High Speed Craft Health Monitoring System

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INTRODUCTION

High speed military craft crewmembers, particularly those onboard planing boats, are often exposed to severe, long-term dynamic conditions characterized by discrete and repeated impacts as the craft repeatedly slams into waves. This exposure often leads to serious musculoskeletal injury. In the late 1990s, the Naval Health Research Center conducted a self-reported injury survey that gave compelling evidence of a disproportionate rate of impact injuries sustained by occupants of Naval Special Warfare (NSW) high speed craft.[1] Other informal studies conducted since have corroborated these findings. While injuries to the knees, shoulders, and lumbar spine of crewmembers are reported, lumbar spine injuries are the most often reported and are generally the most debilitating.

A team of scientists and engineers at the Naval Surface Warfare Center Panama City Division (NSWC PCD), L-3 Communications, and the University of Virginia Center for Applied Biomechanics (UVA CAB) have been investigating this problem and developing models and guidelines since 1994.[2]

One of the most important goals of this research has been to develop a system to monitor the spine health of NSW HSC occupants, leading to the recent demonstration of the prototype HSC Health Monitoring System (HSC HMS). The primary objective of this system is to continuously measure the exposure of Special Warfare Combatant-craft Crewmen (SWCC) to craft dynamic conditions, process the data with a suitable injury assessment algorithm, and provide the resulting data to a database server for use by medical personnel who may appropriately intervene when the cumulative exposure reaches a defined threshold. Important additional benefits of the system include its inherent ability to provide for ride-roughness and man-overboard indicators, and cost-effective HSC impact injury epidemiology that requires simultaneous acquisition of dynamic exposure data with the reporting of impact injury incidents.

APPROACH

The production HSC HMS concept involves the installation of an acceleration data acquisition unit on all NSW HSC, and equipping all SWCCs with a radio frequency identification (RFID) card to establish the presence of specific SWCCs onboard the craft. The data acquisition unit is a modification of the Central Acquisition, Timing and Control Unit (CACTUs) developed earlier by NSWC PCD. The modified unit for the HSC HMS, called CACTUS-II, acquires and stores both craft acceleration and craft/SWCC identification data, and performs initial processing of the data to minimize the amount to be transferred to the database, called the Health Database Server. The partially processed data is continuously written to a standard USB storage device, or “jumpstick,” installed inside the CACTUs-II box. Periodically an assigned person would retrieve the jumpstick for uploading to the Server. The upload process, and routine access to the secure Health Database Server by medical personnel, may be performed on any computer with Internet access (a Client computer). Each time exposure data is uploaded, software within the Server computes and updates the injury metrics, and the Web interface displays the cumulative exposure data against the threshold value for each SWCC, allowing the medical personnel to intervene at their discretion.

THEORY

The dynamic conditions associated with HSC impacts may be embedded within what is usually referred to as whole-body vibration (WBV) that is often analyzed with the ISO 2631 Part 1 WBV standard.[3] HSC impact exposure should however be analyzed with different models and standards that account for its severe and discrete characteristics. NSWC PCD, L-3 Communications, and the University of Virginia Center for Applied Biomechanics (UVA CAB) have investigated this issue for years,[4] leading to the identification of the ISO 2631 Part 5 standard[5] as the best foundation for assessing the potential for injury onboard HSC. The existing Part 5 standard, while the most appropriate for HSC impact assessment, required modifications for application to the HSC HMS.

Original ISO 2631 Part 5 Standard

The original ISO 2631 Part 5 impact injury standard includes two basic components: a front-end “spine dynamics model” that predicts L4 lumbar spine dynamics based on seatpan acceleration measurements, and the “injury model” that computes the spine stress and the career injury metric “R” from the spine dynamics.[5]

The first step within the original ISO 2631 Part 5 algorithm is to compute the three-axis L4 lumbar spine acceleration time history from the measured three-axis seat cushion acceleration time history, or

$$A_{lk}(t) = f\,[A_{sk}(t)] \qquad (1)$$

The subscripts "l" and "s" signify the lumbar and seat cushion acceleration, respectively; and the subscript "k" signifies the three orthogonal components of the acceleration (x, y, and z). The algorithm for computing the longitudinal and lateral (x and y) lumbar acceleration is based on a linear spine model given in the standard, while the algorithm for the dominant vertical direction is in the form of a nonlinear neural net whose coefficients are also provided in the standard. The neural net was derived from motion simulator tests of instrumented human volunteers involving acceleration levels of up to about 4g. Thus the neural net has been questioned for application to the higher acceleration levels associated with HSC.

