

IAC-16,E3,6,12,x35594

Integrating Spaceflight Human System Risk Research

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Abstract

NASA is working to increase the likelihood of human health and performance success during exploration missions as well as to maintain the subsequent long-term health of the crew. To manage the risks in achieving these goals, a system modelled after a Continuous Risk Management framework is in place. “Human System Risks” (Risks) have been identified, and approximately 30 are being actively addressed by NASA’s Human Research Program (HRP). Research plans for each of HRP’s Risks have been developed and are being executed. Inter-disciplinary ties between the research efforts supporting each Risk have been identified; however, efforts to identify and benefit from these connections have been mostly ad hoc. There is growing recognition that solutions developed to address the full set of Risks covering medical, physiological, behavioural, vehicle, and organizational aspects of exploration missions must be integrated across Risks and disciplines. This paper discusses how a framework of factors influencing human health and performance in space is being applied as the backbone for bringing together sometimes disparate information relevant to the individual Risks. The resulting interrelated information enables identification and visualization of connections between Risks and research efforts in a systematic and standardized manner. This paper also discusses the applications of the visualizations and insights into research planning, solicitation, and decision-making processes.

Keywords: risk, research management, integration, crew health

Acronyms/Abbreviations

CFM Contributing Factor Map
CRM Continuous Risk Management
ExMC Exploration Medical Capabilities Element
EVA Extravehicular Activity
HHC Human Health and Countermeasures Element
HRP Human Research Program
HRR Human Research Roadmap
HSRB Human System Risk Board
OIG Office of the Inspector General
NASA National Aeronautics and Space Administration

Continuous Risk Management (CRM) framework and is overseen by Risk stakeholders within the agency from medical, operations, and research areas. The HSRB maintains an official record for each Risk’s relevant evidence base, the mission-specific Risk ratings and their drivers, contributing factors, available countermeasures, metrics, and notable deliverables.

Within the set of Risks managed by the HSRB, many have been identified as requiring research as a significant part of their mitigation and have been assigned to the Human Research Program (HRP) to conduct necessary work. At this time, the HRP is implementing activities for characterizing and providing countermeasures and technologies to address 32 Risks in its research portfolio. Each of these Risks has a research plan that outlines the knowledge gaps that specific tasks are aimed to support as well as the schedule for their execution. Shared gaps and tasks between the Risks are noted in these research plans and are documented in the Human Research Roadmap (HRR) [1]. The HRR also provides general descriptions and context for the Risks.

1. Background

1.1 Context

NASA is committed to mitigating the in-mission and long-term health and performance risks of astronauts to enable safe, reliable, and productive space exploration missions. The NASA Human System Risk Board (HSRB) provides the forum for a process that manages the overall mitigation strategies for these human system risks (called “Risks” in this community) based on the

Common information across the Risks is reflected in the HSRB Risk records and acknowledged in the HRP research plans. However, a systematic approach to better understand the linkages across Risks to form a basis for better integration of work and resources has not been followed. This paper outlines an approach to integrating Risk research and mitigation strategies.

1.2 Motivation

Recent reports from groups that reviewed aspects of NASA's plans for reducing crew health and performance risks provide two examples of external motivation. The Office of the Inspector General (OIG) reported in 2015 the following (emphasis added) [2]:

*"NASA's management of crew health risks could benefit from increased efforts to integrate expertise from all related disciplines. While many life science specialists attempt to utilize the range of available expertise both inside and outside the Agency, NASA lacks a clear path for maximizing expertise and data at both the organizational and Agency level. For example, NASA has no formalized requirements for integrating human health and research among life sciences subject matter experts nor does it maintain a centralized point of coordination to **identify key integration points for human health**... The lack of a coordinated, integrated, and strategic approach may result in more time consuming and costly efforts to develop countermeasures to the numerous human health and performance risks associated with deep space missions."*

