A Platform for Real-time Online Health Analytics during Spaceflight

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Abstract—**Monitoring the health and wellbeing of astronauts during spaceflight is an important aspect of any manned mission. To date the monitoring has been based on a sequential set of discontinuous samplings of physiological data to support initial studies on aspects such as weightlessness, and its impact on the cardiovascular system and to perform proactive monitoring for health status. The research performed and the real-time monitoring has been hampered by the lack of a platform to enable a more continuous approach to real-time monitoring. While any spaceflight is monitored heavily by Mission Control, an important requirement within the context of any spaceflight setting and in particular where there are extended periods with a lack of communication with Mission Control, is the ability for the mission to operate in an autonomous manner. This paper presents a platform to enable real-time astronaut monitoring for prognostics and health management within space medicine using online health analytics. The platform is based on extending previous online health analytics research known as the Artemis and Artemis Cloud platforms which have demonstrated their relevance for multi-patient, multi-diagnosis and multi-stream temporal analysis in real-time for clinical management and research within Neonatal Intensive Care. Artemis and Artemis Cloud source data from a range of medical devices capable of transmission of the signal via wired or wireless connectivity and hence are well suited to process real-time data acquired from astronauts. A key benefit of this platform is its ability to monitor their health and wellbeing onboard the mission as well as enabling the astronaut's physiological data, and other clinical data, to be sent to the platform components at Mission Control at each stage when that communication is available. As a result, researchers at Mission Control would be able to simulate, deploy and tailor predictive analytics and diagnostics during the same spaceflight for greater medical support.**

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1. INTRODUCTION

Space flight enables great advances in scientific discovery. Astronaut health and wellbeing is paramount for any manned space flight. While aspects of the impact of weightlessness on astronaut health have been understood as a result of prior missions, mechanisms have not been available previously for more continuous and ongoing monitoring during the missions. Beyond the impact of weightlessness and radiation, astronauts have the potential to develop a range of medical conditions that could develop when they are not participating in space flight. The earliest and accurate detection of potential onset of these conditions through predictive diagnostics is of significant importance, particularly when the missions involve significant time intervals of days or weeks, and when contact with Mission Control is not possible. In addition, the ability to perform predictive analytics as a means of proactive observation of overall health is also desired. The provision of a platform within the spacecraft to monitor physiology to enable these predictive diagnostics and predictive analytics through the acquisition of physiological data from a range of sensors acquiring data from the astronauts at a high frequency and on an ongoing basis has great potential to support this need.

Recent medical research is demonstrating early research findings that the subtle behaviors of physiological data streams has the potential to provide earlier condition onset detections of many conditions within the neonatal population including late onset neonatal sepsis [1], pneumothorax [2], intraventricular haemorrhage [3], [4] and periventricular leukomalacia [5].

Similarly, in the adult population research is demonstrating the potential for the earlier onset detection from high speed physiological monitoring of conditions such as septic shock, depression [6] and drowsiness [7], for example.

In addition, to the provision of a platform that is established for use during an active space flight that operates within the spacecraft, the opportunity to learn from a rich set of high frequency physiological data will enable the knowledge gained to be used to tune the monitoring of the astronauts during the same flight. As such there is great potential to transfer the data collected to Mission Control during times when connectivity is available to support the knowledge discovery within the data, using simulation together with more powerful and diverse knowledge discovery

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frameworks than those that can be deployed within the spacecraft.

This paper presents a platform to enable real-time astronaut monitoring for prognostics and health management within space medicine using online health analytics. The platform is based on extending previous online health analytics research known as the Artemis and Artemis Cloud platforms which have demonstrated their relevance for online health analytics for Neonatal Intensive Care.

This paper is structured as follows. Related research in the area of astronaut physiological monitoring and bioastronautics is presented in section 2. An introduction to health risks during space flight is presented in section 3 to provide context of the aspects of health more unique to space flight over and above general population health considerations. The Artemis platform is presented in section 4 as a platform for potential extension for use within the context of space flight. Section 5 presents the design for an Online Health Analytics platform for Space Missions. Section 6 discusses the applicability of the use of Artemis Cloud for pre and post mission monitoring. Section 7 introduces the implications and potential applications for this form of online health analytics platform in the terrestrial context. Conclusions and future research directions for clinical research and technology issues are presented in section 8.

