THE MODELING AND MEASUREMENT OF HUMANS IN HIGH SPEED PLANING BOATS UNDER REPEATED VERTICAL IMPACTS

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ABSTRACT

Occupants of naval special warfare (NSW) high speed planing boats experience repeated impacts with amplitudes reaching 10 to 15 g in the vertical direction. Ensign, *et al*. (2000) found compelling evidence of a significant injury problem in a self-reported study of NSW crewmen subjected to repeated impacts on high speed planing boats. Two sea trials were performed in a Mk V Special Operations Craft (SOC) using shock isolated and non-isolated seats. The sea trials provided data with which the relative performance of conventional injury assessment methods used by the naval architecture community can be evaluated. This evaluation includes the assessment of alternative methods for assessing impact injury from dynamic measurement. There is no current injury criterion that is fully acceptable for predicting injury from impact exposure during high speed craft operations. ISO 2631 Part 5 is currently the best injury criterion available. However, the existing injury reference values may result in a substantial limitation of high speed planing craft operations. This paper also presents a numerical model, based on a Madymo (TNO, Inc.) lumped mass seated human mode, to simulate the response of a human under typical high speed planing boat impacts. Using this model, a simplified dynamics model was developed for seated humans to allow evaluation of different impact conditions. The results of the simplified model were compared with the results of the neural net dynamics model specified in ISO 2631 Part 5. For the acceleration impacts above 4 g, the Madymo model produced substantially higher accelerations in the lumbar spine than those calculated using ISO 2631 Part 5. This suggests that the use of the neural net dynamics model of ISO 2631 Part 5 may not be warranted outside of the validated region of +/- 4 g.

Keywords: SPINE, INJURY CRITERIA, BIOMECHANICS, VIBRATIONS, MULTI BODY MODELS

REPEATED SHOCK IMPACTS on occupants during high speed operations in Naval Special Warfare planing boats were initially described by Gollwitzer and Peterson (1994). Occupants of these high speed craft experience repeated impacts with amplitudes reaching 10 to 15 g in the vertical direction. Only recently, however, has the injury potential from such shock impacts been assessed (Bass 2002, Peterson 2003, Bass *et al.* 2003, Bass *et al.* 2004). This paper examines the problem using two different approaches: 1) sea trial data analysis, and 2) numerical modeling. The first is the analysis and discussion of sea trials using instrumented boats and seated humans in a high speed Mk V Special Operations Craft (SOC), shown in Figure 1a. This includes the evaluation of the relative performance of conventional injury assessment methods used by the naval architecture community and alternative methods that may better assess the probability of injury. The second is the further development of a numerical model to simulate the response of a human under typical high speed planing boat impacts in a seated position.

Ensign, *et al*. (2000) found compelling evidence of a significant injury problem in a self-reported study of NSW crewmen subjected to repeated impacts on high speed planing boats. Of the crewmen responding to the survey, 65% sustained boat-related injuries, 89% of which occurred within the first two years of operation. The self-reported injury rate of NSW crewmen (2,687 injuries per 100,000 person year exposure) is well over 5 times higher than that of the Navy average (497 injuries per 100,000 person year exposure). In the mission logs of 72 crewmen, 33% of missions resulted in an injury, while 67% of the reported injuries resulted in chronic pain. Anecdotally, this injury problem is both acute and chronic, reducing both the short-term and the long-term effectiveness of the personnel. The most serious injuries included lower back, neck, shoulder, knee and ankle injuries. Anecdotally, the spectrum of injuries includes a substantial number of intervertebral disc injuries (c.f. Bass *et al.* 2003).

The sea trials examined in this paper occurred in January 2003 and October 2003. The January 2003 sea trial evaluated the performance of four different types of isolated seats, each with different trilinear dampening characteristics. From the January 2003 sea trial, a newly developed shock-isolated seat (Stidd-Taylor v5c), shown in Figure 1b, showed the best dynamic and user-survey response (Klembczyk and Mosher 2003). The isolated seat was then evaluated versus the original non-isolated seat in the October 2003 sea trial. The October

2003 sea trial is of special interest as injury criteria can be assessed on their ability to determine the known improvement of the isolated seat over the non-isolated seat (Klembczyk and Mosher 2003).