Similarly, the Health and Medicine Division of the National Academies of Sciences, Engineering, and Medicine reviewed Evidence Reports that are produced to capture the state of knowledge of the crew health and performance risks. The 2014 report states (emphasis added) [3]:

*"The reports... struggle with **establishing the connections and interactions among risks that are related**, but a bit more tangential (e.g., altered immune response and inadequate nutrition)."*

There is growing recognition within the crew health and performance community that developing solutions to the challenges posed by human spaceflight exploration missions requires crossing discipline boundaries. The HSRB has recently expressed a desire to better integrate the management of the Risks. HRP is recognizing the need to leverage connections to better identify and manage work to more efficiently use constrained research resources across disciplines and support innovative solution development.

In any system development process, *interfaces*, whether they are conceptual, technical, or managerial, are where many challenges appear. The HRP does not currently have a systematic way to identify and manage interfaces and, consequently, has less ability to ensure that the most impactful work across disciplines will be addressed.

In spaceflight systems engineering, discipline and subsystem (e.g., structures, avionics, power, and propulsion) scopes are well defined in a common conceptual model. This enables the management of interfaces throughout the development process, which supports the development of an integrated system. The work discussed in this paper is one approach to addressing this need and can be an early step to improve the scope and interface definitions of the Risks to promote integrated system solution development.

1.3 Purpose and Scope

The specific purpose of this initial exercise was to demonstrate techniques to systematically identify, organize, and manage interfaces among Risks. The scope was intentionally kept limited for this initial effort to determine if future work would be valuable. Input data was limited to existing information, favouring rapid proof-of-concept ideas and results over a more involved project scope and timeline. With this philosophy in mind, existing HSRB Risk records were used as the source of information to characterize each Risk's contributing factors, mitigations, and metrics; and the HRR for a description of the scope of research work for the Risk. Because the baselined Risk records available at that time were created by different experts and were the first versions created as the risk process was being established, the contents in each were at varying levels of completeness. An analysis of the completeness of the information available in this exercise was not included; however, observations to support any future systematic completeness analysis were noted.

2. Approach

Four steps to accomplish its demonstration of techniques were defined:

1) Normalize Risk record content using a common framework of terminology.

This step allowed content in the Risk records provided by experts from different disciplines to be captured in the same conceptual model. The outcome provided the combined data set crossing all available Risk records.

2) Identify Risk interfaces.

In this step, the team defined types of interfaces of interest and then applied the combined data from the Risk records to identify related Risks.

3) Compare to planned research.

Next, a first-pass evaluation of the integration status of Risks that were identified as related in Step 2 was performed. HRP's HRR shows the research plans for each of its Risks, and research activities, called "Tasks", are in place to accomplish those plans. Tasks can be linked to more than one Risk, allowing discipline experts focused on a particular Task to indicate when a Task's work also supports other Risks. The determination of these links has previously been made in an ad hoc manner, but provided the team with one indication of the current state of awareness of conceptual interfaces. The team compared which Risks shared Tasks in the HRR to the set of relationships identified in Step 2 to identify potential collaboration areas.

4) Visualize options for collaborations and their status.

Finally, visualizations were created to support communication of the integration options and their status. These visualizations created the potential for tracking progress of integration in the future.

3. Methods

This section describes the activities undertaken for each of the four steps outlined in the approach.

3.1 Normalize Risk record content using a common framework of terminology

Because Risk record content was created using inputs from different subject matter experts with backgrounds crossing various disciplines, terminology often differed between records, even when similar topics were being addressed. To translate the content of the Risk records to the same conceptual model, a common language was needed. An existing taxonomy of terminology was used as this common language [4]. A visual representation of the taxonomy, called the Contributing Factor Map (CFM), is shown in Figure 1. The white boxes shown on the CFM represent factors influencing human health and performance in spaceflight. The team viewed the factors in the CFM as system variables whose states can contribute to mission success or failure. The states of some factors are considered alterable through the implementation of risk mitigations.