2. RELATED WORK

In 1996, The Task Force of the European Society of Cardiology and the North American Society of Pacing Electrophysiology published seminal work that heart rate variability (HRV) showed great potential as a marker for the relationship between the autonomic nervous system and cardiovascular behavior. They proposed that the autonomic nervous system response to athletic training and rehabilitative exercise programs after various disease states is thought to be a conditioning phenomenon and that HRV data should be useful in understanding the chronological aspects of training and the time to optimal conditioning as it relates to the autonomic influences on the heart. They further proposed that HRV may provide important information about deconditioning with prolonged bed rest and with weightlessness and zero gravity that accompany space flight [8].

On April 17, 1996, the Neurolab Spacelab mission lifted off from the Kennedy Space Center. As part of that mission there were 26 experiments dedicated to studying the effects of weightlessness on the brain and nervous system [9]. In all experiments involving the physiological monitoring of astronauts, they were connected via extensive wired sensors for limited window controlled experimentation supporting experiments relating to a range of tests.

In [10] Aubert et al reported on the monitoring of physiological data from five astronauts in order to assess cardiac autonomic control mechanisms and how this may influence neural response. The study was performed during three scientific European Space Agency (ESA)-Soyuz missions to the International Space Station (ISS; Odissea in 2002, Cervantes in 2003, and Delta in 2004: 10- to 11-day missions). They state that to support their research they *captured beat-to-beat heart rate, brachial blood pressure, and respiratory frequency from five astronauts, taking part in three different short-duration (10 to 11 days) space missions to the International Space Station. Data recording was performed in supine position 1 month before launch; at days 5 or 8 in space; and on days 1, 4, and 25 after landing. Heart rate variability (HRV) parameters were obtained. Measurements were performed in the control condition for 10 min and during a 5-min mental arithmetic stress task, consisting of deducting 17 from a four-digit number, read by a colleague, and orally announcing the result.*

While further analysis can continue to be performed on the datasets collected from the Neurolab Space Lab mission and the three ESA missions where physiological data was collected, there are two fundamental limitations of the research. Firstly, the research is limited by the limited amount of data that was collected through the discontinuous controlled window experimentation model. Second, the controlled positioning of the body during experimentation, due in part to the limitations introduced by the sensor wiring.

Bioastronautics research has emerged as a field of research that assesses the biological and medical effects of space flight. The Bioastronautics Roadmap as presented in [11] is a framework proposed to identify, assess, and manage the biomedical risks for the human system. The Roadmap presents and rates the relative importance of 48 risks for long duration ISS, Lunar, and Mars missions. Within that roadmap, some of the most serious risks for a Mars mission are:

"(a) addressing the requirements for autonomous medical capabilities including pharmacology of space medicine, medical informatics technologies and decision support systems, and skill training and maintenance;

(b) providing radiation protection for carcinogenesis and central nervous system (CNS) affects;

(c) maintaining behavioral health and psychosocial functioning;

(d) developing and validating countermeasures for adaptation affects from microgravity exposure such as accelerated bone loss and sensory-motor function post landing; and

(e) providing efficient and reliable human habitation technologies."

Great opportunities exist in future missions, and in particular long range missions, for extensive predictive analytics and predictive diagnostics together with knowledge discovery to continue to improve their accuracy with higher frequency data capture and real-time analysis.

This research proposes a clinical decision support system platform to support the analysis of physiological data in real-time and its use for predictive diagnostics and predictive analytics in support of risk (a) within the Bioastronautics Roadmap. In so doing it can thus provide the measurement tool that assesses the effectiveness of the strategies created to mitigate the risks detailed in (b) through (e) through real-time monitoring for radiation impact, assist with mental health assessment, measure aspects of microgravity exposure and user mental and physical health assessment tools as a metric for the assessment of the human habitat.

3. HEALTH RISKS DURING SPACE FLIGHT

Bellicia [12] conducted an opinion survey to improve the characterization of medical risk during spaceflight, using a questionnaire designed to elicit space medicine experts' perceptions of the probability, health effect, and mission impact of selected medical events occurring during spaceflight missions of 30-90 days. The experts rated skin disorders as the most likely to occur, but which would have little effect on mission completion or astronaut health. Circulatory diseases were rated as having the lowest probability of occurrence, but the highest effect on the mission or on a crewmember's health.

Astronauts are faced with several health risks during both short- and long-duration spaceflight due to the hostile environment presented in space through weightlessness and potential radiation exposure. Some of these health problems include bone loss, muscle atrophy, cardiac dysrhythmias, and altered orientation [13].