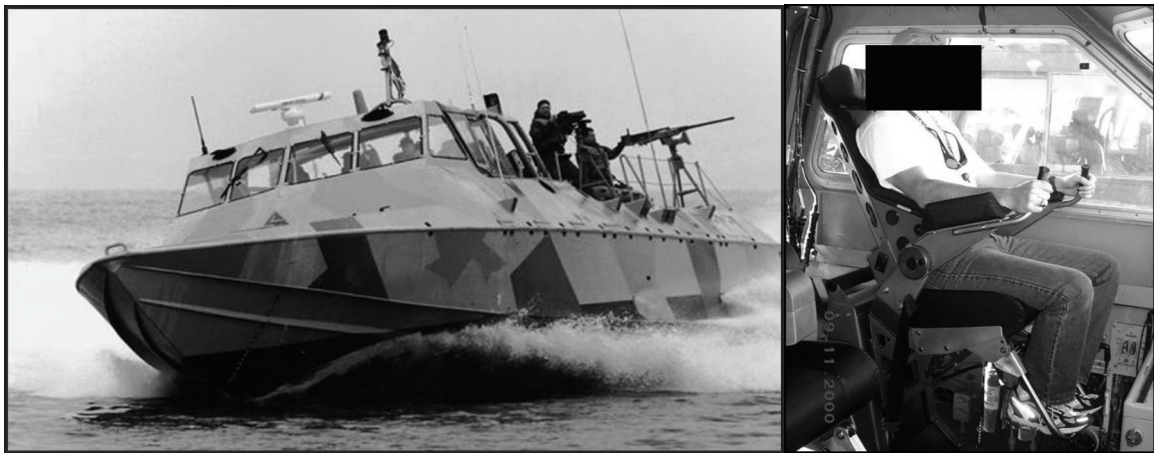

Figure 1. (a) Mk V Special Operations Craft (on left). **(b)** The isolated seat inside (on right).

In addition, a numerical model was developed to simulate the response of the human under high speed planing boat impacts to assess the potential for injuries. The model is based on a Madymo (TNO, Inc) lumped mass human model and is validated using experimental impact pulses taken during sea trials of a MK V SOC in January 2003. The model has been validated for high speed planing boat impacts on occupants in a Stidd Systems v4 rigid seat, hereafter called the non-isolated seat (Bass *et al.* 2003). This investigation includes the further validation of the Madymo model using impacts from the January 2003 sea trial. The resulting three degree-of-freedom model was used to evaluate shock mitigation postures and techniques, and is also being considered as a means to improve the lumbar dynamics model within the dynamics models within existing standard. Additionally, this paper describes conventional methods used by the naval architecture community for assessing impact injury from dynamic measurements, proposed alternative methods, the relative performance of conventional and alternative methods, and a process for integrating new methods into the craft design process.

INJURY CRITERIA: It has been argued that there is no suitable criterion for spinal injuries from repeated shocks at the heave acceleration levels experienced in planing boat operations (Bass *et al*. 2003, Bass *et al.* 2004). However, traditional evaluation methods include the RMS of the vertical acceleration and the frequency weighted RMS from ISO 2631 Part 1 (1985). Alternative evaluation methods investigated in this paper are the power spectral density (PSD), the newer ISO 2631 Part 1 Vibration Dose Value (VDV), the peak acceleration, the Dynamic Response Index (DRI), and ISO 2631 Part 5 (2003).