An example of information obtained from a Risk record is shown in Table 1. The left column shows the type of information obtained from the record, the middle column shows examples of information available for one Risk (the "Renal Risk"), and the third column shows the CFM factors into which the record's information was "binned" or coded to relate the Risk-specific terms to the common conceptual framework of the CFM.

Each of the 32 Risk records were manually read and the terms from each record to the CFM factor bins were coded. Conventions were developed for the coding activity, and cases in which coding was performed independently, results were compared to ensure consistency across the set of records. A single reader evaluated the entire set of record coding results to additionally ensure consistency. Once this step was complete, a data set existed in which each Risk had factors from the CFM identified as its contributing factors, mitigations, and metrics.

Table 1. Example Binning of Risk Record Information with CFM Factors

Information in Risk Record	Example from Renal Stone Risk Record	CFM Factor Bins
Hazards and factors contributing to the Risk	Primary hazard: microgravity (excess calcium excretion, low urine volume, urinary super-saturation)	<ul style="list-style-type: none"> • Acceleration or Gravity • Distance From Earth • Food System • Genitourinary Function • Mission Duration • CO₂
	Secondary hazards: closed environment – (limited H ₂ O resource), distance from Earth	
	Contributing factors: Increased urinary calcium excretion, decreased urine volume, increased urinary super-saturation, dietary factors, mission duration, mission resources, hypercapnia	
Mitigations including available counter-measures	Preventative: screening, crew education, diet, potassium citrate/bisphosphonates	<ul style="list-style-type: none"> • Ground Medical Care • Crew Selection • Food System • In-Flight Medications • Mission Scenarios
	Treatment – return to Earth	
Metrics to assess Risk status progress	Renal stone occurrences	<ul style="list-style-type: none"> • Genitourinary (Systemic Clinical Outcome)