The existing Part 1 algorithm next defines an L4 lumbar spine "acceleration dose" D_k as:

$$D_k = \left[\sum_i (A_{ik})^6 \right]^{1/6} \tag{2}$$

where A_{ik} is the ith peak of the lumbar response acceleration $a_{lk}(t)$ and k again corresponds to the x, y, and z directions. The subscript l is dropped since we are dealing only with the lumbar acceleration. An "equivalent static compressive stress" S_e is calculated as

$$S_e = \left[\sum_{k=x,y,z} (m_k D_k)^6 \right]^{1/6} \tag{3}$$

where m_k are three constants defined in the standard in units of mass. The sixth-power equation gives emphasis to the higher impacts within the exposure time history. A "daily equivalent static compression stress" S_{ed} is computed by normalizing D_k to the acceleration dose D_{kd} for the average daily exposure time as

$$S_{ed} = \left[\sum_{k=x,y,z} (m_k D_{kd})^6 \right]^{1/6} \tag{4}$$

where the "daily dose" D_{kd} is

$$D_{k\,d} = \left[\frac{t_d}{t_m} \right]^{1/6} \tag{5}$$

where t_d is the duration of the daily exposure and t_m is the measurement duration. For consistency, NSWC PCD generally normalizes to an 8-hour daily exposure duration, leading to the metric $S_{ed}8$.

Finally, the career exposure metric R is defined for assessing the adverse health effects resulting from the one-time measurement of acceleration exposure dose, as

$$R = \left[\sum_{i=1}^{n} \left[\frac{S_{ed} \cdot days^{1/6}}{S_{ui} - c} \right]^6 \right]^{1/6} \tag{6}$$

where *days* is the expected number of exposure days per year, n is the expected number of years of exposure, c is a constant that represents the static stress due to gravitational force, and S_{ui} is a constant. S_{ui} is the ultimate strength of the lumbar spine for a person of age $(b + i)$ years with b being the age at which the exposure begins. The equation given in the standard for S_{ui} is

$$S_{ui} = 6.75 - 0.066(b + i) \tag{7}$$

The standard provides threshold limits for the career exposure metric R, based on the general population.

Modified ISO 2631 Part 5 Standard for HSC HMS

The Navy/UVA/L-3 team developed three modifications of the ISO 2631 Part 5 standard necessary for application to the HSC HMS: 1) the calculation is based on deck acceleration, not seatpan accelerations, since seatpan measurements for all SWCCs is impractical; 2) the neural net for computing the lumbar acceleration was replaced with a new model that is more accurate for the high-level exposures associated with HSC and; 3) the career metric *R* calculation within the Part 5 injury algorithm was replaced with a new "Cumulative-R" algorithm, suitable for cumulative exposures rather than a single measurement as is assumed with the original standard.

For application of the ISO 2631 Part 5 injury model to the deck acceleration, UVA CAB developed a new model of the seat and spine based on seated-human simulations using TNO's highly regarded and well validated lumped-mass model MADYMO (MAthematical DYNamics MOdel). UVA CAB then derived a computationally efficient "metamodel" that reproduces the MADYMO model results, for use in the HSC HMS software.

The L4 lumbar acceleration time history is now computed as

$$A_{lk}(t) = TF_{dlk}\, A_{dk}(t) \tag{8}$$

where $A_{dk}(t)$ is the three-axis deck acceleration time history, and TF_{dlk} is the transfer function between the deck and L4 lumbar spine. This transfer function is the metamodel that is based on the seated-human MADYMO simulations.

The next important modification of the ISO 2631 Part 5 standard was to predict injury from a career-long series of exposure measurements rather than from one representative measurement. The L4 lumbar spine three-axis "acceleration dose" D_k is computed as before with Equation 2. Here, however, the acceleration dose values D_x, D_y, and D_z from each data segment are added to "running cumulative dose values" D_{xc}, D_{yc}, and D_{zc} through the formulas:

$$\begin{aligned} D_{xcn} &= (D_{xc}^{6} + D_{x}^{6})^{(1/6)} \\ D_{ycn} &= (D_{yc}^{6} + D_{y}^{6})^{(1/6)} \\ D_{zcn} &= (D_{zc}^{6} + D_{z}^{6})^{(1/6)} \end{aligned} \tag{9}$$

where the subscript *n* represents the *new* cumulative dose value after the addition of the current dose value to the previously saved value. Therefore aside from the necessary constants, only three values must be stored.