The traditional evaluation methods are both based on the root-mean-square of the vertical acceleration profile. The frequency weighted RMS from ISO 2631 Part 1 (1985) weights the signal for different frequencies based on the manner in which the frequency content affects health, comfort, and perception. The basic RMS is a measure of the mean power within the entire bandwidth of the signal, and although a lower RMS corresponds to less power within the system, it may not correlate to crew comfort or injury (Payne, 1978). The frequency weighted RMS addresses this issue; however, it is not validated for the higher crest factors which are seen in planing boat operations. A crest factor is defined as the maximum amplitude of the frequency-weighted signal, divided by the RMS of the frequency-weighted signal (ISO 2631 Part 1, 1997). The newer ISO 2631 Part 1 (1997) standard includes the Vibration Dose Value (VDV), used for higher crest factors. It is computed as the root-mean-quad of the frequency-weighted acceleration. This better accounts for acceleration peaks that are potentially more injurious but have a small effect in an RMS calculation. The PSD [10 $\log_{10}(g^2/Hz)$] is computed for the acceleration profiles over the 0.1 to 100 Hz range using a 4096 point Hamming window with 50% overlap. The 4-8 Hz bandwidth is examined because it is generally associated with human torso dynamics and discomfort (ISO 2631 Part 1, 1997). The average PSD value within this range is computed and presented.

One of the difficulties in the field of planing boat impacts is that the 'traditional criteria', as discussed above, that are used to assess injuries are often not based on injury criteria. For example, RMS vibration in high speed boat impact has not been associated or correlated with injuries in the biomechanics literature. For example, ISO-2631 Part 1 is based on discomfort boundaries, not injury boundaries. However, these have been used as injury indicators in the design of craft. There are, however, two existing spinal injury criteria that may be appropriate for repeated vertically dominated impacts at levels, DRI and ISO 2631 Part 5.

The DRI (Payne, 1962) was developed by the U.S. Air Force as a spinal injury measure of the short duration vertical accelerations in aircraft ejection seats. The DRI uses a simple mechanical spring-damper model of the spine to represent the spinal column stiffness and dampening characteristics. A DRI value is obtained based on the maximum spinal compression predicted with the model. Stech and Payne (1969) correlated spinal injury rates to DRI values using 364 non-fatal seat ejections from six different aircraft. They found that DRI values for single impact events of 15.2, 18.0, and 22.8 correspond to 0.5% (low), 5% (medium) and 50% (high) risks of spinal injury.

The ISO 2631 Part 5 (2003) was developed by the U.S. Army to assess the risk of spinal injury involved with the vibration and shocks experienced by occupants of Army tactical ground vehicles (U.S. Army, 1998). The injury model within this standard is based on a vertebral body failure assessment from laboratory experiments. The spine dynamics model is represented by a nonlinear neural network for the heave direction (vertical-z) and a linear lumped parameter model for the surge (forward-x) and sway (lateral-y) directions. The heave model was developed based on the shock transmission of acceleration between the seat and the human volunteers. Ethical constraints prevented the volunteers from exposure to impacts greater than 4 g (Morrison *et al*. 1999); thus the vertical dynamic model developed for the standard is limited to the +/- 4 g range. The standard has not been validated at the higher impact levels that are seen on high speed planing boats. The parameter of interest within this standard is the daily equivalent static compressive dose, S_{ed}, normalized to an exposure time of 8 hours, $S_{ed}(8)$, in units of MPa. This will be referred to as the Spinal Stress Dose. Another parameter of interest is the R-value, from which the risk of spinal injury over the course of a career can be quantified. An R-value below 0.8 corresponds to a low lifetime risk of injury, and an R-value obove 1.2 corresponds to a high lifetime risk of injury.

METHODOLOGY

SEA TRIAL DATA: In January 2003, a Mk V SOC was outfitted with four different isolated seats termed v5a, v5b, v5c, and v5d, which were located in the front row of the craft. An instrumented sea trial was conducted during a transit from the Naval Amphibious Base in Little Creek, Virginia to the King's Bay Submarine Base in Georgia while recording acceleration data in the heave, surge, and sway directions. The sea conditions during the transit included significant wave heights of 5 to 6 feet with 3 to 4 foot wind waves. A three-axis accelerometer and a three-axis angular rate sensor were located on the deck along the centerline of the boat. Three-axis accelerometers were located on the seat frame (above the isolator) and seat pad (between the occupant and the seat pad) on each of the instrumented seats, as well as on the occupants' backs on the L4 lumbar spine and the occupant helmets. Of the four seats, the v5c seat, which is referred to as the isolated seat, was chosen as the best seat by experienced occupants and its data is analyzed in this paper.