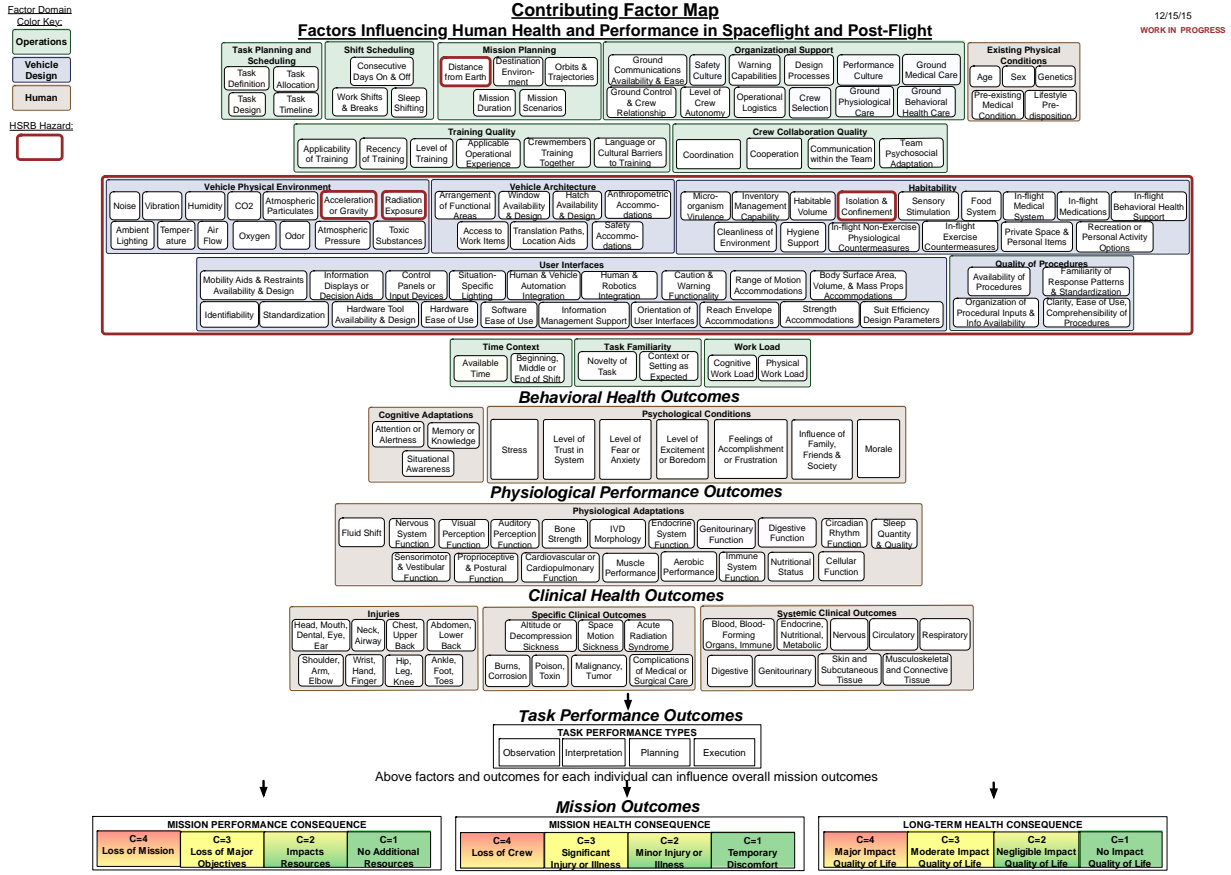


Figure 1. Contributing Factor Map version applied for the work discussed in this paper. The white boxes shown on the CFM represent factors influencing human health and performance in spaceflight.

3.2 Identify Risk interfaces

Six interface types were defined for this exercise:

1. Risks whose scope of work addresses contributing factors of other Risks
2. Risks whose scope of work addresses mitigations of other Risks
3. Risks whose scope of work addresses metrics of other Risks
4. Risks that share common contributing factors
5. Risks that share common mitigation factors
6. Risks that share common metrics

Creation of the content for interface types 1-3 required defining the scope of work for each Risk in terms of the CFM factors. The Risk descriptions from the Risk records and research summaries from the HRR were used to identify factors that represented each Risk's scope of work. A simple example is the scope defined for the Renal Risk. The scope was represented by two factors in Figure 1: the factor "Genitourinary Function", shown in the Physiological Performance Outcomes area of the CFM, and the "Genitourinary Systemic Clinical Outcome" factor,

shown in the Clinical Health Outcomes area of the chart.

At this point, each Risk had factors in the CFM identified as its contributing factors, mitigations, metrics, and scope of work. The data set was then imported into a network visualization tool called Gephi [5]. The tool allowed organization of the data set and creation of initial visualizations of the interfaces across Risks.

An example interface identification network is shown in Figure 2. The Risks are shown as the nodes in the network, and a line, or "edge" in network terminology, is drawn between Risks when an interface exists. This example includes the first three types of interfaces, and the line convention is:

1. Risk at the head of the arrow has contributing factor(s) in the scope of the Risk at the arrow start.
2. Risk at the head of the arrow has mitigation(s) in the scope of the Risk at the arrow start.
3. Risk at the head of the arrow has metric(s) in the scope of the Risk at the arrow start.

In short, work taking place in a Risk at an arrow start should influence the state of a Risk at the arrow head.

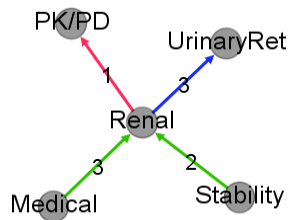


Fig. 2. Interfaces between the Renal Risk and other Risks. Nodes represent Risks, and edges indicate interfaces between Risks. Numbers 1, 2, and 3 indicate the interface type. Edge colors indicate whether the risks share tasks in the HRR (green: shared tasks; red: no shared tasks; blue: N/A – one of the Risks associated with the edge is not an HRP Risk). See Appendix A for the full names of the Risks.

