error bounds) as the number of missions increases.

Discussion

Analysis of the data revealed clear evidence that spaceflight is associated with increased risk of HNP. These increases were 745 astronaut missions (long-duration), 51 capsule landings (short-duration or type of landing vehicle had an effect. One of the most important questions addressed by this study was to separate the effects of spaceflight from those of the general astronaut training and lifestyle.

Effect of demographic explanatory variables. There was no strong evidence that gender, height, weight, BMI, or a history of high-performance jet aircraft piloting had an effect on HNP risk (Table 5). However astronauts that were older at the time of selection had to have higher risk (p = 0.018). In addition, pre-Shuttle astronauts had generally lower risk of HNP (p = 0.02).

Future Work

To better assess the effects of spaceflight on HNP risk, additional crewmember data would be ideal. In addition to the U.S. Astronauts included in this study, additional information may be available from the international partners, which could increase the dataset substantially. Additional crewmembers for astronauts immediately after landing may also be advised to prevent HNP occurrence at the times of highest risk. Finally, continued surveillance of crewmembers after spaceflight could allow a better understanding of this trend.

These results may also be beneficial to current studies of the intervertebral disc and additional analyzes of these data in concert with the data from the current studies may improve our understanding of the mechanism of HNP after spaceflight.

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References