From the three cumulative dose values, the "equivalent static compressive stress" S_e is computed as before from Equation 3. The equation for "daily equivalent static compressive stress" is not used because we are not normalizing to a particular daily exposure period such as eight hours.

Finally, the Cumulative-R value *CR* is computed for each occupant by dividing S_e by S_u-c (dependant on the age of the operator), as

$$CR = S_e / S_u\text{-}c \tag{10}$$

Note that the days and years are no longer included in the equation for CR because we are not normalizing to days or to years, but rather accumulating the exposure based on a long-term continuing sequence of craft operations.

The HSC HMS includes two basic hardware/software subsystems: the boat-mounted CACTUs-II and RFID subsystem; and the Health Database Server subsystem.

CACTUs-II: DATAFLOW AND ARCHITECTURE

Figure 1 illustrates the dataflow for the boat-mounted CACTUs-II side of the system. From top-to-bottom, the figure shows the GPS antenna that provides time and date data, the three-axis sensor unit (accelerometers), the RFID tags and RFID reader to identify the SWCCs, the two processors within the CACTUs-II box, and the removable storage (jumpstick).

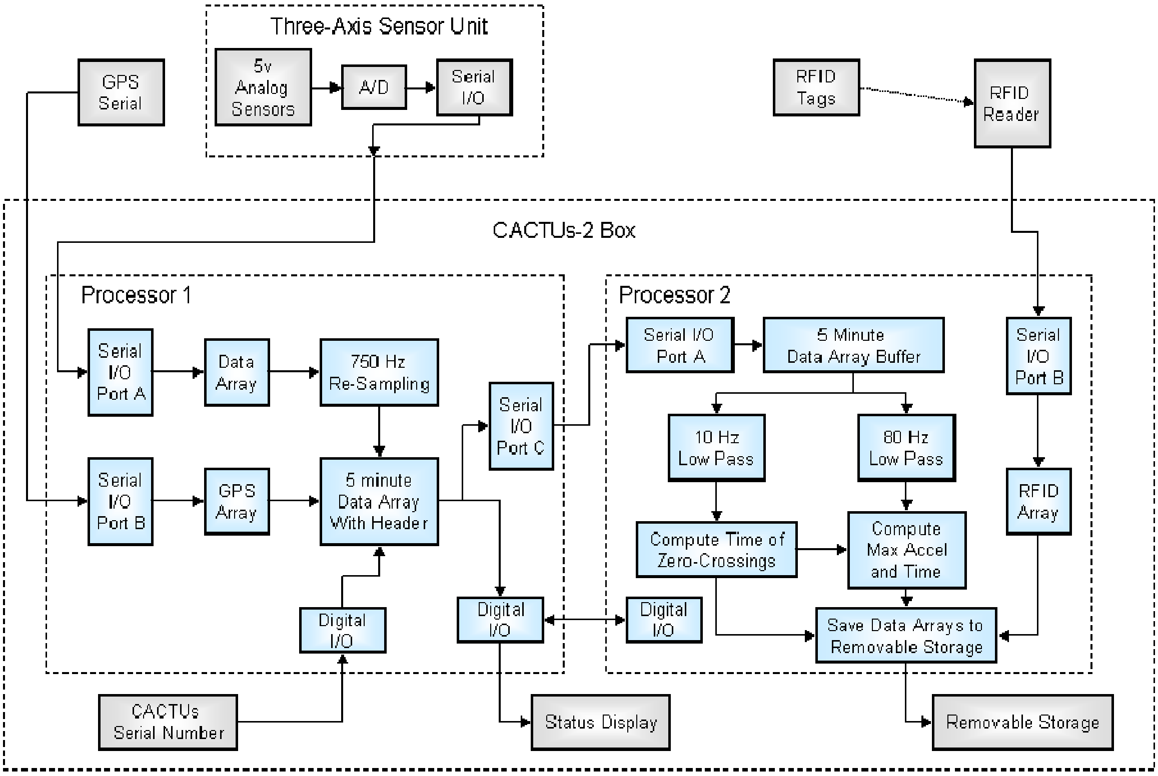


Figure 1. HSC HMS Boat-Mounted Software and Hardware (Patent Applied For)