Blaber et al further notes in [13] that "a major challenge in the evolution of space medicine is to determine how the physiological adaption to space may alter the pathophysiology of disease and the manifestation of illness and injury in space". They conclude that this motivates ground-based (simulated micro-gravity) studies. While much can be learned from micro-gravity studies, that knowledge does not replace what can be learned from long range space missions, but rather can be used to derive the initial set of online health analytics algorithms that then can be assessed and tuned during actual long range space missions.

4. ARTEMIS

Artemis, is a platform for online health analytics enabling concurrent multi-patient, multi-diagnosis and multi-stream temporal analysis in real-time for clinical management and research. The Artemis platform is represented in Figure 1.

The Data Acquisition component enables the provision of real-time synchronous medical device data and asynchronous Clinical Information Management System (CIMS) data. This data is then forwarded for analysis within the Online Analysis component which operates in real-time. For this real-time component, Artemis employs IBM's InfoSphere Streams, a novel streaming middleware system that processes data in real-time and then enables data storage within the Data Persistency component. It is capable of processing and then storing the raw data and derived data from multiple infants at the rate they are generated [14]. For the Knowledge Extraction component, Artemis utilizes a newly proposed temporal data mining approach [15].

Processing of over 1200 readings a second per patient to demonstrate predictive analytics and predictive diagnostics has been proven using this platform.

Artemis Cloud demonstrates the Artemis platform when operating in a cloud computing context to provide remote online health analytics by enabling interaction with the various components of Artemis via a series of web services [14], [16]. The clinical function of Artemis Cloud is to provide a service to healthcare facilities, including remote healthcare facilities, with minimal local IT support. Secondly, it provides a framework that could be used for ambulatory patient support for patients with conditions such as diabetes, cancer and leukemia.

The initial case study context for Artemis and Artemis cloud was neonatology, that is, the intensive care of premature and ill term newborn infants. Premature and term newborn infants, have to adapt to a new environment post birth. The heart function, for example, changes as a result of the birthing process. In the case of the premature infant, this overall adaption becomes complex as it occurs earlier than planned and as a result they are at risk of developing a range of conditions resulting from their premature birth. Their vital signs such as heart rate, respiration, blood oxygen and blood pressure are monitored constantly to ensure the health of vital organs as they continue to grow and mature in their development. As a population, newborn infants who are at similar gestational ages have similar growth and development occurring. At certain stages and ages of development they are more at risk of the development of specific conditions than others. Late onset neonatal sepsis (LONS), a form of healthcare facility acquired infection, is not diagnosed within the first 72 hours of life as prior to that the infection is considered to have occurred during the birthing process. As a result, algorithms are designed based on the needs of the premature and ill term infants within the context of conditions that have a temporal or time dependent aspect, such as LONS, an environmental aspect, such as the context of the complications of prematurity, or are independent of either in nature.