In October 2003, a second sea trial was performed to compare the non-isolated seat to the isolated seat. Both seats were placed in the front row of a Mk V SOC and instrumented in the same fashion as the January 2003 trial. The acceleration data was obtained in seas with a significant wave height of approximately 4 feet, for varying craft headings, in the area around the Naval Amphibious Base in Little Creek, Virginia.

The portion of the January dataset with the greatest dynamics (active portion) is approximately 4 hours in duration and the active portion of the October dataset is approximately 48 minutes. Within these datasets, there are 9,496 discrete impact events with peak accelerations greater than 0.5 g. This acceleration value (0.5 g) was taken to be a lower threshold of interest for repeated impact injury. Of these, 8,211 occurred in the January dataset and 1,285 occurred in the October dataset. These impact events include 1,141 impacts greater than 2 g (982 from the January dataset and 159 from the October dataset) and 119 impacts greater than 4 g (113 from the January dataset and 6 from the October dataset).

The acceleration data was sampled using a 12-bit A/D converter at 1250 Hz in the January sea trial and 750 Hz in the October sea trial. Both were low-passed filtered, for anti-aliasing, at 250 Hz. Measurements from the January sea trials suggested that, in practice, the power above a frequency of ~100 Hz is limited. So, the sample frequency was reduced for the October sea trial to reduce the data acquired from the tests. The original raw data was then demeaned. A phaseless 8-pole Butterworth lowpass filter was then used to filter the data to 80 Hz. The October 2003 acceleration data was analyzed using 30-second intervals, 45-second intervals, and the entire time history. Both short segments correspond to worst-case sea conditions.

Conventional methods of analysis examined in this paper include the root-mean-square (RMS) of the acceleration time history and ISO 2631 Part 1 (1985). Alternative impact injury design rules investigated include the Dynamic Response Index (DRI), the VDV from ISO 2631 Part 1 (1997), the ISO 2631 Part 5 (2003), the bandwidth-limited power spectral density (PSD), and the peak acceleration of the seat pad for individual impact events. Feedback from U.S. Navy Special Warfare combatant-craft crewmen over the course of many hours in the new isolated seats has established their greatly improved performance relative to the original non-isolated seat (Klembczyk and Mosher 2003). The October dataset directly compares the performance between the non-isolated seat and the isolated seat. So, the injury criteria can be evaluated based on

their ability to discriminate the improvement in the isolated seat over the non-isolated seen in the user surveys of the shock isolated seats from January 2003.

Some injury criteria involve analysis of individual impact events. For these cases, the datasets are separated into discrete impact events of approximately 1-2 seconds in total duration by first performing a low frequency filter (10 Hz, phaseless 8 pole Butterworth lowpass filter) to identify the negative zero crossings in the deck heave dataset as shown in Figure 2, where a negative zero crossing is defined as a zero-crossing from a positive to negative value. The time values of these negative zero crossings are taken to delineate the boundaries of each impact event. After the impact events are identified using the low frequency filter, data with higher frequency components (80 Hz) is used to analyze the individual impact events.