Each time the boat power is turned on, and when the craft speed exceeds a programmable threshold value, Processor 1 accepts the GPS and accelerometer data, re-samples the accelerometer signal at 750 Hz, creates GPS-time-stamped 5-minute time segments, and passes the segment data to Processor 2. Processor 2 computes the acceleration peaks within each 5-minute segment by first low-pass filtering the data at 10 Hz with a zero phase-shift digital filter to identify the time corresponding zero crossings. The 750 Hz data is also low-pass-filtered at 80 Hz, in compliance with the ISO 2631 Part 5 requirements. Finally, the zero-crossing times are used within the 80 Hz signal to identify the acceleration peaks within each 5-minute segment. Craft identification data is stored on each CACTUs-II unit and passed through the processors to the jumpstick, to allow the Server to select the correct deck-to-lumbar transfer function, which will vary with the posture and type of seat. To minimize storage requirements, only the GPS time/date data, craft/SWCC identification data, and acceleration peak values and associated times are stored on the jumpstick.

The CACTUs-II hardware is shown in Figure 2. The figure shows the GPS antenna, the waterproof CACTUs-II box (shown open) with power supply and two processors, the jumpstick that is inserted in the box, the waterproof three-axis accelerometer box (shown open), one of the RFID tags worn by each crewmember, and the RFID antenna.

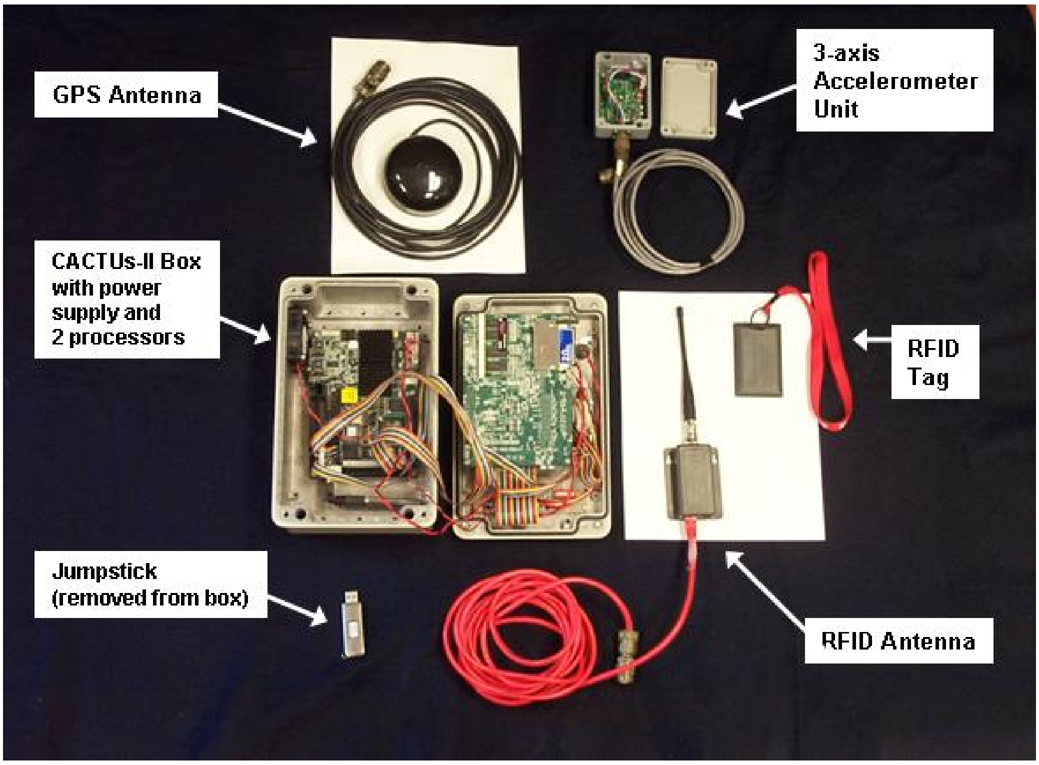


Figure 2. HSC HMS Hardware Mounted on Craft

Two useful features that could be readily integrated within the CACTUs-II system include an automated man-overboard indicator and a ride-roughness indicator. These could be easily implemented since the CACTUs-II continuously monitors craft dynamics, GPS data, and the presence (or absence) of SWCCs onboard. An integrated ride-roughness and man-overboard indicator, shown conceptually in Figure 3, could be include a green-yellow-red display and audible alarm. The device could also become a training tool for teaching helmsmen to minimize dangerous dynamic exposure to SWCCs.