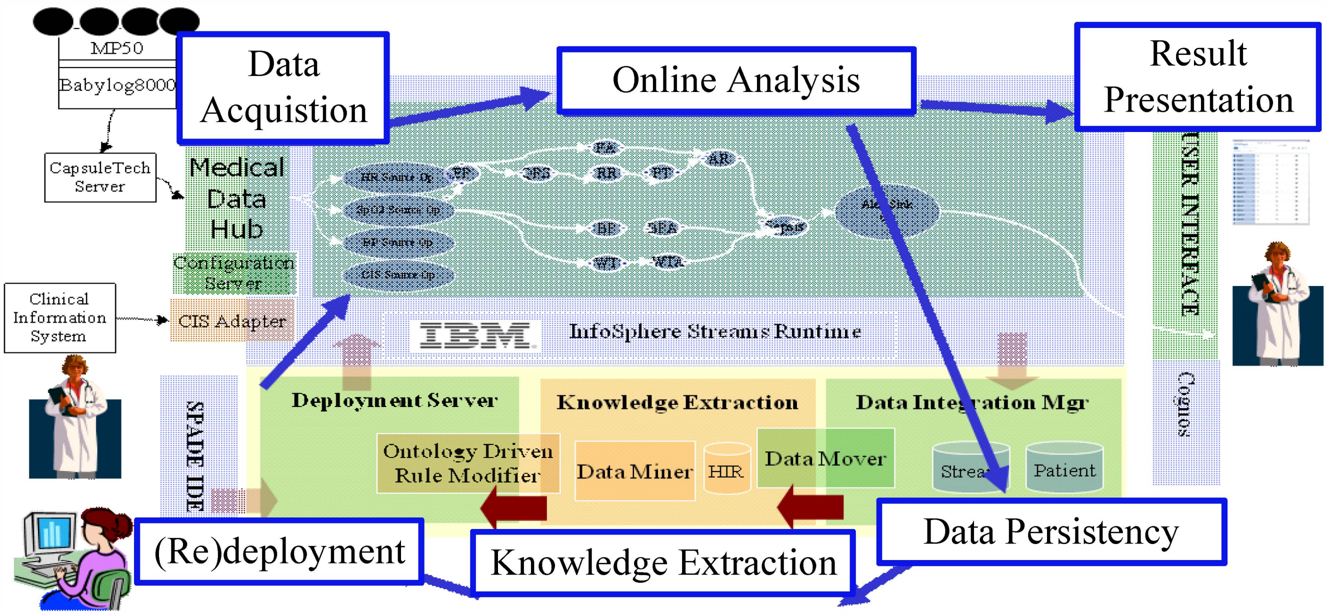

Figure 1. Artemis Framework [14]

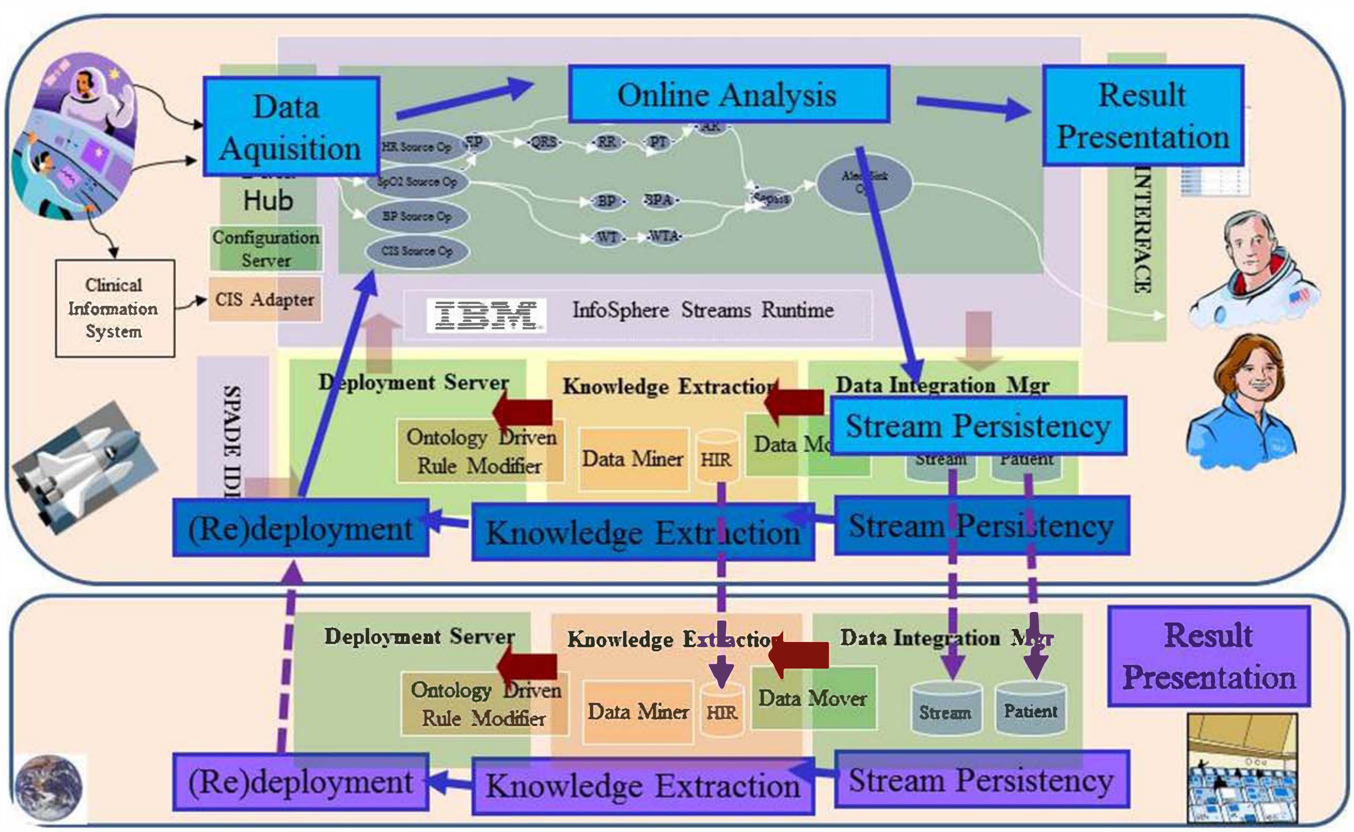

Figure 2. Online Health Analytics During Spaceflight

Similarly to the birth of an infant, an astronaut during a manned mission has physiological adaption in space due to microgravity that necessitates additional medical observation as an environmental aspect. In addition, it occurs within the context of the temporal distance from takeoff and leaving Earth's atmosphere. The monitoring for impacts of radiation present another environmental factor for which tailored algorithms would be developed. Monitoring of physical and mental health on an ongoing basis are general observations that need to be adapted within the environmental and temporal context. Upon their return to Earth, similar health observations can occur during their adaption back to gravity again.

