Computers in Biology and Medicine 40 (2010) 635–642

Contents lists available at ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/cbm

A biomedical sensor system for real-time monitoring of astronauts' physiological parameters during extra-vehicular activities

Ding-Yu Fei [a,*], Xiaoming Zhao [a,b], Cosmin Boanca [b], Esther Hughes [c], Ou Bai [a], Ronald Merrell [b], Azhar Rafiq [b]

[a] Department of Biomedical Engineering, Virginia Commonwealth University, P.O. Box 843067, Richmond, VA 23284-3067, USA
[b] Department of Surgery, Virginia Commonwealth University, P.O. Box 843067, Richmond, VA 23284-3067, USA
[c] Department of Electrical Engineering, Virginia Commonwealth University, P.O. Box 843067, Richmond, VA 23284-3067, USA

ARTICLE INFO

Article history:
Received 7 November 2008
Accepted 4 May 2010

Keywords:
Biomedical sensor
Extra-vehicle activities (EVA)
Monitoring of physiological parameters
Network systems

ABSTRACT

Objective: To design and test an embedded biomedical sensor system that can monitor astronauts' comprehensive physiological parameters, and provide real-time data display during extra-vehicle activities (EVA) in the space exploration.

Methods: An embedded system was developed with an array of biomedical sensors that can be integrated into the spacesuit. Wired communications were tested for physiological data acquisition and data transmission to a computer mounted on the spacesuit during task performances simulating EVA sessions.

Results: The sensor integration, data collection and communication, and the real-time data monitoring were successfully validated in the NASA field tests.

Conclusions: The developed system may work as an embedded system for monitoring health status during long-term space mission.

1. Introduction

To guide future space crew healthcare, the Institute of Medicine published "Safe Passage-Astronaut Care for Exploration Missions" [1]. The report noted that there was insufficient knowledge about the risks to human health during space flight beyond earth orbit and that all reasonable efforts should be undertaken to acquire that knowledge and effectively mitigate risks. Traditionally, the heart rate is the only physiological parameter monitored during NASA extra-vehicle activities (EVA). Today's advanced spacesuit concepts incorporate self-contained life-support systems (both the American and Russian spacesuits) and modular components (the American spacesuit) [2]. EVA spacesuits are a key enabling technology for space operations, particularly during maintenance and exploration missions [3]. Crew members have accomplished successful EVA wearing a variety of spacesuits that have evolved into today's self-contained, modular designs. Crew monitoring within the spacesuit during EVA assists in providing insight to capabilities of the crew member during mission task performances as well as the suit's environmental monitoring critical to completion of mission requirements. This degree of medical monitoring is classified as "Autonomous Medical Care" in NASA's Bioastronautics Roadmap [1]. Within the Bioastronautics Roadmap the capacity for monitoring and prevention is classified as risk #19 under the area defined as "Medical Care" to support the reduction in risk of life threatening medical conditions. Further elaboration in this risk area states the requirement for the need to identify "appropriate informatics tools to automate monitoring crew health".

Earlier attempts to monitor crew status have included data analysis from indirect measurements during Apollo missions to understand crew energy expenditures [4]. These efforts included three independent analysis of heart rate, oxygen levels within the suit, and the level of cooling in the liquid cooling garment within the suit to determine crewmen energy expenditures. The EVA Physiology, Systems and Performance (EPSP) Project sponsored by the NASA Human Research Program (HRP) is placing requests for more detailed and accurate data to be recorded relative to astronaut health monitoring [5]. Such efforts are raising awareness for the need to deploy effective and comprehensive physiological monitoring in order to develop accurate documentation of astronaut health during EVA and event performance. To fill the gap for effective monitoring we propose in this study a biomedical sensor system, Space Sock, to provide real-time monitoring of astronauts' comprehensive physiological parameters during EVA. This system integrates the concepts of modular design so that the spacesuits can adapt in different environments, such as microgravity, lunar, and Martian environment exposures with flexible configuration adjustments.

---

* Corresponding author.
E-mail address: fei@vcu.edu (D.Y. Fei).

0010-4825/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compbiomed.2010.05.001

The Space Sock system provides continuous monitoring of critical physiological parameters that are essential for the assessment and management of personal health status. Such parameters have been identified in other mobile device configurations [6]. Monitoring physiological data trends is similar to a deep sea diving exercise such that real time monitoring allows for careful assessment of human factors variables relative to task completion during longer duration EVA sessions planned for planetary explorations. Additional benefits include the capability to infer metabolic rate and correlate with portion of consumables remaining in the suit relative to EVA session duration to fully monitor productivity of an astronaut without overexertion. In order to fulfill the requirement to provide a comprehensive physiological monitoring for astronauts in the suit at durations of 8 h or more effective system architecture lessons from clinical practice in terrestrial setting were adapted.

System designs for patient monitoring in health care have been researched and developed to view real-time physiological data with remote access for clinical review in instances such as telemedicine, home-care, patient transport, as well as in hospital observation [7–12]. Wearable sensors and their informatics systems can monitor patients over extensive periods of time and serve to advance protocols for clinical practice such as remote Intensive Care Unit monitoring [13]. In order for biomedical sensor systems to be practical and wearable they rely on embedded sensors network, comfortable sensing interface, and miniaturized design without interfering with daily activities of the individual being monitored [14–16]. The biomedical sensor suite in this study utilized the most essential biomedical sensor components to allow relevant physiological monitoring. With the system architecture established to acquire data continuously from within the suit the need for redundancy in routing data between VPack and the CAI Pack required the additional implementation of wireless capabilities.