3.3 Compare to planned research

Steps 1 and 2 provide one indication of interfaces among Risks based on inputs captured in the HSRB Risk records. Next, an indication of the status of interfaces was developed. The simplest starting point for this limited scope exercise was to capture whether related Risks shared any Tasks in their research plans, as indicated by shared Tasks in the HRR.

Coloured interface lines were used as indication of Risks sharing Tasks in the network representation, as show in Figure 2. A green line indicates that the connected Risks share Tasks in the HRR, while a red line indicates that the Risks do not share any Tasks in the HRR. Because some HSRB Risks do not require research, they are not part of HRP’s research plan as shown in the HRR. Therefore, these connections are shown with a blue line to indicate that shared research is not applicable.

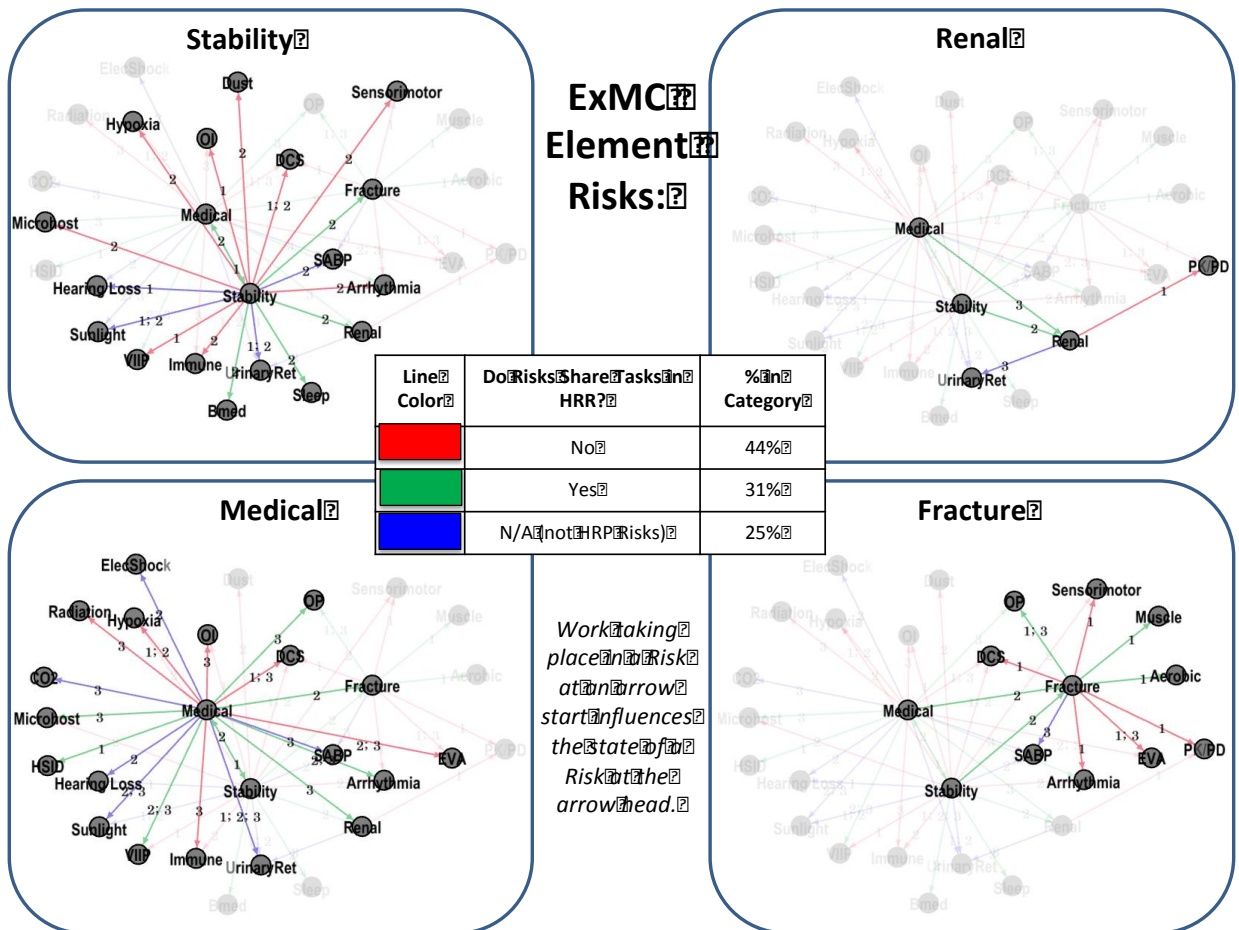


Figure 3: Interfaces between all four of the ExMC Risks (nodes with same title as encompassing box) and related Risks (connected nodes). Edge numbers indicate the interface type (1, 2, or 3), and edge colors indicate whether the Risks share tasks in the HRR. The percentages shown in the legend indicate the proportions of the Risk interfaces associated with shared and unshared tasks, as well as the proportion of interfaces associated with non-HRP Risks. (See Appendix A for the full names of the Risks.)

3.4 Visualize options for collaborations and their status

The Gephi program was used to produce additional views of the combined data set. For example, one of the six management groups, or Elements, within HRP, the Exploration Medical Capabilities (ExMC) Element, was responsible at the time of this exercise for four Risks with the short titles Medical, Stability, Renal, and Fracture. Figure 3 shows these four Risks on the same presentation chart with statistics indicating the interface percentage according to task sharing status based on the HRR. This gives an Element-level overview of integration status with other Elements' areas of research and provides a metric for tracking progress as future work becomes more integrated.