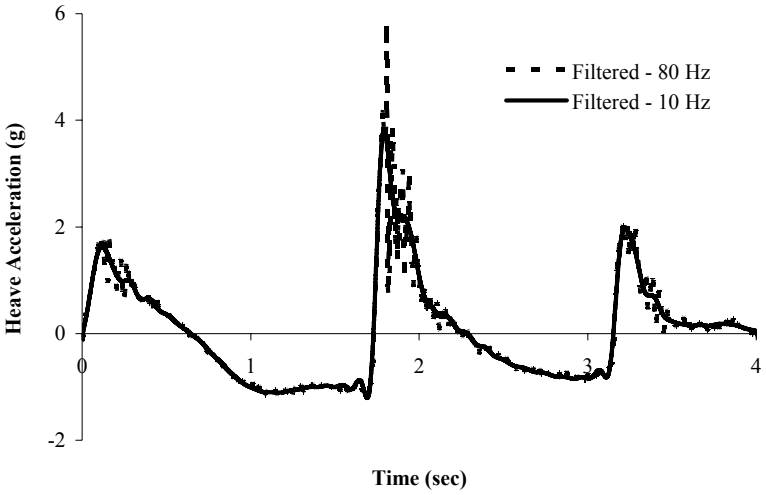

Figure 2. Isolation of data into single impacts using the 10 Hz filtered data to find the zero-crossings.

For each impact the acceleration profiles of the deck, the isolated seat and the non-isolated seats are extracted based on their individual zero-crossings as shown in Figure 3. Various injury criteria are evaluated for each impact event. These injury criteria are the peak acceleration of the seat pad, the Dynamic Response Index (DRI), and the Spinal Stress Dose ($S_{ed}(8)$) which is the 8 hour normalized daily equivalent static compression dose from ISO 2631 Part 5 (2003). The deck peak acceleration is binned in discrete acceleration ranges of 0.25 g, and the injury criteria are averaged within the bins to produce a single value within each bin. Impacts below 0.5 g were excluded from the single impact event analysis assuming impact injuries were unlikely at this level.

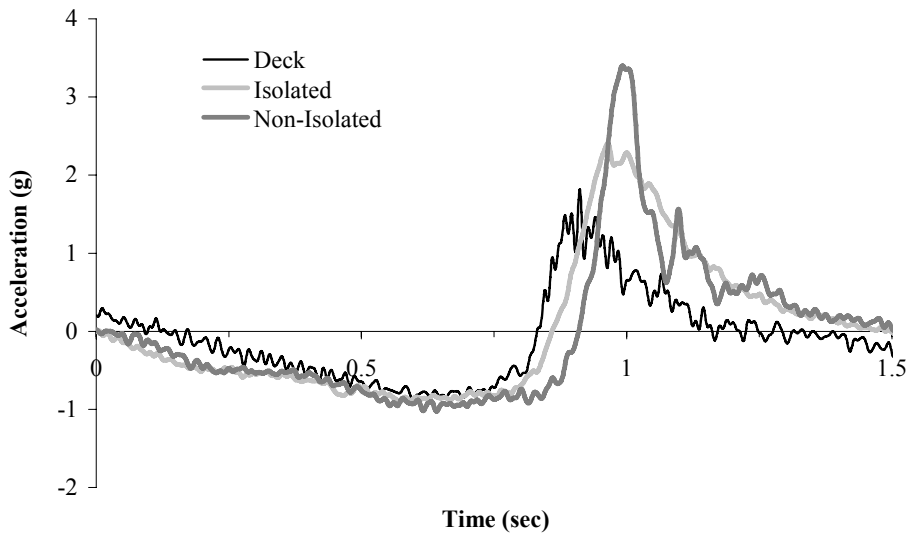

Figure 3. Individual impact event showing the time history of the acceleration profile of the deck and the isolated and non-isolated seats.

NUMERICAL MODELING: A Madymo lumped mass human model (version 6.0) was developed in this study for the seated occupant of a non-isolated seat on the MK V SOC. The model is a lumped mass simulation of a 50th percentile male (Happee *et al.* 2000, Happee *et al.* 1998) in a seated posture as shown in Figure 4. The underlying Madymo human model is intended as an omni-directional model of the human body for impact studies. Most of the skeletal structure is defined as rigid bodies connected by joints. Flexible bodies are used in the rib cage structure to allow appropriate thoracic deformation, and the exterior surface is implemented as a contact surface. A multidimensional contact force has been defined for each connected lumped mass. These joint force properties have been designed using nonlinear stiffness functions. The effect of energy dissipation has been modeled using damping or hysteresis (Happee *et al.* 2000). The spinal masses in this model are of particular importance and are shown in Figure 5. The basic model has been validated using frontal impact sled tests on volunteers, frontal and lateral impactor tests using cadavers, impactor tests in various body regions including the upper extremities, lateral cadaver sled tests, and rearward volunteer and cadaver impact tests (Happee *et al.* 2000).