The combination of the integrated/intelligent sensors and wireless technology provides a common wearable human monitoring platform named wireless body area network (BAN) [17,18]. Wireless protocols such as Bluetooth^{TM}, WLAN (Wireless Local Area Network), WiMAX (Worldwide Interoperability for Microwave Access), GSM (Global System for Mobile), and CDMA (Code Division Multiple Access) have been successfully integrated into different physiological monitoring systems, allowing low-cost and commercial applications. Several telemedicine systems which were based on Bluetooth and Internet have been investigated for chronic disease home health care [19,20]. Some groups have demonstrated the feasibility of using GSM cellular phones and wireless application protocol (WAP) as a telemedicine platform for patient monitoring [21,22].

In this study, an embedded Space Sock system was developed to integrate a heterogeneous sensor network in order to monitor comprehensive physiological parameters, especially those relative to peripheral blood flow during EVA excursions. The system was used to validate the informatics capabilities with local data archive to a computer pack in the spacesuit, and display the data to the astronaut using a helmet mounted display for real time trending.

2. Methods

The Space Sock system's overview with hardware components for capturing physiological signals are illustrated in Fig. 1. In the following sections a brief description of the system is given, followed by performance evaluation efforts during field tests supervised by NASA's EVA division based in Johnson Space Center, Houston, TX. The Space Sock system consists of (1) a sensing sock, (2) a sensor processor module titled VPack (VCU Pack), and (3) a space suit CAIPack (Communications, Avionics and Informatics Pack) computer. The sensing sock accommodates a comfortable wearable fabric interface for anchoring physiological sensors to the skin surface with non-invasive capability. As the middleware of the Space Sock system, the sensor processor module (VPack) provides power and circuit interfaces for the network of sensors, and supports initial data processing. In addition, it has capability to connect to the CAIPack using directly wired communication. The CAIPack serves as a local hub for data management with the capacity to store the acquired physiological data packets and present the corresponding information for astronauts on a helmet mounted display. In addition, the CAIPack uses wireless communication capacity to route data packets to remote consultants such as the flight surgeons at Mission Control Center in Houston, TX.

2.1. Acquisition of biomedical sensor signals

A non-invasive multiple sensor system has been designed so that the weight and size of the system is minimal to be maintained within the space suit configurations, and can be economical with power consumption for extended EVA mission. In the current design, the sensing sock contains a plethysmograph sensor (AD Instruments, Colorado Springs, CO), a Galvin skin resistance sensor (Stoelting, Wood Dale, IL), a skin temperature sensor (PASPORT, Roseville, CA), and a pulse oximetry sensor (Nonin, Plymouth, MN). The plethysmograph uses an infrared photoelectric sensor to detect changes in tissue blood perfusion, and it can be used to correlate the blood volume change with respiration. Skin resistance is measured as an indicator of stress using impaired sweat response with two electrodes on the skin surface [23–25]. A low voltage is applied to the sensor circuit and the circuit calculates the skin conductively by the measured voltage across the two electrodes with a known, nearly constant and weak current between the two electrodes. The skin temperature sensor measures the temperature on the body surface. The pulse oximeter used in this system includes an infrared photoelectric probe attached to the skin surface of the astronaut's toe. It uses a non-invasive method to monitor the percentage of hemoglobin (Hb) saturated with oxygen (SpO_2), as well as the heart rate (HR). The digital output of the oximeter consists of 3 packets per second and each packet consists of 125 bytes. Each packet contains 4-beat and 8-beat average values of HR and SpO_2, respectively. The oximeter sensor status such as disconnection, artifact, and out of track, as well as packet checksum are also included in the packet. By implementing embedded sensor technology into the fabric of the socks, each physiological sensor or status sensor for the astronaut can be an element of the integrated space suite environment.

One constraint in the space suit environment is the high oxygen content once the suit is pressurized. This higher oxygen level hampers the inclusion of any electronic circuit or battery systems to within the suit environment. In the Space Sock system, the sensors were connected by standard data cables to circuit systems external to the suit after passing through the feed through port as depicted in Fig. 1. The connectors on either sides of the feed through port allowed for ready replacement of cable systems and sensor components in case of failure. The consequence of a longer cable configuration between sensor placement and circuit board systems for data management was managed by placing the cable securely against the crew skin surface.

2.2. Biomedical sensor signal conditioning

The infrastructure of the VPack was built based on an open sensor interface platform so that the system can integrate the

