Adaption-Based Analytics for Assessment of Human Deconditioning during Deep Space Exploration

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Abstract— **Technological and scientific advancements continue to enable safe prolonged human presence in space, while extending the boundaries of manned exploration from low-Earth orbit into deep space. As humankind prepares to embark on exploration-class missions, to the Moon and Mars, mission objectives, risks and challenges become more complex and vastly different from the majority of human manned space exploration experience known to-date. The potential health risks associated with deep space exploration are expected to amplify, the mitigation of which would necessitate complex and autonomous in-flight medical capacity, which has not been available to-date. The logistics of medical care delivery in-flight have been significantly limited by impracticality of existing biomedical monitoring modalities and retrospective data analytics methods and techniques. Conventionally, physiological health monitoring has been discontinuous and extremely limited, hindering the usability and practicality of the acquired data to support clinical decision-making in-flight. This paper presents an integrated big data framework that utilizes stream computing to support real-time autonomous clinical-decision making in-flight. The proposed framework extends previous research known as the Artemis and Artemis Cloud platforms by integrating multi-source, multi-type data to provide in-depth adaption-based assessment and identify the activity of the various compensatory reactions of regulatory mechanisms, which have been known to impact human health in weightlessness. The instantiation of the proposed big data integrated framework is demonstrated within the context of a ground-based 5-day Dry Immersion study. More specifically, the paper demonstrates the potential to support adaption-based analytics-as-a-service within the context of space medicine. Further to that, adaption-based analytics are enhanced through the introduction of multimodal real-time analytics. The multimodal adaption-based analytics are based on traditional data sampling and a sliding-window approach for analysis of the heart rate variability (HRV) and its features. The introduction of a sliding-window approach offers numerous benefits, including increased sample size, greater stability of numerical estimates, de-trending of the HRV to ensure the observed patterns are attributed to an actual physiological response rather than noise or artefacts. As such, the proposed adaption-based analytics-as-a-service demonstrate great potential to identify unstable physiological states and support proactive prognostics, diagnostics and health management during spaceflight. Additionally, the proposed approach contributes to meaningful use of the acquired physiological data in-flight.**

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1. INTRODUCTION

Human presence in space continues to expand beyond the margin of the low Earth orbit, as the humankind prepares to embark on the journey of deep space exploration. Exploration-class missions to destinations such as the Moon and Mars are presenting new scientific and technological challenges, while amplifying the potential health risks associated with long-distance, long duration human presence in space.

Missions to the Moon and Mars will present complex and vastly different risks, from the majority of manned space exploration experience known to-date, as the human exploration expands outside of the Earth's protective magnetic field.

The threats associated with the deep space exploration can be broadly classified into three categories, namely environmental, health-related and technological [1]. Environmental threats are characterized by increased exposure to galactic cosmic rays (GCR), extreme temperature variations, remoteness from Earth, isolation, and lack of gravitational force [1]. Environmental factors contribute to health-related contingencies, impacting physical, mental and social well-being of the crew. All of which have important implications on occupational performance, execution of mission objectives and safe return to Earth.

Adaptation mechanisms of the human body will continuously be challenged, in an attempt to withstand exposure to environmental, physiological and psychological stressors, so as to preserve health and optimal occupational performance. The implications of which will further be amplified by technological constrains and anticipated communication delays. Moreover, the operational logistics of deconditioned crew member retrieval from exploration-class missions is anticipated to be extremely complex and time-consuming, if at all possible [1]. As such, mitigation of known and unknown health-related risks during deep-space exploration necessitates the development of a comprehensive, autonomous in-flight medical capacity so as to support prognosis, diagnosis and treatment of medical contingencies that have the potential to arise in-flight. To-date, no such medical system has been available, while the prognostics, diagnostics and health management in space continue to be fragmented and extremely limited. The impracticality of existing biomedical monitoring modalities and retrospective data analytics methods and techniques further hinder the meaningful use of the acquired health-related data to support informed clinical decision-making in-flight.

This paper presents an integrated big data framework that utilizes stream computing to support real-time autonomous clinical-decision making in-flight. The proposed framework extends previous research known as the Artemis and Artemis Cloud platforms [2] by integrating multi-source, multi-type data to provide in-depth adaption-based assessment and identify the activity of the various compensatory reactions of regulatory mechanisms, which have been known to impact human health in weightlessness. The clinical significance of the proposed framework is demonstrated within the context of a ground-based analog study, namely the 5-day Dry Immersion [3]. More specifically it demonstrates the capability of the proposed platform to support adaption-based analytics-as-a-service on the basis of the multi-modal analysis of the heart rate variability and its features. It demonstrates a promising potential to identify unstable physiological states and support proactive prognostic, diagnostic and health management during spaceflight. In turn, contributing to an efficient and meaningful use of the acquired physiological data to inform clinical decision-making in-flight.