Numerical modeling was performed to compare the Madymo simulation results with sea trial data to allow comparison with internal human injury criteria such as ISO 2631 Part 5 and to investigate design, countermeasures, postures and restraint concepts. For all cases, the model was initially seated and equilibrated in a single g environment. Modeled variables include the effect of occupant restraints and a comparison of Madymo and ISO 2631 Part 5 dynamics on ISO 2631 Part 5 injury calculations for impacts inside and outside of its design range.

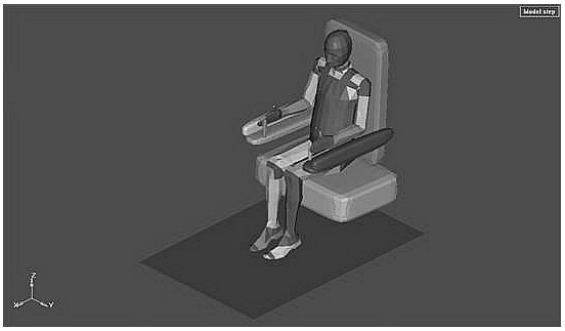

Figure 4. Madymo human model in a non-isolated seat.

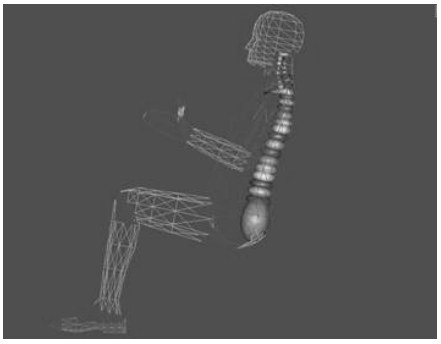

Figure 5. Madymo human model (emphasis on spinal masses).

Experimental dynamics data is generally used to validate numerical models over a range of input conditions. For the Madymo seated human model, validation datasets were selected from experimental data taken using instrumented volunteers in a Mk V SOC under way. The data includes six degree of freedom dynamics of the hip and head of selected occupants and six degree of freedom data from the deck of the craft. Four typical impact profiles derived from dynamics data from an earlier January 2002 set of sea trials (Peterson, 2003) were chosen to validate the Madymo model. Of these, two are within the range of validation of ISO 2631 Part 5 and two are outside. The datasets are characterized as a high vertical acceleration (~10 g peak acceleration), shown in Figure 6, a moderate vertical acceleration (~4 g peak acceleration), a small vertical acceleration (~2 g peak acceleration), and a high acceleration with large rotation (~10 g peak acceleration).

Once validated, the model is used to predict human responses based on given impact conditions. Injuries can be predicted based on the forces, moments, and acceleration values within the human response model. When these values surpass injury threshold values, an injury is presumed to occur. The model can also be used to compare different conditions such as the occupant being belted versus unbelted, and to assess the validity of different dynamic models, such as the ISO 2631 Part 5 model. This paper examines the ISO 2631 Part 5 dynamics model for impacts in and outside of its design range.

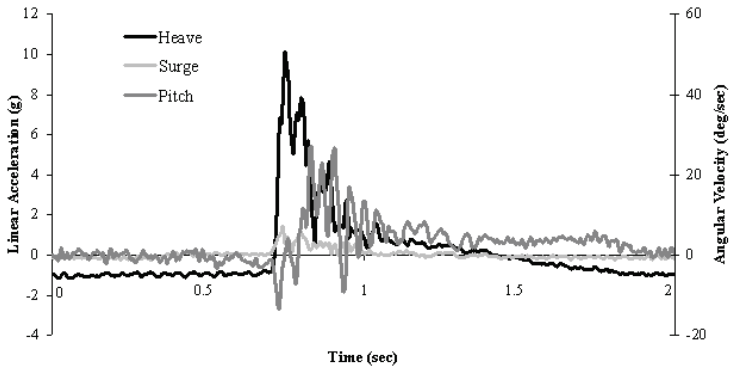

Figure 6. Linear and rotational acceleration time histories for large heave deck input for Madymo validation.