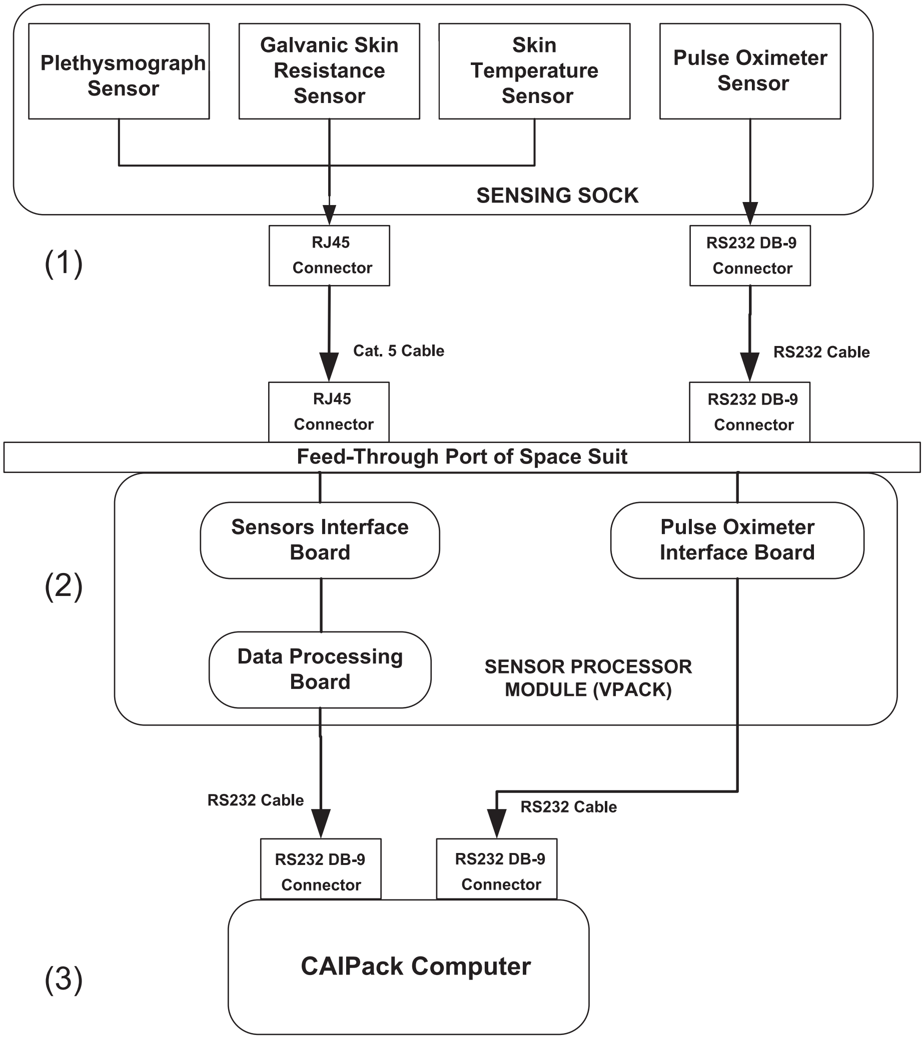


Fig. 1. Schematic representation of the Space Sock system architecture illustrating integrated hardware components for data routing from biomedical sensors to backend data base in computer system. The system includes (1) Sensing sock, (2) Senor processor module (VPack), and (3) CAIPack computer.

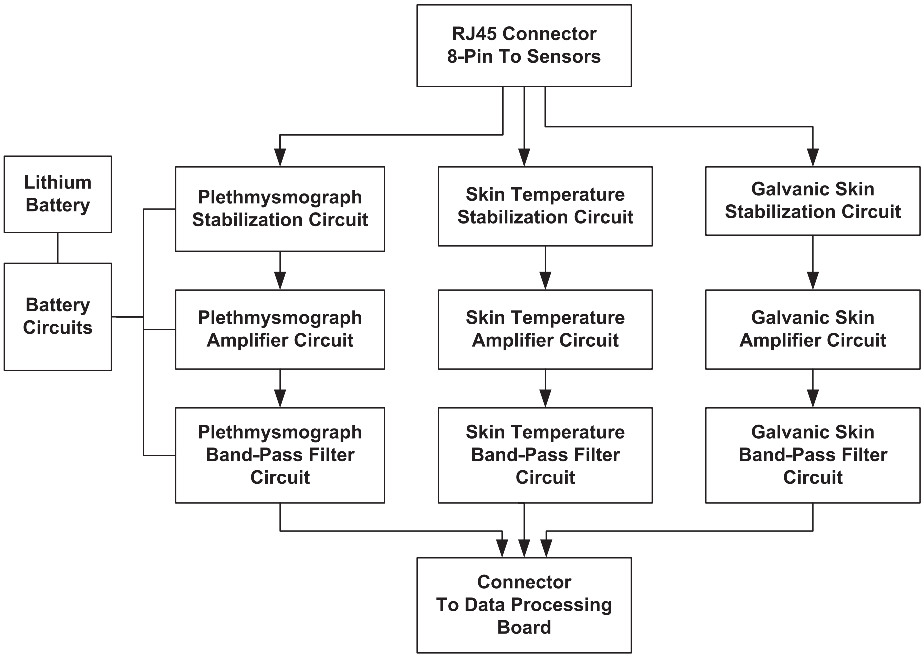


Fig. 2. Functional structure of VPack sensors interface board.

current suite of physiological sensors, but can also provide a standard interface for future sensors integration. The hardware of the VPack consists of a sensors interface board, a data processing board, and a pulse oximeter interface board, as illustrated in Fig. 1. The sensors interface board and data processing board are employed to retrieve and process the analog signals input from the sensors. Fig. 2 shows the functional structure of the VPack sensors interface board. Three channel analog signals from the plethysmograph sensor, Galvinic skin resistance sensor, and skin temperature sensor input to the board. The board stabilizes and gains the analog signal voltages to obtain the desired span. Band-pass filter circuits are used to remove the undesired frequencies from the amplified signals. The filtered signals from the 3 channels are sent to a 12-Bit A/D converter in the data processing board. The converted digital data are processed and formatted into RS232 package for wired communication. The digital signals from the pulse oximeter are formatted and connected to the RS232 port through the circuits on the pulse oximeter interface board.