2. Related Work

Logistics of medical care delivery in space

The International Space Station (ISS) is a permanently inhabited human laboratory in the low Earth Orbit. The ISS consists of multiple flight systems that provide the necessary living conditions to enable safe prolonged human presence in space.

The flight system of particular interest, within the context of this publication, is the existing Crew Health Care System (CHeCS) [4]. The CHeCS consists of three sub-systems, namely the countermeasure system, environmental system and health maintenance system, which collectively provide medical and environmental capabilities to ensure health and safety of the crew [4]. The existing CHeCS is fragmented, while the individual sub-systems offer independent functionality. The prognostic and diagnostic capacity of the system is further limited by the scheduled and discontinuous data acquisition, and retrospective data processing techniques, most of which occur terrestrially, upon mission completion. As a result, provision of health management is limited to reactive, rather than a proactive approach, imposing significant limitations on the ability to support health, wellness and adaption-based analytics in-flight. However, with increasing distance and duration of exploration-class missions and anticipated communication delays, there is an urgent need for a health management paradigm change, so as to support proactive and efficient prognostics, diagnostics and medical care in-flight.

Adaption-based analytics

Scientific evidence suggests that the overall performance of the human body can be assessed on the basis of the heart rate variability analysis [5-7]. It has been demonstrated that patterns and behaviors of the various heart rate variability indices have been closely linked with the onset of transitional health states, maladaptive responses and deconditioning of body systems experienced during spaceflight.

Baevsky *et al.*, have previously proposed the functional health state algorithm, as means to assess the level of health and wellness of the Russian cosmonauts [6]. The functional health state algorithm is based on the principles of stepwise discriminative heart rate variability analysis, used to compute two canonical variables, namely the L_1 and L_2. The generalized equations of the variables are presented below, where HR is the heart rate, SI is the stress index, pNN50 is the number of RR intervals differing by more than 50ms and the HF is the high-frequency spectral power.

$$L_1 = 0.112HR + 1.006SI + 0.047pNN50 + 0.086HF$$

$$L_2 = 0.140HR + 0.165SI + 1.293pNN50 + 0.623HF$$

The L_1 and L_2 are representative of the systems tension and the amount of functional reserves, used to determine the state of adaptation and activity of regulatory mechanisms. The two canonical variables are then used to establish a phase plane of functional states, schematically represented in Figure 1 and described in detail in [5-7].

Despite the capability of the functional health state assessment to support proactive prognostics, diagnostics and inform health management, its application has been hindered by the limitations of the existing biomedical monitoring modalities. More specifically, retrospective in-batch data processing was made possible only upon mission completion and return of the crew to Earth. As such, this approach has been rendered invaluable during the mission and necessitated exploration of novel methods and techniques to support real-time or near real-time adaption-based analytics, so as to improve the usability of the acquired data and inform clinical decision-making in-flight.

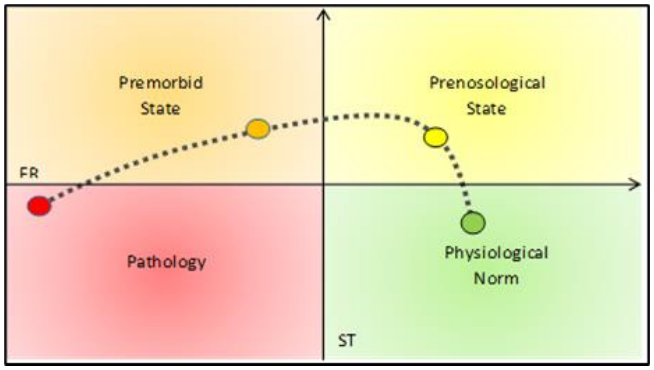

Figure 1. The phase plane of functional states [7].

ARTEMIS

Artemis platform was named after the Greek Goddess associated with protecting child-bearing women and young children, as the primary application of the platform was within the neonatal intensive care unit. In prior research, the Artemis, big data analytics platform, has been proposed to support real-time online health analytics during spaceflight [2]. Artemis platform is schematically represented in Figure 2 and described in detail in [2, 8]. The main components of the platform include data collection, data buffering and transmission, online analytics, data persistency, knowledge extraction, (re)deployment and results presentation.