Another example view is shown in Figure 4. This example focuses on interface Type 4, indicating HSRB Risks that share contributing factors. The focus of this example is ExMC's Medical Risk (the central node), and other HSRB Risks are shown at the perimeter. A line is drawn if the outer HSRB Risk shares a contributing factor with the central Medical Risk, and the thickness of the line indicates the number of shared contributing factors. As in the previous figures, the colors of the lines in Figure 5 indicate whether the Risks share Tasks in the research plan represented in the HRR. The colors of the nodes indicate the HRP Element that is responsible for the research supporting that Risk. This view provides useful insight into the associations between Risks, such as that between the Medical Risk and the Extravehicular Activity (EVA) Risk. These two Risks appear to share many contributing factors but do not yet share research Tasks as indicated in the HRR.

4. Outcomes

Insights to inform Element planning can be gained from such an approach. For example, based on the visualizations provided in Figures 3 and 4, the ExMC Element is found to have a high potential for fruitful untapped collaborations with the Human Health Countermeasures (HHC) Element. The lower left box in Figure 3, focusing on the Medical Risk, shows that 5 of the 6 red edges are connected to Risks managed by the HHC Element. Figure 4 shows that 9 of the 13 red edges are connected to HHC Risks. The connection between the Medical and EVA Risks is one prominent example, and in looking at the global data set, we can describe why collaborations may make sense. For example, Figure 3 indicates that interface type 2 exists, and the data set shows us that the EVA Risk relies on the medical system as a mitigation. Looking into interface type 3 reveals that a key metric of the EVA community is occurrence of

injuries while in an EVA suit, which is in the scope of what medical system planning must accommodate.