2.3. Routing of data from Space Sock

The VPack within the Space Sock system is configured to communicate with the CAIPack by either wired or wireless connection. The wired communication between VPack and CAIPack is achieved via two standard wired RS232 ports as illustrated in Fig. 1. The sensors interface board and data processing board are employed to retrieve and process the analog signal inputs from the sensors. A PCMCIA Dual Serial I/O card (Socket Communication, Newark, CA) in CAI Pack is used to provide the two serial communications ports for direct data transmission. For redundancy in data acquisition the system was built with an Initium Bluetooth transceiver (Lemos, Fairfield, CT), the VPack middleware can also communicate with the Bluetooth

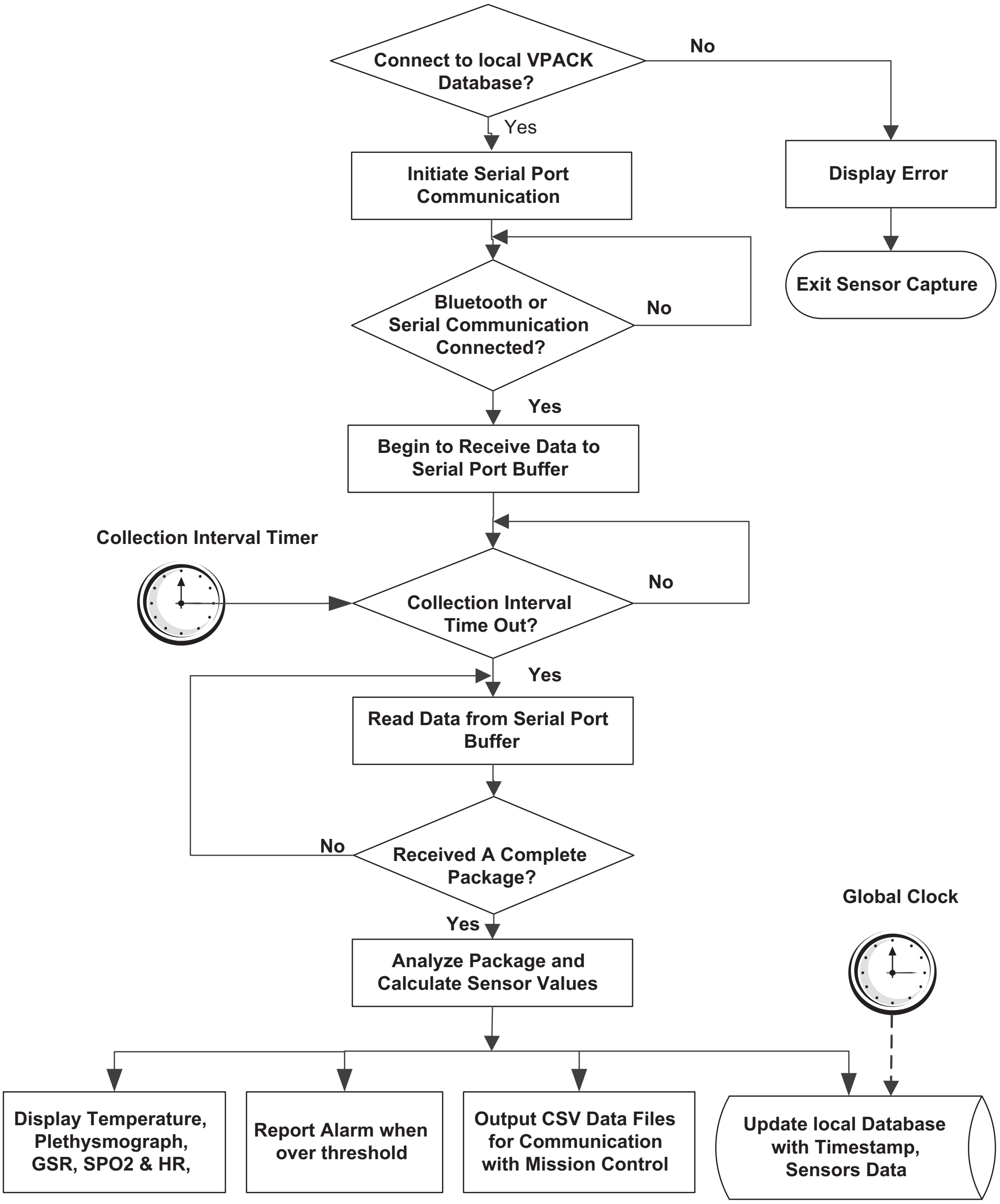


Fig. 3. Space Sock system software functional algorithm illustrating configuration for data handling.

transceiver in the CAI Pack. Bluetooth communication creates virtual serial ports and connections which allow data package to be delivered to CAI Pack wirelessly.

2.4. *Archiving of data packets from Space Sock*

Fig. 3 illustrates the software's data handling flowchart in CAIPack. The software module was developed in Visual Basic (Microsoft, Redmond, WA) in Windows XP platform. The overall software functions are to create standard RS232 connections or Bluetooth wireless connections, read sensor data packages, validate and archive the data as well as provide visual displays of the data values in real time. The software schedules to query the standard serial ports during wired communication or wireless communication and receive data every 200 ms. Every received data package is validated against the predefined data structures. Only when a complete data package is received and there is no data loss or alternation the VPack Software produces Comma Separated Values (CSV) data files. Both the time stamps and physiological values are automatically updated to the VPack database for backup and later analysis. The data validation functions are then performed to compare the physiological data with predefined thresholds. The predefined thresholds are input individually based on accepted norms in the medical literature relative to the test subject's age and gender. Additionally, an alarm will be reported in case of any abnormal fluctuations away from accepted thresholds. This alarm is displayed in red color bar in the monitoring interface with the corresponding physiological value to attract attention of both astronaut and mission control as illustrated in Fig. 5. The alarm signal is also stored into VPack local Microsoft Access database (Microsoft, Redmond, WA).

2.5. *System validation in field studies*

Each field session was conducted following a full safety review to ensure the biomedical sensor system met all mission requirements for crew safety in space suit tests according to policies set by NASA Occupational Safety and Health Programs, and the research review board at Johnson Space Center, Houston, TX. Safety parameters were approved relative to no harm from the biomedical sensor placement within the pressurized suit setup including electrical as well as fire hazard precautions. Each simulated EVA session was conducted daily for 4 consecutive days in each of the two annual field sessions. The acquisition and archiving of biomedical sensor data was initiated with power up of VPack and CAIPack systems once the physical movement of the crew member was approved by mission specialists during each of the daily field exploration sessions.