The Artemis platform adapted a novel big data approach, which recognized the complexity, variety and volume of the data that was generated by biomedical monitoring modalities and remained unleveraged by existing information technology systems. It has been specifically designed to support acquisition and processing of physiological data streams. A data stream is an unbounded data set that has the capability to be processed as the data is being generated, rather than waiting for the data collection instance to complete, in order to initiate data processing. The platform utilizes stream-computing paradigm in order to enable real-time online analytics with the capability to concurrently analyze multiple physiological data streams to screen for multiple clinical conditions. However, the inability of the platform to support acquisition of file-based data packets, generated by existing biomedical monitoring modalities used in-flight, has necessitated development of extensions to the platform, presented in section to follow. Further changes to the platform have been motivated by conceptual architecture of autonomous clinical decision support system presented in [9]. The ultimate goal was to design an integrated big data framework within which physiological, environmental, activity and psychological data can be merged to support wholistic health-related assessments of the crew [10].

3. INTEGRATED BIG DATA FRAMEWORK

Emerging technological and scientific advancements continue to pave the way for practical continuous health monitoring, while present new opportunities to support clinical discovery and early detection monitoring. There is a promising potential to support timely data acquisition and real-time or near real-time data analytics, so as to leverage the invaluable potential of the acquired physiological data to inform prognostic, diagnostic and health management capacity in-flight. As such, there is a need for data platforms to be able to effectively respond to technological innovations, while still maintain compatibility with existing health-related monitoring modalities.

An integrated big data framework, which originates from prior Artemis and Artemis Cloud research, has been designed to address the limitations of existing information technology systems, while support integration of the various data formats. The framework is schematically represented in Figure 3 and described in detail in [10]. More specifically, it is a platform that supports the entire data life cycle and as such overcomes the issue of data smoothing and data loss. It provides the infrastructure to support the continuity of data flow, beginning with the data collection, all the way through to data reporting and storage. Moreover, it offers insights into real-time functionality of the human body through the real-time and near real-time online analytics capability.

The architectural components adopted from prior Artemis research include Data Persistency, Knowledge Discovery, (re)Deployment, Online Analytics and the streaming adaptive application programming interface of the Data Integration component. The novel extensions of the platform include Data Collection, Middleware Data Capture, message sub-flow and linkage of data within the Data Integration component, and Results Presentation. In addition, the Online

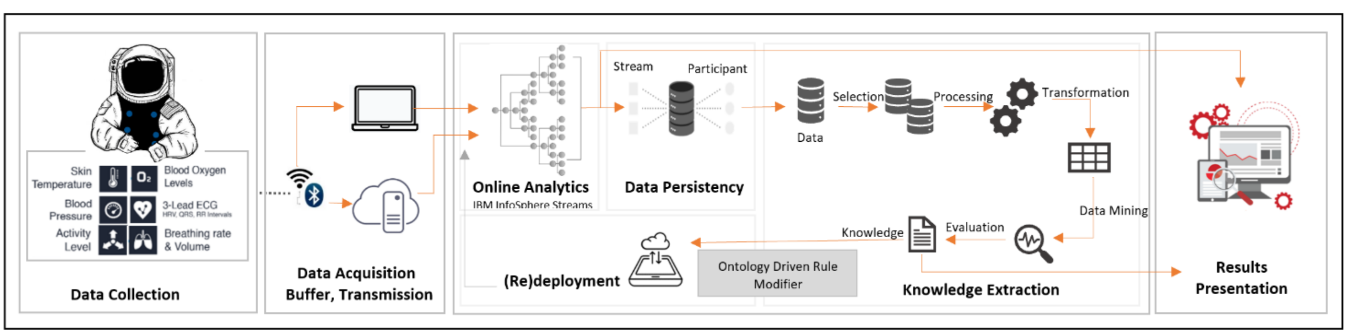

Figure 2. Artemis architecture for online health analytics during spaceflight [8].