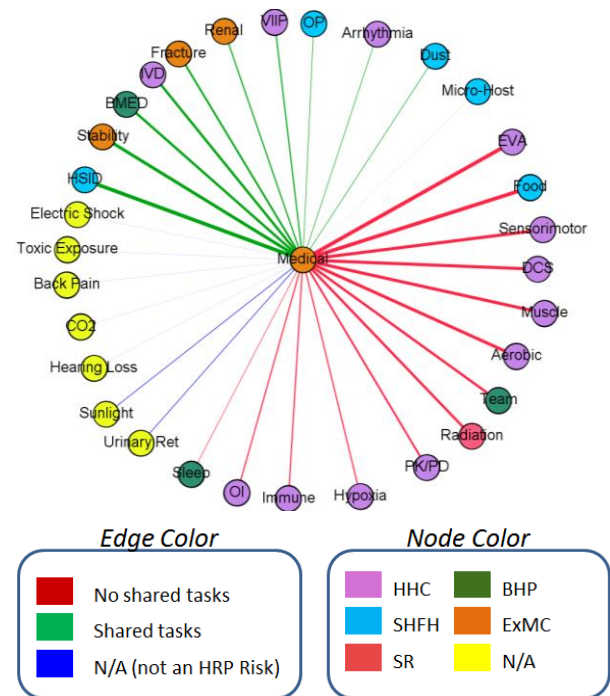


Figure 4: Identification of HSRB Risks that share contributing factors with the Medical Risk, with edges colored according to whether the Risks share common tasks in the research plan and nodes colored according to HRP Element. See Appendix B for Element names. Line thickness indicates the number of common contributing factors. N/A: not an HRP Risk.

In addition, Figure 4 indicates that the EVA and Medical Risks share multiple contributing factors. The global data set informs us that the factors Acceleration or Gravity, Destination Environment, Distance from Earth, Food System, Mission Scenarios, Nutritional Status, Pre-existing Medical Condition, and Radiation Exposure are in common. Common factors, such as Destination Environment and Mission Scenarios, indicate topics of potentially fruitful collaboration.

This approach and its demonstration led HRP Program Management to ask whether similar ideas could be used to identify integration opportunities for research solicitation topics. Topic development in the past was previously performed by each Element more or less independently without significant cross-Element coordination. More recently, however, the data set created as part of this work was used to generate collaboration ideas across Elements for the expected solicitation topics. These ideas were then discussed across Elements in an open, collegial

manner during Program meetings. In addition, meetings and communication took place outside of the Program forums to solidify topic collaborations. This led to a set of research solicitation topics that incorporated needs from multiple Risks and Elements.

5. Future Work

Future work includes the continued application of the global data set and network tools to identify integration ideas in support of research solicitation topic development. We are currently holding lessons-learned activities to obtain feedback on the new topic development process within which the integration ideas were discussed. Feedback from across HRP will inform next steps on any supporting tool evolution.

There are several areas of potential future efforts. First, assumptions made in developing the global data set could be reduced to increase confidence in results. The mapping between the terms in the HSRB Risk records and the CFM factors could be validated with experts, along with the assumptions of which factors from the CFM best represent the scope of work within a Risk. In addition, integration ideas identified during team discussions could be fed back into the global data set.

A systematic evaluation of the interface ideas is also possible. The edge colors discussed here were a simple representation of whether Risks shared Tasks or whether Task sharing was not applicable (in the case of non-HRP Risks). However, it is recognized that the identification of shared Tasks does not necessarily indicate that adequate integration is in place. On the other hand, it is possible that no Tasks are shared because discussion of potential collaborations revealed that shared tasks do not make sense practically or scientifically. Therefore, it is possible to extend the link evaluations (in addition to N/A) to those shown in Table 2.

Table 2. Potential future link evaluation categories

No new action	New action
Shared Tasks in place, and adequate integration is in place	Shared Tasks in place, but additional integration is needed
Shared Tasks not in place, but adequate integration is in place	Shared Tasks not in place, and additional integration is needed

Tracking the progress of cross-Element integration is another potential application. As time progresses and research plans are updated, one would expect to see the edge colors change from red to green, or from categories requiring action to those not requiring action if classifications as in Table 2 were used. The statistics at both Element and Program

levels summarizing these categorizations could be tracked to provide metrics revealing integration progress over time.

In addition, as work within HRP moves toward reducing Risks by maturing system capabilities for exploration missions, increased efforts to integrate from organizational and technical perspectives will be required. Tools such as the one described here can provide support to the Elements in identifying and managing the various interfaces required to develop systems that will effectively address the wide range of crew needs and vehicle integration constraints.