Data capture to the local CAIPack during field tests was monitored with secured remote access within the established LAN setup by field session support crew designated by NASA. Following each field session data archived to the CAIPack was removed using secure peripheral data storage capabilities and stored in a secure server provided by this study team. Analysis of the data was made at the close of each session to observe any data drop offs or missed trends during EVA sessions.

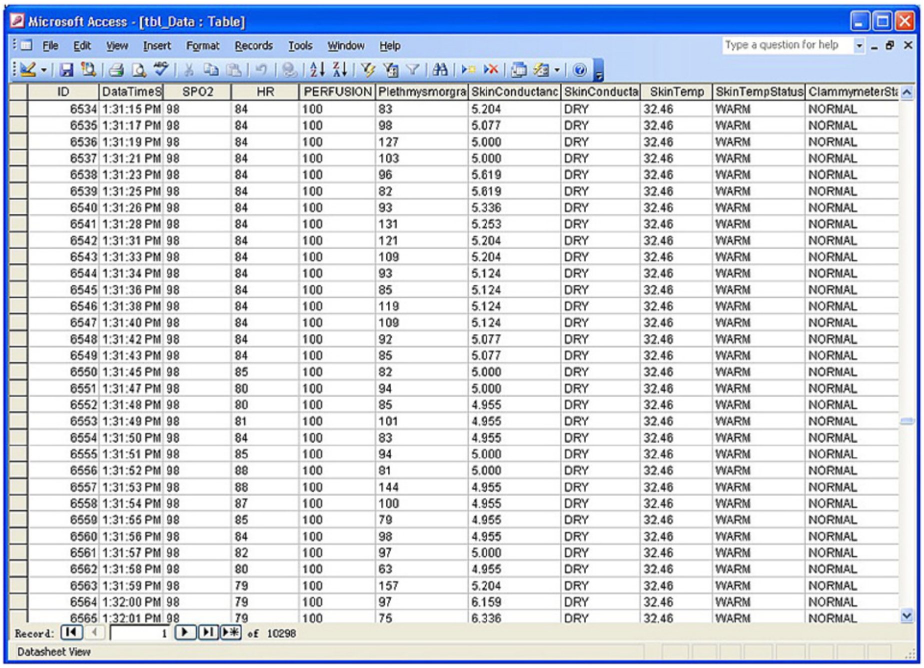
Two investigators performed direct review of the data streams archived spanning the field test session for the data by querying the backend database. The specific criteria used to assess review of the physiological record was conducted to look for data drop outs and to identify trending of data over time of the field exercise. Graphical interfaces of the raw data stacks were used for easier data review. Both investigators compared the results with an assessment to determine whether quality of data trends were consistent in each field exercise period. No criteria were applied to correlate data metric trends with specific physical activity since data monitoring was done remotely and no access was provided for direct observation of physical activity of the crew during the field exercises. Audio communication channels were restricted to direct communication with mission control which also prevented cross referencing any data trends to physical activity by the crew member. Reviewers of databases were blinded to each other's initial reviews, and full disclosure was made during team review of data trends and system functionality.

3. Results

The biomedical sensor system integration, data collection process, and data display were validated during field tests at the Meteor Crater in Flagstaff, AZ with the application of physiological monitoring during simulated terrain exploration exercises using NASA's MIII space suit (Hamilton Sundstrand, Norwalk, CT). The Space Sock system was tested and verified during two annual field tests in collaboration with NASA's geological field survey exercises in a two crew member format to simulated EVA practices. The sensors system and hardware were successfully integrated in the fully pressurized space suits after isolating all electrical components and power sources to within the customized VPack system which was housed external to the suit since the atmosphere within the suit is composed of high oxygen levels reflecting standard practice for lunar explorations.

The core VPack hardware, which encloses the sensor process module, was successfully miniaturized and integrated into one small box, in dimensions of 4.6 in × 2.7 in × 1.5 in so that it can fit the limited space in the backpack of spacesuit. The temperature sensor, skin conductance sensor, and plethysmograph sensor were connected to this middleware via a category 5 cable while SPO_2 sensor was connected to the middleware via a DB-9 cable. These umbilical connections as illustrated in Fig. 1 achieved the quick connect and disconnect requirements for safety in case of fire hazard as well as allowing for separation of the sensor system from CAIPack system till the crew member was inside the suit completely. The power was supplied by two 9-V batteries, which can support continuous information collection for greater than 36 h. The total duration of data capture varied depending on numerous variables such as functionality of the suit, physical strain of the crew performing exploration exercises, and communication limitations between crew entering the crater rim and support staff at simulated mission control. On the average biomedical sensor data was captured at regular 2 s intervals with a total duration of 2 h and archived into the database within the CAIPack as illustrated in Fig. 4. The column separated data values spanning all field sessions indicated no error in actual capture or archiving of data into the database. The crews were closely monitored by the entire team of NASA scientists from Johnson Space Center relative to their conducting geological explorations and thus no strain was experienced by any crew in the suit. As a result no biomedical sensor data packet trends were recorded that would reflect a stressed physiological interval as defined by physiological data that were outside the clinically accepted norms for human performance as matched to age and gender of the test crew in the suit. No safety concerns were raised during the entire field tests.

