This Directed Acyclic Graph and write-up is an excerpt from a larger NASA document.

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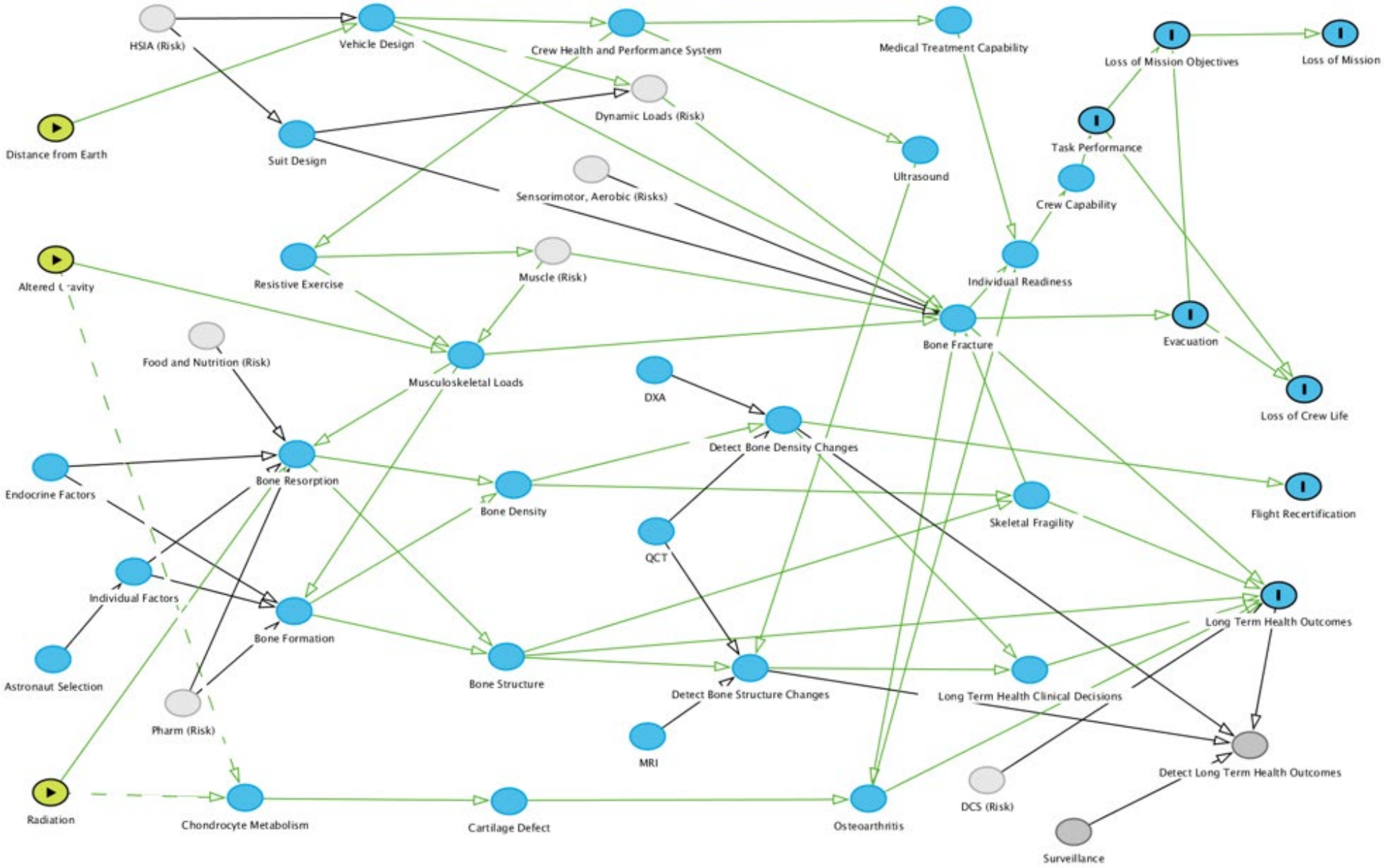
Directed Acyclic Graphs: A Tool for Understanding the NASA Spaceflight Human System Risks

Human System Risk Board

October 2022

Risk of Bone Fracture due to Spaceflight-induced Changes to Bone (Bone Fracture Risk)



Bone Fracture Risk DAG Narrative

The Bone Fracture DAG centers around the **Bone Fracture** node that has two types of inputs. Those that affect the loads that the bone experiences, and those that make the bone more fragile i.e., **Skeletal Fragility**.

- Nodes that affect the loads the bone experiences include:
  - **Musculoskeletal Loads** is dependent in part by **Altered Gravity**, the **Resistive Exercise** designed into the **Crew Health and Performance System**, and the effects of **Muscle (Risk)** on the bone.
  - **Vehicle Design** and **Suit Design**.
  - **Dynamic Loads (Risk)** governs the loads experienced in landing scenarios for planetary surfaces. This is heavily influenced by **Vehicle Design** and **Suit Design** as well.
  - **Sensorimotor** and **Aerobic (Risks)** can influence the likelihood of experiencing high loads from falling or operational errors.
  - **Muscle (Risk)** includes the muscular loads on the bone and muscular support that change with muscular atrophy. This is dependent on the **Resistive Exercise** designed into the **Crew Health and Performance System**.
- Nodes that affect **Skeletal Fragility** include:
  - **Bone Density** refers to mass and mineral density within the bone.
  - **Bone Structure** refers to changes in the trabecular structure internal to the bone and areal structure of the bone.
  - Changes to both of these occur as a result of unbalanced **Bone Remodeling** here shown as two sub-nodes:
    - **Bone Resorption** performed by Osteoclast cells and dependent on **Musculoskeletal Loads**, **Endocrine Factors** such as estrogen, **Individual Factors**, medications used here represented by **Pharm (Risk)**, and **Nutrients** here represented by **Food and Nutrition (Risk).**
    - **Bone Formation** performed by Osteoblast cells and dependent on all of the same nodes as above *except* for **Food and Nutrition (Risk)**.
- It is hypothesized that **Chondrocyte Metabolism** may be affected by **Altered Gravity** and **Radiation.** These connections are shown as dotted lines because of the paucity of evidence supporting this assertion. If so, this can lead to **Cartilage Defects** and **Osteoarthritis** that can contribute to **Individual Readiness** and **Crew Capability** for example, when dealing with joint pain. **Osteoarthritis** can also occur in some cases of **Bone Fracture**.
- **Skeletal Fragility** if permanent can cause osteoporosis and contribute to **Long Term Health Outcomes**. Similarly chronic joint pain such as arthritis can contribute to **Long Term Health Outcomes**.
- Monitoring countermeasures that can be performed before and after flights such as **DXA**, **QCT**, and **MRI** enable us to **Detect Bone Density Changes** and **Detect Bone Structure Changes**. Detecting these can lead to **Long Term Health Clinical Decisions** such as orthopedic interventions or medication use that can decrease the likelihood or severity of **Long Term Health Outcomes.** Currently there is no arrow connecting **Detect Bone Structure Changes** to **Flight**

Recertification because we do not have a clinical trigger that is identified. However, research into both technology and clinical validation is in progress.

- Ultrasound may provide an option to **Detect Bone Structure Changes** occurring in flight if the capability is designed into the **Crew Health and Performance System**.