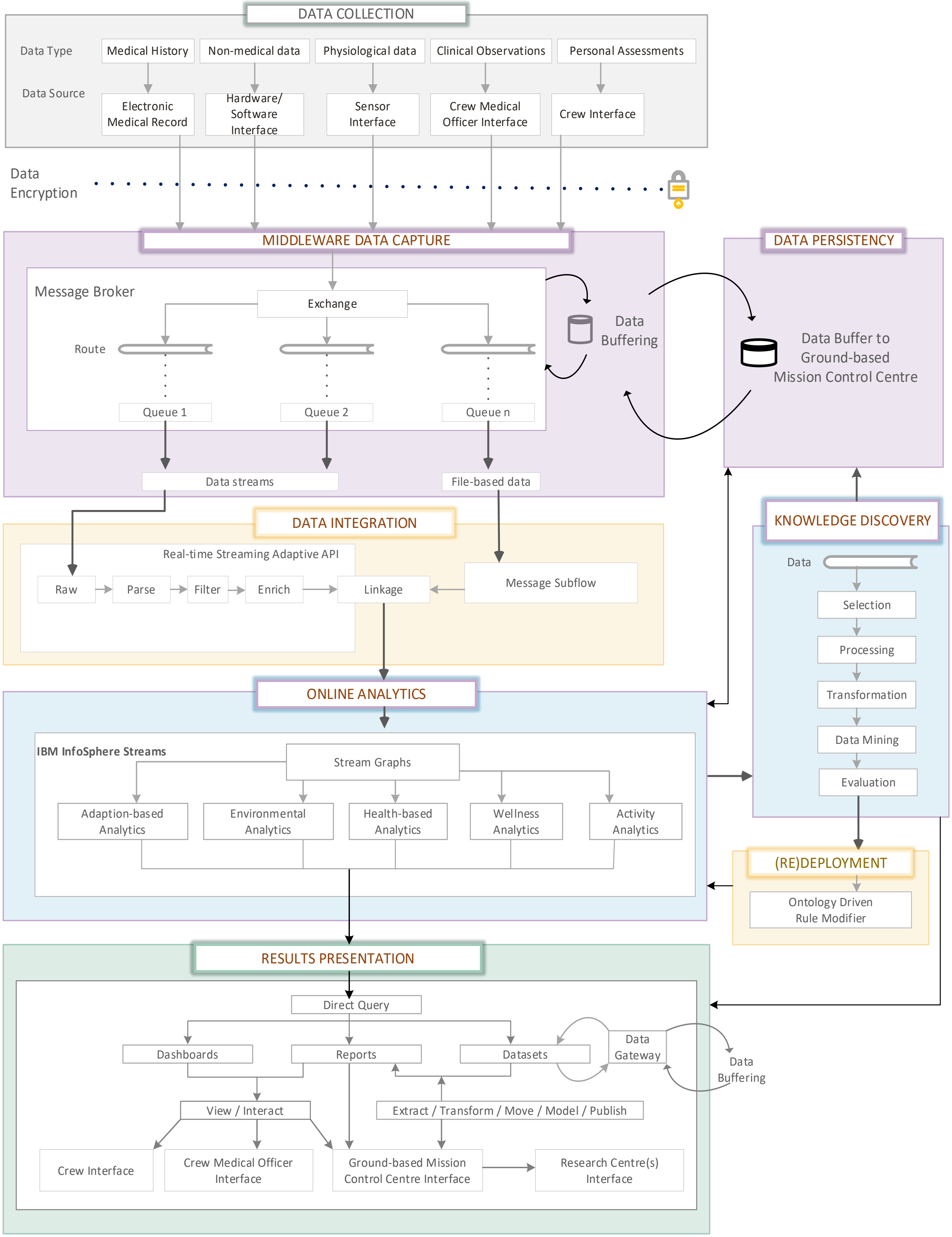

Figure 3. The proposed framework of health analytics as a service aboard the ISS [10].

Analytics component, adaption-based analytics in particular, have been extended through an introduction of multi-modal adaption assessments. More specifically, the adaption-based analytics are performed utilizing traditional and a sliding-window data sampling approach, documented in [8]. Meanwhile, the traditional functional health state algorithm is redeployed as a MATLAB instance within the integrated framework.

It is important to note, that the Middleware Data Capture component was introduced to serve as a data intermediary between data producer (data collection component) and data consumer (data integration component). Essentially, it enables data routing through a predefined series of protocols, so as to generate two main types of queues, namely the data stream queue and the file-based data queue, in preparation for consumption by the data integration component. In addition, the Middleware Data Capture component is tightly-coupled with a buffering mechanism, in order to ensure all incoming data is persistently stored, should there be an outage of any of the downstream components.

4. FRAMEWORK DEMONSTRATION

The instantiation of the integrated big data framework has been demonstrated within the context of terrestrial analog study, namely the Dry Immersion. The Dry Immersion study was performed at the Institute of Biomedical Problems of the Russian Academy of Sciences, described in detail in [3]. The overarching objective of the study was to acquire new scientific evidence and test novel technologies and methods developed for space application. The ethics approval for the research study was granted by IBMP Research Ethics Board, and the Ontario Tech University Research Ethics Board under REB# 15-047 Integration of Russian Cosmonaut Monitoring with Artemis and Artemis Cloud.

The study duration was five (5) days and consisted of a cohort of twelve (12) male participants, between the ages of 29±2 years old, with an average height of 177±1cm and weight of 70.2±2.6kg. The study cohort was further subdivided into a control and an experimental group. The experimental group wore a penguin suit on a daily basis for the total daily duration of four hours. The penguin suit, is also known as the suit of axial loading, which through an activity of tensioning devices stimulates the musculoskeletal system, so as to counter some of the deleterious effects induced by simulated weightlessness.