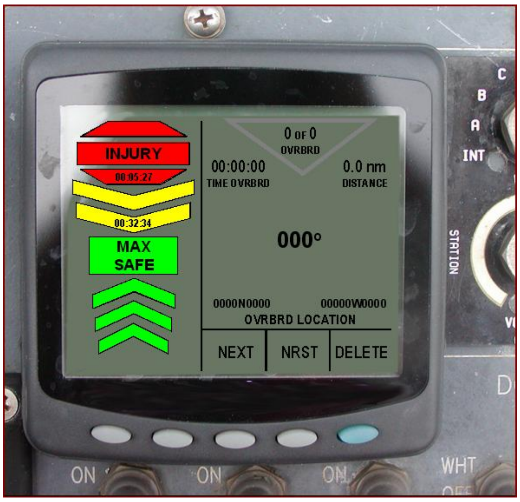


Figure 3. Ride Roughness Indicator

HEALTH DATABASE SERVER: DATAFLOW AND ARCHITECTURE

The software on the Health Database Server updates the Cumulative-R (CR) metric following each upload of acceleration peaks, time/date data, and craft/SWCC identification data. The C-code software within the Server essentially computes Equations 8, 2, 9, and 10 for each 5-minute segment, and includes routines to match the CR values with individual crewmembers from different craft.

The 1 GB jumpstick is capable of storing approximately 1000 five-minute segments. This number of segments corresponds to months of typical craft operation time. Therefore downloading from the CACTUs-II unit and uploading to the Server is infrequently required. Since Server access by medical personnel is desirable to appropriately monitor exposure to the SWCCs, more frequent downloading may be appropriate.

The client-server arrangement is shown in Figure 4. During each data transfer, an assigned person would retrieve the jumpstick from the CACTUs-II box for insertion into a Client computer with Internet access. Medical personnel would then have full access to the exposure data through any Client computer. Persons responsible for maintaining the Server site may access the system via the Client or Server to monitor its operation and modify its features.