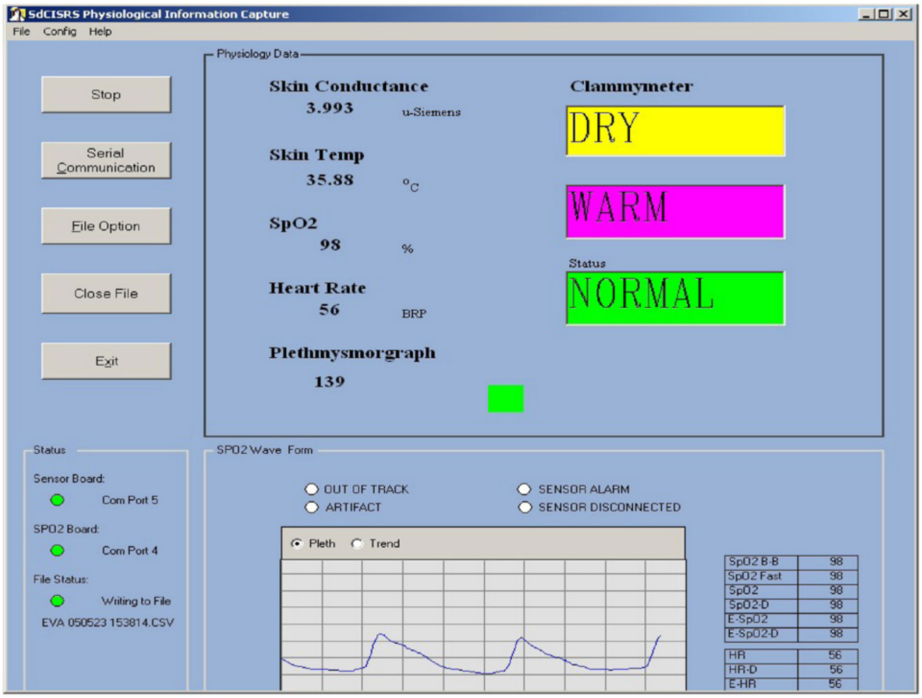
Physiological information monitoring was displayed to a customized visual interface as is illustrated in Fig. 5. Skin conductance, skin temperature, SpO_2, heart rate, and plethysmograph were successfully captured from embedded sensors along with the galvanic skin resistance. The acquired data were displayed in text fields, labels, and waveforms with color coded status bars for



ID	DataTimeS	SPO2	HR	PERFUSION	Plethmysmorgra	SkinConductanc	SkinConducta	SkinTemp	SkinTempStatus	ClammymeterSta
6534	1:31:15 PM	98	84	100	83	5.204	DRY	32.46	WARM	NORMAL
6535	1:31:17 PM	98	84	100	98	5.077	DRY	32.46	WARM	NORMAL
6536	1:31:19 PM	98	84	100	127	5.000	DRY	32.46	WARM	NORMAL
6537	1:31:21 PM	98	84	100	103	5.000	DRY	32.46	WARM	NORMAL
6538	1:31:23 PM	98	84	100	96	5.619	DRY	32.46	WARM	NORMAL
6539	1:31:25 PM	98	84	100	82	5.619	DRY	32.46	WARM	NORMAL
6540	1:31:26 PM	98	84	100	93	5.336	DRY	32.46	WARM	NORMAL
6541	1:31:28 PM	98	84	100	131	5.253	DRY	32.46	WARM	NORMAL
6542	1:31:31 PM	98	84	100	121	5.204	DRY	32.46	WARM	NORMAL
6543	1:31:33 PM	98	84	100	109	5.204	DRY	32.46	WARM	NORMAL
6544	1:31:34 PM	98	84	100	93	5.124	DRY	32.46	WARM	NORMAL
6545	1:31:36 PM	98	84	100	85	5.124	DRY	32.46	WARM	NORMAL
6546	1:31:38 PM	98	84	100	119	5.124	DRY	32.46	WARM	NORMAL
6547	1:31:40 PM	98	84	100	109	5.124	DRY	32.46	WARM	NORMAL
6548	1:31:42 PM	98	84	100	92	5.077	DRY	32.46	WARM	NORMAL
6549	1:31:43 PM	98	84	100	85	5.077	DRY	32.46	WARM	NORMAL
6550	1:31:45 PM	98	85	100	82	5.000	DRY	32.46	WARM	NORMAL
6551	1:31:47 PM	98	80	100	94	5.000	DRY	32.46	WARM	NORMAL
6552	1:31:48 PM	98	80	100	85	4.955	DRY	32.46	WARM	NORMAL
6553	1:31:49 PM	98	81	100	101	4.955	DRY	32.46	WARM	NORMAL
6554	1:31:50 PM	98	84	100	83	4.955	DRY	32.46	WARM	NORMAL
6555	1:31:51 PM	98	85	100	94	5.000	DRY	32.46	WARM	NORMAL
6556	1:31:52 PM	98	88	100	81	5.000	DRY	32.46	WARM	NORMAL
6557	1:31:53 PM	98	88	100	144	4.955	DRY	32.46	WARM	NORMAL
6558	1:31:54 PM	98	87	100	100	4.955	DRY	32.46	WARM	NORMAL
6559	1:31:55 PM	98	85	100	79	4.955	DRY	32.46	WARM	NORMAL
6560	1:31:56 PM	98	84	100	98	4.955	DRY	32.46	WARM	NORMAL
6561	1:31:57 PM	98	82	100	97	5.000	DRY	32.46	WARM	NORMAL
6562	1:31:58 PM	98	80	100	63	4.955	DRY	32.46	WARM	NORMAL
6563	1:31:59 PM	98	79	100	157	5.204	DRY	32.46	WARM	NORMAL
6564	1:32:00 PM	98	79	100	97	6.159	DRY	32.46	WARM	NORMAL
6565	1:32:01 PM	98	79	100	75	6.336	DRY	32.46	WARM	NORMAL

Record: 1 of 10298

Fig. 4. Range of sample physiological data bits archived in backend database within hub PC system with continuous run of VPack system.