Within the study, two single-person dry immersion baths, thermoregulated at 33^0C, were utilized. A thin elastic fabric barrier was used to prevent direct skin to water contact and enable safe prolong exposure to the conditions of simulated weightlessness. The head-out depth supine immersion of the study subjects was selected for the purpose of the study. The study participants remained relatively motionless with limited ability to exit the baths for a daily average of 10-15 minutes to perform personal hygiene.

The data collection, electrocardiogram acquisition in particular, was performed exclusively at night time with the collect and store Holter-style monitor, known as the Cosmocard. The Cosmocard was a device of choice, given its current use aboard the Russian segment of the ISS. Following each instance of data collection, the device was docked for data acquisition and transmission to occur. The specifics of data collection modality presented fundamental limitations to the approbation of the proposed framework, as such the data was later replayed to simulate real-time data acquisition. The heart rate variability indices were sampled utilizing a traditional data sampling approach, and each data tuple was representative of a five-minute time window, on which further analysis were performed.

The adaption-based analytics were performed utilizing a re-engineered functional health state algorithm as an instance within MATLAB environment, so as to enable near real-time and real-time functionality. The efficacy of the re-engineered functional health state algorithm has been tested by cross-referencing the hourly L_1 and L_2 values for Subject 1 for the entire duration of the study. The hourly summaries of means and standard deviations of the canonical variables computed with two algorithm instantiations, the conventional and re-engineered, are schematically represented in Figure 4. In Figure 4, the respective days of the study are abbreviated as D1 for Day 1, D2 for Day 2, D3 for Day 3 and so on. As becomes apparent from the figure, the efficacy of the re-engineered algorithm is supported by a low standard deviation. The minor variances that are observed are mainly attributed to the differences in the QRS complex and R-peak detection algorithms.

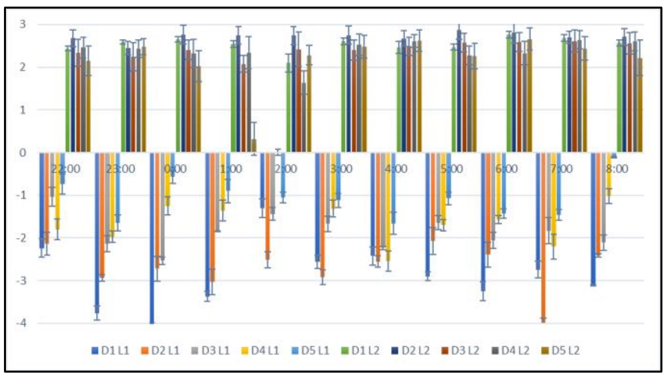

Figure 4. Cross-referenced values of canonical variables with two algorithm instantiations, presented as hourly means and standard deviations for Subject 1 during the entire duration of the study.

The individual results of adaption-based analytics observed during the Dry Immersion study are summarized as hourly averages of canonical variables in Figures 5-6. The data is presented in a traditional format, as the phase plane of functional states for the entire duration of the study. It should be noted that even subject numbers represent the control