RESULTS

SEA TRIAL DATA: Table 1 includes the results of the conventional injury criteria used by the naval architecture community and the proposed alternative injury criteria used in the analysis of the October 2003 dataset. Further, the results of the conventional and alternative injury criteria applied to the isolated seat in the January 2003 dataset are given in Table 2. The ride produced while on the isolated seat in this sea trial was said to be at an acceptable level for the sea conditions (sea state 3) by eight experienced operators. In contrast, the ride in the existing non-isolated seats was deemed not acceptable at the same sea conditions. Without long term epidemiology to assess the presence of injuries in the operators from use of either seat, the values of the injury criteria represent threshold values that could represent tolerable levels to human occupants.

The peak acceleration and DRI require single impacts for evaluation. The ISO-2631 Part 5 spinal stress dose is also considered using a single impact analysis. After evaluation of the single impacts, the injury criterion values obtained are subsequently binned by deck peak acceleration to produce a histogram that shows the general trend of the injury criterion with respect to the deck peak acceleration. The peak acceleration and DRI are evaluated from the heave acceleration of the seat pad, and the ISO 2631 Part 5 spinal stress dose is evaluated using all three directional components at the seat pad.

In all of the datasets, it is clear that the RMS value does not discriminate between the isolated and the rigid seat. The RMS is not a good measure of discrete impacts over long duration waveforms. The other measures including the ISO 2631 P1 RMS, VDV, 1/10 highest DRI, ISO-2631 Part 5 and bandwidth-limited PSD show good discrimination between the seats. Only DRI and ISO-2631 Part 5 are biomechanically based on injury, and only ISO-2631 Part 5 has substantial validation for repeated impacts.

	30 Second Interval			45 Second Interval			Entire Data Set		
Criteria	**Rigid**	**Isolated**	**% Impr**	**Rigid**	**Isolated**	**% Impr**	**Rigid**	**Isolated**	**% Impr**
Traditional									
RMS	0.62	0.63	- 1.6%	0.76	0.75	1.3%	0.38	0.35	8.6%
ISO 2631 P1 RMS	3.01	2.19	27.2%	4.15	2.58	37.8%	1.41	0.94	33.3%
Alternative									
ISO 2631 P1 VDV	9.22	6.24	32.3%	11.80	7.02	40.5%	4.97	2.91	41.4%
$1/10^{th}$ DRI	3.0	2.3	23.3%	4.7	3.4	27.7%	4.7	3.0	36.2%
ISO 2631 P5 S_{ed}	7.93	6.58	17.0%	11.0	8.35	24.1%	6.22	4.18	32.8%
BW-Limited PSD	-28.1 db	-34.3 db	22.1%	-26.0 db	-33.5 db	28.8%	-36.4 db	-45.0 db	23.6%

Table 1. Comparison of the non-isolated (rigid) and isolated seat in the October 2003 sea trial using conventional and alternative analyses.

Criteria	**January Results**
Traditional	
RMS	0.47
ISO 2631 P1 ('85) RMS	0.92
Alternative	
ISO 2631 P1 ('97) VDV	3.80
ISO 2631 P5 Sed (8 hr)	5.87
BW-Limited PSD	-44.4 db

Table 2. Results of conventional and alternative analysis for the isolated seat in the January 2003 sea trials.

The histogram for the peak acceleration for the October dataset is given in Figure 7. The advantage of the isolated seat for the largest number of impacts above 0.5g deck impact acceleration is clear within each bin. The total weighted percent increase of the isolated seat over the non-isolated seat is 18.7%. Both the isolated and the

non-isolated seats show higher acceleration values during an impact event leading to higher peak acceleration values compared to the deck. The trends of the DRI (Figure 8) and ISO 2631 Part 5 (Figure 9) histograms are very similar to the peak acceleration histogram, giving similar weighted increases of 18.9% and 18.2% respectively.