Skin Conductance 3.993 u-Siemens

Skin Temp 35.88 °C

SpO2 98 %

Heart Rate 56 BRP

Plethmysmorgraph 139

Clammymeter DRY

WARM

Status NORMAL

Status

Sensor Board: Com Port 5

SPO2 Board: Com Port 4

File Status: Writing to File

EVA 050523 153814.CSV

SpO2 B-B	98
SpO2 Fast	98
SpO2	98
SpO2-D	98
E-SpO2	98
E-SpO2-D	98
HR	56
HR-D	56
E-HR	56

Fig. 5. Space Sock system graphic interface displaying physiological information monitoring conducted in real-time. This interface is displayed to a miniature helmet mounted display as well as monitors remotely to mission control.

effortless viewing by the crew in the suit. With the combined information obtained from galvanic skin resistance and skin temperature this system can readily identify cold/dry skin, cold/sweaty skin, hot/dry skin, and hot/sweaty skin in conjunction with the other physiological status metrics. The communication status using serial ports, as well as database archiving status was monitored on the same screen. In the incidence that the astronaut's physiological reading is beyond the preset threshold, an instant alarm can be triggered and displayed on the screen at the remote consultant site in real-time. The alert can be presented to both astronaut and consultants at remote site for immediate response so that detrimental human conditions could be avoided during the EVA session in space exploration. Overall, this system of sensors, communication, data processing, and alerts was effective as a health status monitoring tool for astronauts during simulated terrain exploration in space missions.

4. Discussion

In this study, a multiple sensors suite was implemented and tested for NASA's planned EVA session during future space missions. Embedded sensors system makes it possible to implement noninvasive physiology monitoring within the limit of the space suit and provides long power duration. The results demonstrated that the monitoring of physiological parameters at the most distant site of digits on the feet can be beneficial since the injuries from EVA sessions have been mostly to the nail beds [23]. This is a reflection of the multilayer garment creating a lack of tactile sensation at the tips of digits during task performances. Our limited field test sessions did not provide any documented incidences of injuries to the feet during terrain explorations with full space suit deployment as an exact replica of current use systems. However, peripheral monitoring can be an asset for terrestrial health monitoring such as altered blood flow to distant sites such as with diabetic individuals. NASA EVA field tests provided validation that the Space Sock system with embedded sensor platform can collect and monitor astronauts' real-time physiological information. The information could also be displayed to both the astronauts and the Mission Control Center. The feature of data display to the crew member in the suit provided self-awareness similar to a sea diver who needs to monitor physiological capabilities and current status. Reliability and stability of the Space Sock system have also been verified during the tests and showed that both hardware and software can work effectively in extreme environments. These findings are an improvement from earlier efforts to integrate physiological monitoring within the suit. Data shared in round table discussion pointed to the findings of ECG leads not functioning in suit's pressurized environment due to gas expansions in the skin surface causing adhesive pads to bulge away from skin surface [26]. Additional discussions have noted that the use of heart rate monitors such as the Oregon Scientific heat rate monitor watch only displays to an LCD monitor on the wrist.

Further development for the VPack will aim to accomplish sensor integration to monitor more physiological and body status, such as respiration rate and 3-D body acceleration. Such capabilities will allow for more detailed analysis of human performance during the long duration EVA sessions planned for planetary surface explorations. Accelerometer readings relative to gait allow for remote monitoring of the level of movement as well as level of impact if an adverse event where to occur. Translation of such capability is paramount to home monitoring of chronically ill patients such as those recovering from stroke events.

Because the current and the possible further developed VPack provide the ability for continuous monitoring over time and recording of the comprehensive physiological information, when applied to human factor studies the collected data from a variety of environments can be used to establish safety parameters relative to space and other environmental studies. The developed system could be a contribution not only for astronauts' safety but for human physiology relative to metabolic rate analysis during long duration task performance sessions. The concern towards analysis of metabolic rate is critical considering the microenvironment of the suit has a fixed supply of consumables that are scrubbed and recycled for continuous use. Instances of over exertion can generate British Thermal Units (BTU) beyond the capacity of the environmental controls of the suit.

Several technical and human issues are still needed to be investigated and solved for further development of the Space Sock system. For example, the current pulse oximeter sensor technology enables the measurement of arterial oxygen saturation of hemoglobin, heart rate, and perfusion, relying on the principle of differential light absorption by hemoglobin and oxyhemoglobin. The function of a pulse oximeter is affected by many variables, and human motion is one of the biggest challenges that could lead to artifact reading or no reading. Since astronauts will carry on planetary exploration missions, such as picking up rocks and digging underneath the dune, the next generation pulse oximeter that are motion tolerant will have to be analyzed to obtain stable readings.

The architecture of the interoperable sensor networks and communications of the Space Sock system are based on an open system, which can be easily updated and migrated for other applications such as use with patients at home with remote monitoring. This capacity to obtain medical informatics, archive the information, and relay to remote sites for automated analysis is a possible component to Institute of Medicine's identification for a transformation in health care delivery in the US [27]. Transforming primary care becomes possible with the practice of the patient-centered medical home (PCMH) [28]. The PCMH, originally described in the 1960s by the American Academy of Pediatrics, is a health care setting that facilitates partnerships between individual patients/families and their personal health care providers [29]. With remote monitoring capabilities and provisions for relay of medical informatics securely to a central database within an electronic medical record the patient centered care transforms to a coordinated care approach with enhanced clinical access for both the patient and physician.

Conflict of interest statement

None declared.

Acknowledgements

Support for this research was provided through grants from NASA's Marshall Space Center.