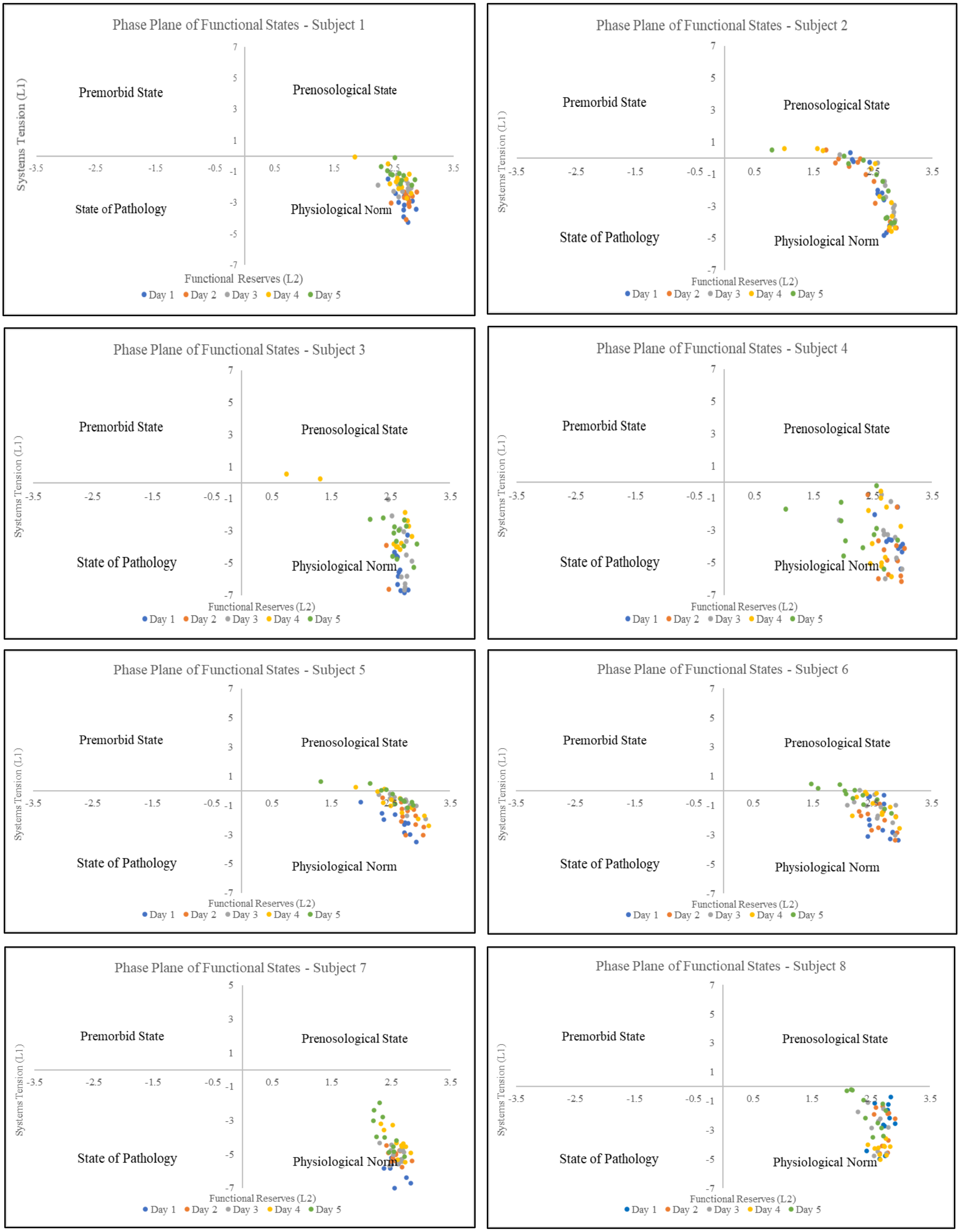

Figure 5. Activity of adaptation mechanisms represented as the phase plane of functional states for Subjects 1-8 for the entire duration of the Dry Immersion Study.