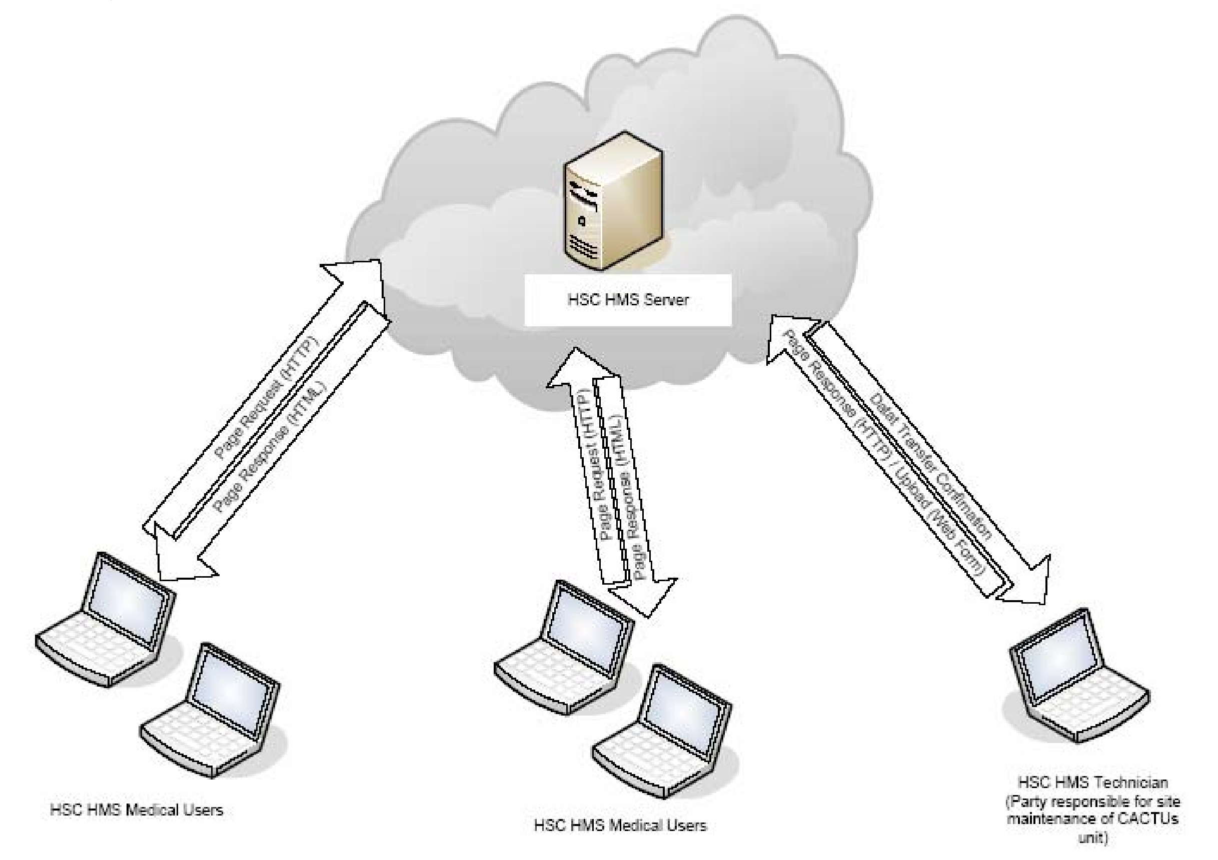
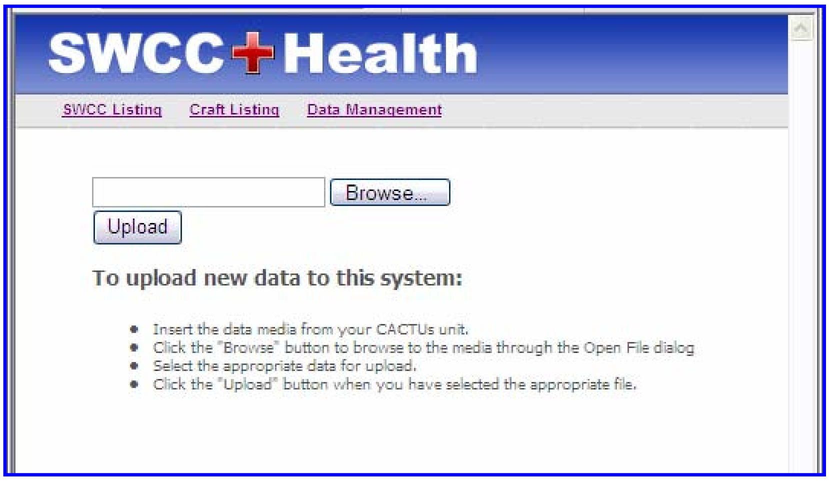


Figure 4. HSC HMS Client-Server Arrangement

The upload page on the Client computer Web interface is shown in Figure 5. This page is used by the medical personnel to upload data from the jumpstick. The process is fully automated for ease of operation.