As a result, the Artemis and Artemis Cloud platforms have great opportunity for reapplication within this context and show potential to address the challenge introduced by Blaber [13] by enabling constant physiological monitoring to determine how the pathophysiology of disease and the manifestation of illness and injury may alter in space.

5. Online Health Analytics During Space Missions

The proposed architectural model for the online health analytics platform during spaceflight is presented in Figure 2 which also includes the components that would exist for use by Mission Control. Further details on each of the major components in Figure 2 are provided in the following subsections.

Data Acquisition - Spacecraft

To extend the Artemis platform to support online health analytics during space missions, there is a need to design the mechanism for the acquisition of physiological data from the astronauts on a more regular basis than has been achieved during previous missions. This acquisition must not impede them in their various activities. Artemis sources data from a range of medical devices capable of transmitting the signal via wired or wireless connectivity, and hence, is well suited to process real-time data acquired from astronauts. While in previous missions the provision of physiological data has been through the use of extensive wired acquisition, opportunities exist to explore the use of signal acquisition through the use of ingestible capsules, sensored clothing or other sensing device. Further research on this is outside the scope of this paper but presents future work opportunities for both the development of the sensor acquisition mechanism together with the transmission protocols used.

In addition to the physiological data, an environment to collect the other relevant clinical data needs to be created. The design of that system is outside the scope of this paper, however, of relevance to this paper are the protocols used for the transmission of relevant clinical information from that environment to this platform to provide the necessary additional information for the online analytics. It is envisaged that that communication would utilize a standardized protocol such as Health Level 7 (HL7).

Online Analysis - Spacecraft

The online analysis environment would operate in real-time onboard the spacecraft providing predictive analytics and predictive diagnostics in real-time for the astronauts. Algorithms to enable the observation of the Bioastronautics Roadmap risks (b) through (e) would be deployed within the online analysis environment prior to take off enabling the autonomous operation of algorithms onboard the spacecraft. Additional algorithms to support general health observation would also be deployed.

Algorithms to detect known pathophysiologies that exist as physiological data features, also known as temporal abstractions, can be included within this environment. This enables their connection with the condition or conditions that the pathophysiology can be associated with. In our research to date, we have demonstrated these new online analytics approaches for pathophysiological behaviors associated with the late onset neonatal sepsis category of infection [17] together with the classification of neonatal spells [18].

Result Presentation - Spacecraft

Diagnostics, analytics and raw physiological data, when required, could be viewed in real-time, and retrospectively, by the astronauts to enable the ongoing management of their health and wellbeing through the result presentation component.

Data Persistency - Spacecraft

All data collected and all analytics generated would be persistently stored within the data storage layer within the spacecraft to support retrospective analysis on board the spacecraft.

Knowledge Extraction - Spacecraft

The astronauts would have the ability to analyse the data collected retrospectively using the knowledge extraction layer for local research based on any local studies they had planned previously or determined to investigate during the mission. A method to support the identification of new or updated pathophysiological behaviors is found in [15].

Deployment and Redeployment - Spacecraft

While the initial clinical rules will result in the initial predictive diagnostics and predictive analytics algorithm deployment prior to lift off from Earth, it is anticipated that updates to existing clinical rules and new clinical rules would be deployed within the environment on the spacecraft during the mission. This deployment and redeployment component enables the pathophysiological behaviours discovered during the knowledge extraction stage to be deployed within the real-time analysis component.

Result Presentation – Mission Control

Just as within the spacecraft, diagnostics, analytics and raw physiological data, when required, could be viewed in real-time and retrospectively by those at Mission Control. This would enable the ongoing observational management of the health and wellbeing of astronauts by the Mission Control based medical support team through the Result Presentation component.