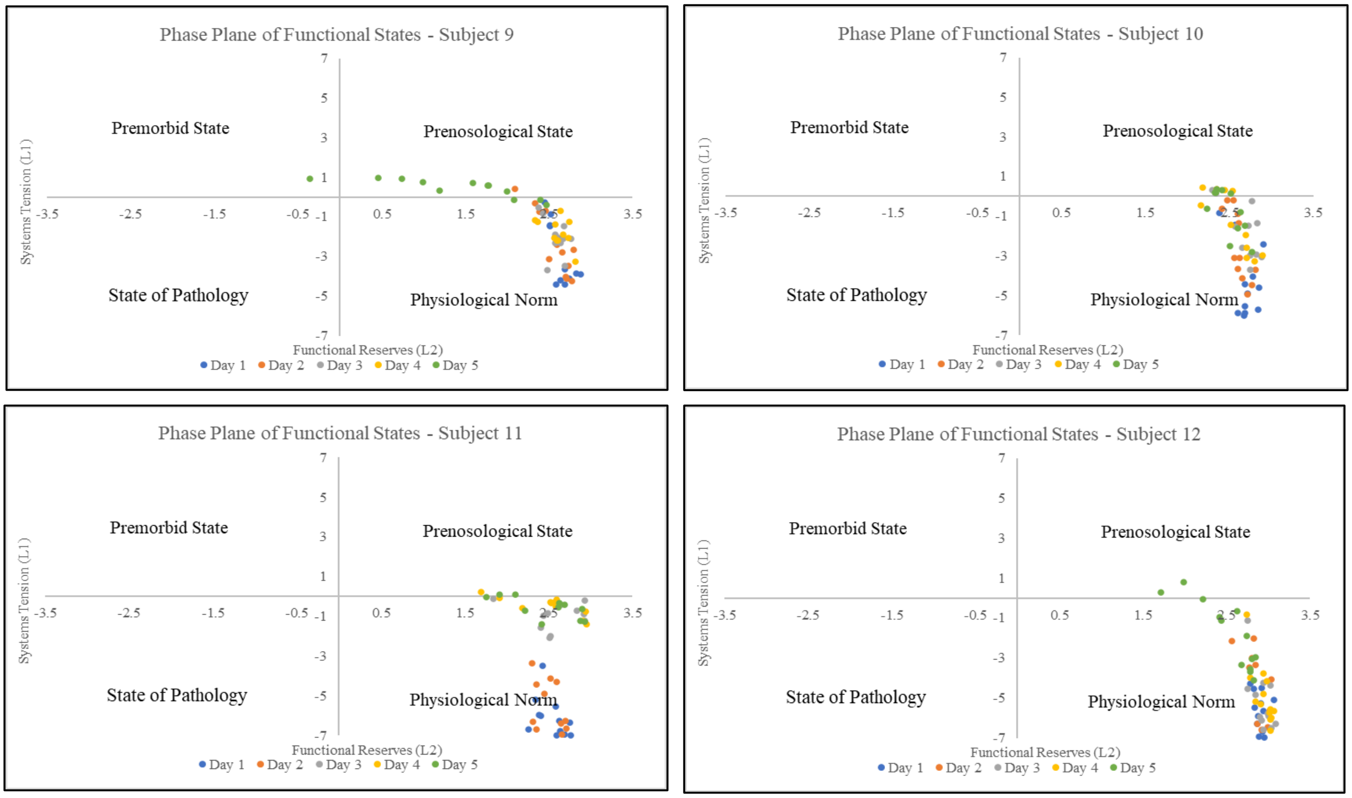

Figure 6. Activity of adaptation mechanisms represented as the phase plane of functional states for Subjects 9-12 for the entire duration of the Dry Immersion Study.

group, while odd correspond to the experimental group. As becomes apparent, there is a lot of inter- and intra-individual differences that can be observed, signifying a dynamic activity of the regulatory mechanisms throughout the entire duration of the study. In addition, most of the study participants remained within the state of physiological norm, or just on the verge of Prenosological State. This further signifies that as the study duration progressed, the study participants experienced elevated levels of systems tension, which triggered activation of functional reserves, so as to maintain an optimal level of health and well-being. Moreover, prior research has documented that significant stress index variations, characterized by elevated systems tension, are indicative of increased sympathetic activity of regulatory mechanisms [3, 8, 11]. In addition, stress index variations have been linked to onset of painful stimuli attributed to the environmental conditions of simulated weightlessness, within immersion baths [11].

Throughout the duration of the study, it was recognized that increased level of humidity had affected the functionality of acquired signal, QRS complex and R-peak detection, and subsequent analytics have been impacted. As such, necessitating an in-depth analysis of the raw ECG signal and whenever necessary, manual removal of the artefacts. This further led to an important realization of the constrains surrounding the limited dataset sizes that are available within the context of spaceflight environment.

To further validate the numerical estimates that have been obtained, and ensure that the observed response has been attributed to physiological activity of regulatory mechanisms rather than noise or artefacts, a sliding-window data sampling approach has been used. Contrary to the traditional data processing approach, when the five-minute data tuples are generated at time 0:00-4:59, 5:00-9:59, 10:00-14:59, the data tuples have been generated at a frequency of a 1-minute sliding window, more specifically at the time 0:00-4:59, 01:00-5:59, 02:00-6:59 and so on. As such, a much larger array of data has been generated within the same data set, contributing to improved quality and greater stability of numeral estimates.

The preliminary prototype of a sliding-window approach for adaption-based analytics is demonstrated on Subject 1 throughout the entire duration of the Dry Immersion study. The data is presented as 5-minute aggregates of the corresponding canonical variable values, schematically represented in Figure 7. Figure 7 further reveals the dynamic activity of regulatory mechanisms between each of the calculated data tuples, demonstrating a promising potential of the proposed approach to support early detection of unstable states and discovery of new clinically significant physiological patterns, retrospectively and in real-time.

Overall, the instantiation of multi-modal adaption-based analytics-as-a-service within the integrated big data