References

[1] Institute of Medicine, Safe passage-astronaut care for exploration missions, Available at 〈http://iom.edu/Object.File/Master/4/144/0.pdf〉.
[2] D.J. Newman, Life in extreme environment: how will human perform on mars? Gravitational Space Biol. Bull. 13 (2000) 35–48.
[3] D. Newman, M. Barrat, Life support and performance issues for extravehicular activity (EVA), in: S. Churchill, O. Heinz (Eds.), Fundamentals of Space Life Sciences, Chapter 22, Krieger Publishing Company, 1997.
[4] J.M. Waligora, W.R. Hawkins, G.F. Humbert, L.J. Nelson, S.J. Vogel, L.H. Kuznetz, Apollo Experience Report Assessment of Metabolic Expenditures, NASA Publishing, Washington, DC, 2001.
[5] M. Gernhardt, J. Jones, EVA Physiology, Systems and Performance Suit Requirement Recommendation, Johnson Space Center, NASA Publishing, Houston, TX, 2006.
[6] A. Lymberis, Research and development of smart wearable health applications: the challenge ahead, Stud. Health Technol. Inf. 108 (2004) 155–161.
[7] R. Satava, P.B. Angood, B. Harnett, C. Macedonia, R. Merrell, The physiologic cipher at altitude and real-time monitoring of climbers on Mount Everest, Telemed. J. e-Health 6 (2000) 303–313.
[8] I. Korhonen, J. Pärkkä, M. van Gils, Health monitoring in the home of the future, IEEE Eng. Med. Biol. Mag. 22 (2003) 66–73.
[9] A. Gandsas, K. Montgomery, R. Altrudi, D. McKenas, In-flight continuous vital sign telemetry via the Internet, Aviat. Space Environ. Med. 71 (2000).
[10] M.L. Moy, S.J. Mentzer, J.J. Reilly, Ambulatory monitoring of cumulative living activity, IEEE Eng. Med. Biol. Mag. 22 (2003) 89–95.
[11] H.H. Asada, P. Shaltis, A. Reisner, R.C. Rhand Hutchinson, Mobile monitoring with wearable photoplethysmographic biosensors, IEEE Eng. Med. Biol. Mag. 22 (2003) 28–40.
[12] E. Waterhouse, New horizons in ambulatory electroencephalography, IEEE Eng. Med. Biol. Mag. 22 (2003) 74–80.
[13] C.D. Kramer, E.M. Kalla, The challenge of designing biomedical equipment duration low-gravity missions, in: Proceedings of the Sixteenth Southern Biomedical Engineering Conference, April 1997, pp. 30–37.
[14] S. Park, S. Jayaraman, Enhancing the quality of life through wearable technology, IEEE Eng. Med. Biol. Mag. 22 (2003) 41–48.

[15] R. Paradiso, G. Loriga, N. Taccini, A wearable health care system based on knitted integrated sensors, IEEE Trans. Inf. Technol. Biomed. 9 (2005) 337–344.

[16] K. Johansen, S. Ellegaard, S. Wex, Detection of nocturnal hypoglycemia in insulin-treated diabetics by a skin temperature—skin conductance meter, Acta Med. Scand. 220 (1986) 213–217.

[17] A. Kailas, M.A. Ingram, Wireless aspects of telehealth, Wireless Pers. Commun. 51 (2009) 673–686.

[18] E. Jovanov, A.O. Lords, D. Raskovic, et al., Stress monitoring using a distributed wireless intelligent sensor system, IEEE Eng. Med. Biol. Mag. 22 (2003) 49–55.

[19] X. Zhao, D.Y. Fei, C.R. Doarn, B. Harnett, R.C. Merrell, A telemedicine system for wireless home healthcare based on Bluetooth and the Internet, Telemed. J. e-Health 10 (Suppl. 2) (2004) S–110-S-116.

[20] J. Yao, R. Schmitz, S. Warren, A wearable point-of-care system for home use that incorporates plug-and-play and wireless standards, IEEE Trans. Inf. Technol. Biomed. 9 (2005) 363–371.

[21] K. Hung, Y.T. Zhang, Implementation of a WAP-based telemedicine system for patient monitoring, IEEE Trans. Inf. Technol. Biomed. 7 (2003) 101–107.

[22] R.H. Istepanian, et al., Design of mobile telemedicine systems using GSM and IS-54 cellular telephone standards, J. Telemed. Telecare (1998) 80–82.

[23] J.J. McComb, X.P. Qian, J.D. Veldhuis, J. McGlone, R.L. Norman, Neuroendocrine responses to psychological stress in eumenorrheic and oligomenorrheic women, Stress 9 (2006) 141–151.

[24] R. Brunner, C. Müller, P. Parzer, F. Resch, Psychophysiological indicators of stress reactivity in adolescent psychiatric patients with dissociative symptomatology, Psychopathology 41 (2008) 330–335.

[25] E. Gulbandilar, A. Cimbiz, M. Sari, H. Ozden, Relationship between skin resistance level and static balance in type II diabetic subjects, Diabetes Res. Clin. Pract. 82 (2008) 335–339.

[26] R. A Scheuring, J. Jones, J. Novak, J. Polk, D. Gillis, J. Schmid, J. Duncan, J. Davis, The Apollo medical operations project: recommendations to improve crew health and performance for future exploration missions and lunar surface explorations, Acta Astronaut. 63 (2008) 980–987.

[27] Institute of Medicine, Crossing the Quality Chasm: A New Health System for the 21st Century, National Academy Press, Washington, DC, 2001.

[28] K. Davis, S.C. Schoenbaum, A.M. Audet, A 2020 vision of patient-centered primary care, J. Gen. Intern. Med. 20 (2005) 953–957.

[29] C. Sia, T.F. Tonniges, E. Osterhus, S. Taba, History of the medical home concept, Pediatrics 113 (2004) S1473–S1478.