Data Persistency – Mission Control

To support knowledge discovery at Mission Control, mechanisms need to be established to transmit the data acquired from the astronauts together with any derived analytics to Mission Control. In our research to date, we have demonstrated transmission of physiological data using HL7 formatted data transfer [16], DICOM encoded data [19], XML encoded data [20] together with a direct IBM DB2 database extraction, secure transfer and load [14]. Further research is required to determine the most appropriate protocol to use for the transmission of data from the spacecraft and mission control. Other clinical data could be transferred using a standardized HL7 protocol.

Knowledge Extraction – Mission Control

Mission Control requires a more extensive knowledge discovery environment with greater resources for increased simulation and knowledge discovery. In this way, the overall platform can support not only the monitoring of health and wellbeing during the mission, but can enable the astronaut's physiological data, together with other clinical data, to be sent to the platform components at Mission Control at each stage when that communication is available. As a result, in addition to the predictive analytics and predictive diagnostics that are performed locally on the spacecraft using this platform, researchers and medical support staff at Mission Control would be able to perform greater amounts of simulations and predictive analytics during the spaceflight mission than would otherwise be performed within the spacecraft alone. Challenges that they will face are the small sample size of data for some research and techniques to enable rare events to appear to have a greater distribution within the study population may need to be employed during those research studies.

Deployment and Redeployment – Mission Control

Researchers at Mission Control require the ability to be able to deploy and tailor predictive analytics and diagnostics during the same spaceflight to provide greater medical support based on evidence based research outcomes from their knowledge extraction research.

6. Pre and Post Mission Monitoring

The health of astronauts prior to any space mission is monitored over an extended period of time. In addition, upon their return, their readjustment to gravity could also be monitored together with other healthcare observations.

As noted earlier, the Artemis Cloud platform has been demonstrated to support remote patient monitoring for monitoring of ambulatory patients and the pre and post mission health monitoring can be classed as having similar functional needs.

Similar techniques for data acquisition could be used for the collection of physiological data during these two phases and the data can be sent securely through the internet to the Artemis Cloud infrastructure where appropriate online analyses for diagnostics and analytics could be performed.

Resultant data would be made available to the supporting medical team for viewing at any time, or with notification if alerts were activated.

7. Terrestrial Implications and Applications

The Japanese Exploration Space Agency (JAXA) note that from some perspectives, the International Space Station (ISS) has many similarities to an extremely remote outpost, given that doctors will not always be present and medical equipment and facilities are limited [21].

While not exposed to complications relating to weightlessness and increased radiation exposure, researchers stationed within the various Antarctic research stations, for example, can be considered as being stationed at an extremely remote outpost especially during the southern hemisphere winter.

While constant monitoring may not be required in this setting, the ability to establish a platform for regular health status checks and the ability for remote monitoring of their health and also potentially monitoring of mental state through measures such as changes in heart rate variability has the potential to improve healthcare support for those researchers.

8. Conclusion and Future Work

This paper has presented a platform to enable real-time patient monitoring for prognostics and health management within space medicine using online health analytics. A key benefit of this platform is its ability to support not only the monitoring of health and wellbeing during the mission, but to enable the astronaut's physiological data, together with other clinical data, to be sent to the platform components at Mission Control at each stage when that communication is available. As a result, in addition to the predictive analytics and predictive diagnostics that are performed locally on the spacecraft using this platform, researchers and medical support staff at Mission Control would be able to perform greater amounts of simulations and predictive analytics during the spaceflight mission than would otherwise be performed within the spacecraft alone. As a result, researchers at Mission Control would be able to deploy and tailor predictive analytics and diagnostics during the same spaceflight to provide greater medical support.

This paper further demonstrates an approach for pre and post mission monitoring together with the terrestrial implications and applications of the mission specific components proposed.

As noted in this paper, there are many areas for future research in preparation for future long range missions. Mechanisms for data acquisition need to be determined that support the collection of all the physiological data required in the least invasive way for the astronauts.

The Bioastronautics Roadmap can be used to design the initially proposed online analytics required for real-time astronaut monitoring. In this way, known physiological data related pathophysiological behaviors together with the associated clinical data can be transformed into deployable modules within the online analytics environment.

Methods to support clinical research by Mission Control and potentially within the spacecraft need to be supported that account for the small sample size of data that will be available and potentially utilize the other data that has been collected from past missions.

Protocols for transmission of data from the physiological sensors to the platform within the spacecraft together with the protocols for transmission of the clinical data to that platform need to be defined. The protocols for the transmission of the clinical and physiological data to mission control need to be defined. Finally the protocols for the transmission of new rules from Mission Control and the spacecraft need to be defined.

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