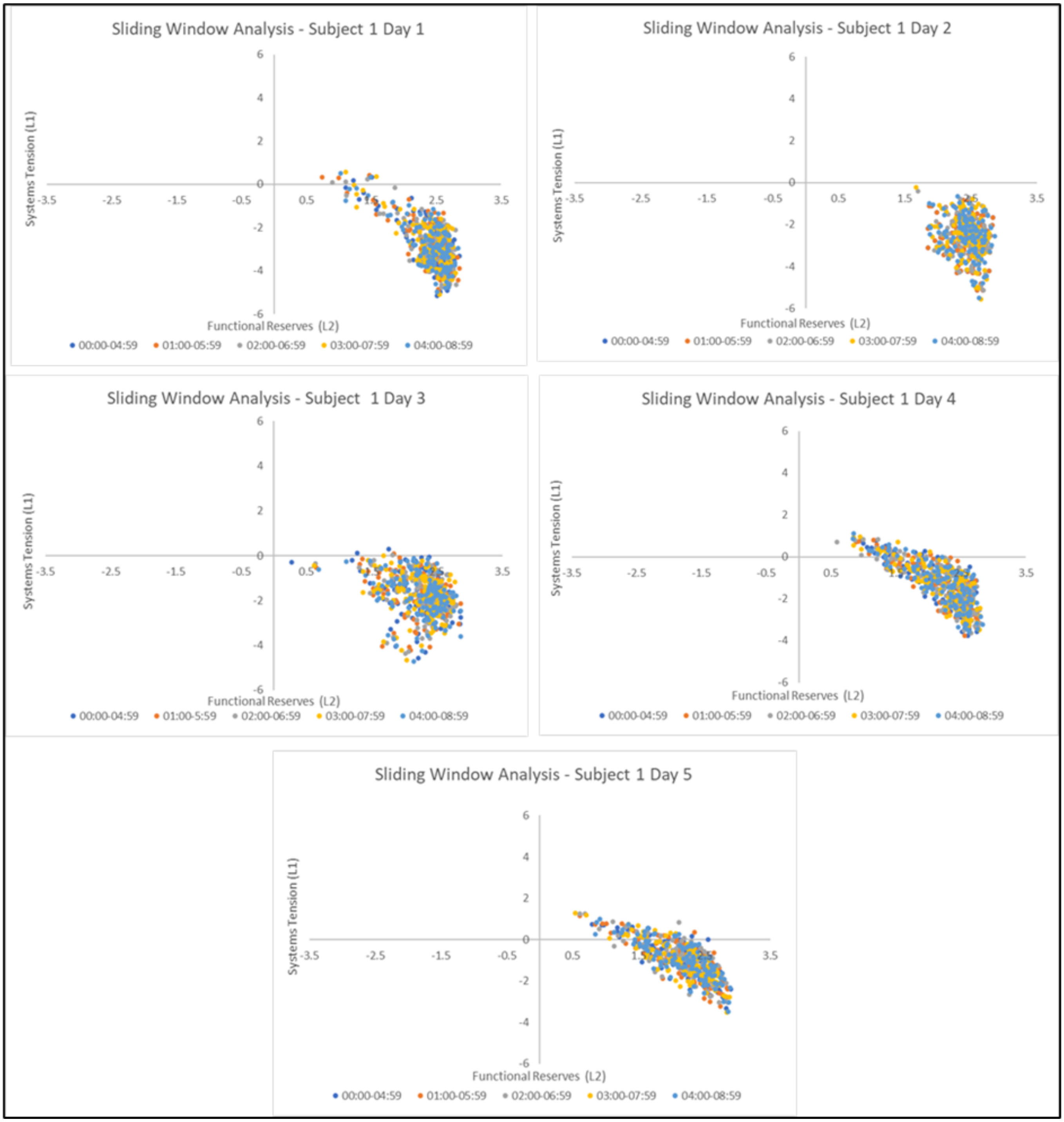

Figure 7. The instantiation of the sliding-window analysis prototype within the context of the Dry Immersion study.

framework has demonstrated great potential to support proactive prognostics, diagnostics and health management of weightlessness-induced deconditioning. It has demonstrated the potential to address the dataset size limitations by enabling the generation of larger arrays of data within the same datasets. Further contributing to a greater stability and accuracy of the performed computations, all while de-trending the HRV signal to ensure authenticity of the observed response, and removal of noise or artefacts.

5. Conclusion

This paper presented an integrated big data framework that recognized the breadth and depth of the various data types and sources that are of relevance for assessment of human health and performance during spaceflight. The proposed framework demonstrated an innovative approach in enabling the synthesis of the various data formats, to support comprehensive analytics and meaningful and efficient use of the acquired data. The clinical significance of the proposed framework was demonstrated with multi-modal adaption-based analytics-as-a-service, within the context of a ground-based Dry Immersion study. The traditional adaption-based analytics were enhanced through the introduction of a sliding-window data sampling approach for analysis of the relevant heart rate variability indices. It has further demonstrated that the dynamics of regulatory mechanisms, signifying adaptive capacity of the human body, change throughout the duration of the experiment in response to task-specific activities or the respective periods of the circadian rhythm, associated with specific activity of organ systems. The instantiation of the proposed framework further revealed the importance of assessment of each 5-minute interval, while the introduction of the sliding-window approach demonstrated great potential to support de-trending of the HRV to establish causal relationships between a particular stressor and the produced physiological response. As such, the application and instantiation of the proposed framework and multi-modal adaption-based analytics demonstrate great potential to enhance early detection monitoring and inform clinical decision making in-flight. Thereby, contributing to practical and meaningful use of physiological data during deep space exploration.

ACKNOWLEDGEMENTS

This research has been supported by the Canada Research Chairs program (#950-203427 and #950-225945) and the Canadian Foundation for Innovation (#203427).

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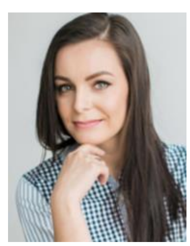
BIOGRAPHY



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