6. Conclusions

In this paper, we demonstrated approaches to systematically identify, organize, and manage interfaces among crew health and performance risks for which research-based mitigation work is managed by the HRP. Using a taxonomy for standardizing information in available Risk records from the HSRB and HRP and applying visualization techniques, we identified inherent linkages among Risks that otherwise could have been overlooked. A basis for discussion of whether further integration efforts are needed for known relationships was also provided. Various types of interfaces were defined that could provide additional perspective for improving prioritization of risk mitigation work in an environment where resources are increasingly constrained. The insights revealed by the use of these techniques not only support important decisions (e.g., on solicitation development, Element planning, and coordination) but also enhance communication of the integration of these Risks to various stakeholders and potential contributors to solutions that efficiently address these Risks. The systematic approach also facilitates the tracking of the status of these integration and collaboration opportunities, a capability that is still needed for the management of research work within the HRP and the general risk mitigation strategies within the HSRB.

Appendix A. Risk Abbreviations Used in Figures

Aerobic	Risk of Reduced Physical Performance Capabilities due to Reduced Aerobic Capacity
Arrhythmia	Risk of Cardiac Rhythm Problems
Back Pain	Risk of Space Adaptation Back Pain
BMed	Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders
DCS	Risk of Decompression Sickness
Dust	Risk of Adverse Health & Performance Effects of Celestial Dust Exposure
Electric Shock	Risk to Crew Health due to Electrical Shock

EVA	Risk of Injury and Compromised Performance due to EVA Operations
Food	Risk of Performance Decrement and Crew Illness due to an Inadequate Food System
Fracture	Risk of Bone Fracture due to Spaceflight-induced Changes to Bone
Hearing Loss	Risk of Hearing Loss related to Spaceflight
HSID	Risk of Reduced Crew Performance and of Injury due to Inadequate Human-System Interaction Design
Hypoxia	Risk of Reduced Crew Health and Performance due to Hypobaric Hypoxia
Immune	Risk of Adverse Health Event due to Altered Immune Response
IVD	Concern of Intervertebral Disc Damage upon and immediately after Re-exposure to Gravity
Medical	Risk of Adverse Health Outcomes & Decrements in Performance due to Inflight Medical Conditions
Microhost	Risk of Adverse Health Effects due to Host-Microorganism Interactions
Muscle	Risk of Impaired Performance due to Reduced Muscle Mass, Strength & Endurance
Nutrition	Risk of Inadequate Nutrition
OI	Risk of Orthostatic Intolerance during Re-exposure to Gravity
OP	Risk of Injury from Dynamic Loads
Osteo	Risk of Early Onset Osteoporosis due to Spaceflight
PK/PD	Concern of Clinically Relevant Unpredicted Effects of Medication
Radiation	Risk of Adverse Health Outcomes and Performance Decrements resulting from Space Radiation Exposure
Renal	Risk of Renal Stone Formation
Sensorimotor	Risk of Impaired Control of Spacecraft/Associated Systems and Decreased Mobility due to Vestibular/Sensorimotor Alterations Associated with Spaceflight

Sleep	Risk of Performance Decrements and Adverse Health Outcomes Resulting from Sleep Loss, Circadian Desynchronization, and Work Overload
Stability	Risk of Ineffective or Toxic Medications due to Long-Term Storage
Sunlight Team	Risk of Injury from Sunlight Exposure Risk of Performance and Behavioral Health Decrements due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation within a Team
Toxic Exposure	Risk of Toxic Exposure
Urinary Ret	Risk of Urinary Retention
VIIP	Risk of Spaceflight-Induced Intracranial Hypertension/Vision Alterations

Appendix B. HRP Element Names

BHP	Behavioral Health and Performance
ExMC	Exploration Medical Capability
HHC	Human Health and Countermeasures
SHFH	Space Human Factors and Habitability
SR	Space Radiation

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