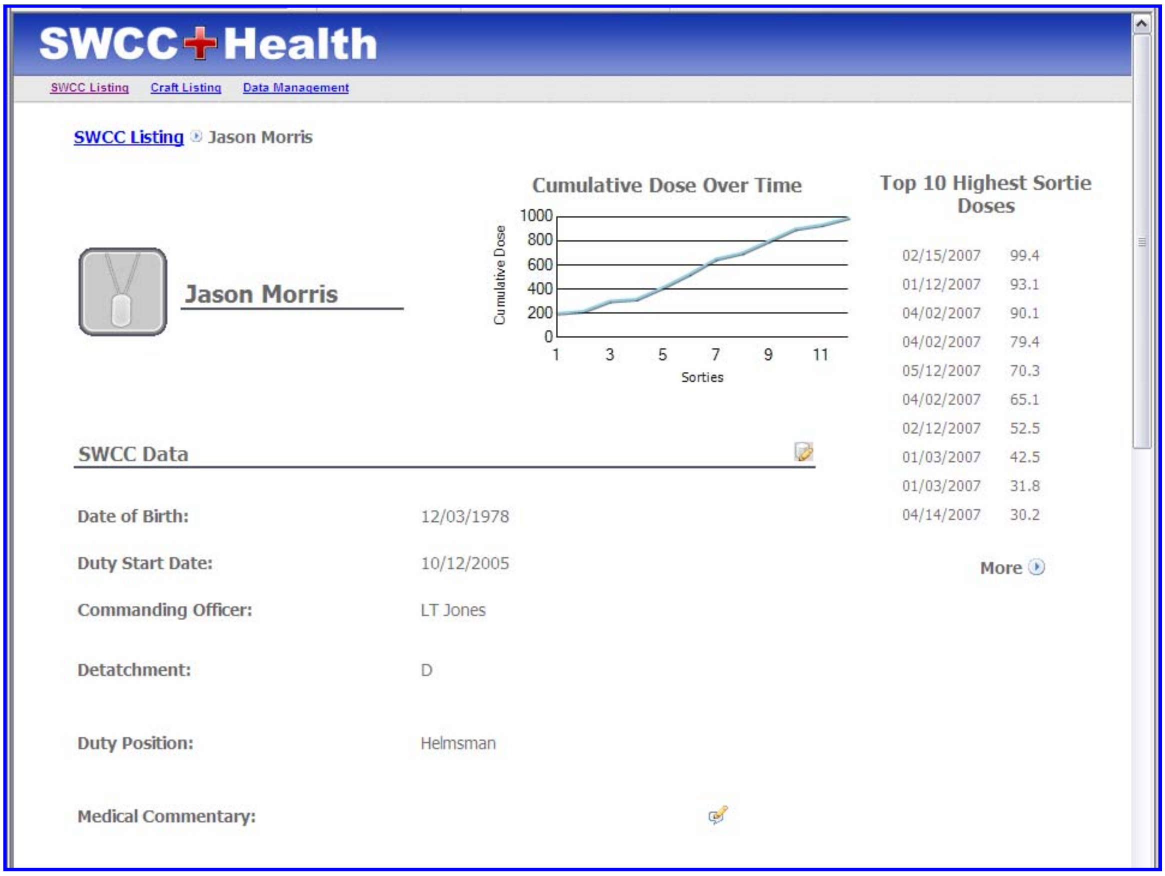


To upload new data to this system:

- Insert the data media from your CACTUs unit.
- Click the "Browse" button to browse to the media through the Open File dialog
- Select the appropriate data for upload.
- Click the "Upload" button when you have selected the appropriate file.

Figure 5. Health Database Server Web Interface for Data Upload to Server

Figure 6 shows another page from the Web interface, one of the SWCC pages that plot the Cumulative-R and the sortie-by-sortie doses. The SWCC pages also include necessary SWCC-related information that may be modified by the medical personnel. The SWCC shown in the web page is fictitious.



Jason Morris

Top 10 Highest Sortie Doses

02/15/2007	99.4
01/12/2007	93.1
04/02/2007	90.1
04/02/2007	79.4
05/12/2007	70.3
04/02/2007	65.1
02/12/2007	52.5
01/03/2007	42.5
01/03/2007	31.8
04/14/2007	30.2

SWCC Data

Date of Birth:	12/03/1978
Duty Start Date:	10/12/2005
Commanding Officer:	LT Jones
Detatchment:	D
Duty Position:	Helmsman
Medical Commentary:	

Figure 6. Health Database Server Web Interface for SWCC Exposure Data

CONCLUSIONS

The HSC HMS system will provide the NSW HSC community with a simple, cost-effective means for monitoring the spine health of SWCCs, and will provide the research community with the long-awaited means for cost-effectively investigating the cause-effect epidemiology of HSC impact injury. The system will also provide an excellent foundation for automated man-overboard and ride-roughness indicators. Given the successful demonstration of the prototype hardware and software, NSWC PCD and its partners hope to next develop improvements to the system, build a sufficient number of units for integration into all HSC NSW craft, and provide end-user training.

ACKNOWLEDGEMENTS

The authors are grateful to the Office of Naval Research and the U. S. Special Operations Command for sponsoring this effort. Other investigators who played a major role in the development of the HSC HMS include Eric Tuovila of NSWC PCD, who built the CACTUs-II hardware; and Dennis Coats, Steve Dawson, and Jason Whitaker of L-3 Communications who adapted and developed software for installation in the CACTUs-II and Server.

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