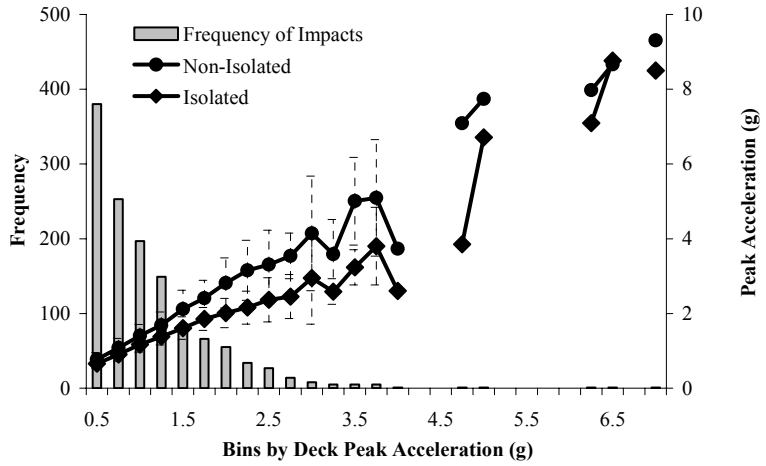

Figure 7. Histogram relating the peak acceleration of individual impacts seen at the seat pad of both the non-isolated and isolated seats to the peak acceleration of the deck (October 2003 dataset)

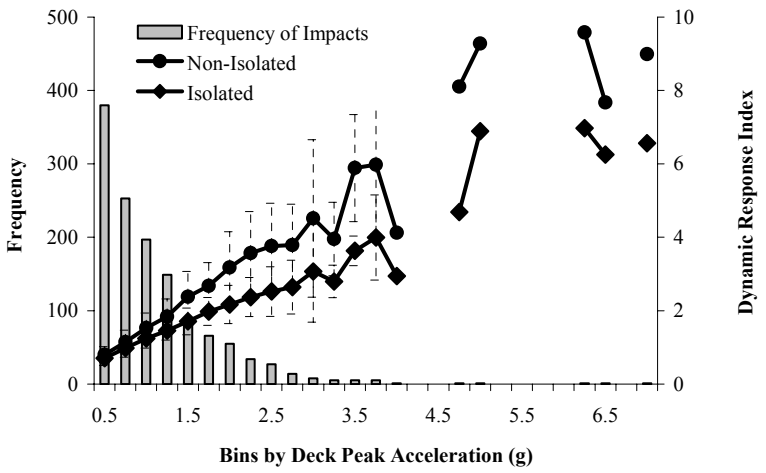

Figure 8. Histogram relating the dynamic response index of individual impacts of both the non-isolated and isolated seats to the peak acceleration of the deck (October 2003 dataset)

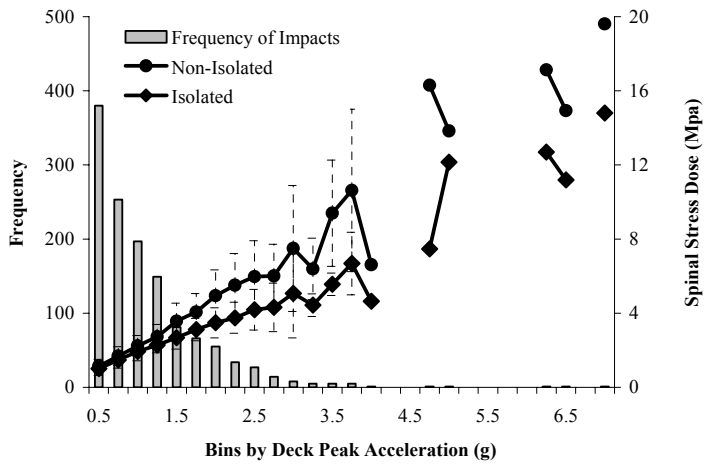

Figure 9. Histogram relating the Spinal Stress Dose of individual impacts of both the non-isolated and the isolated seats to the peak acceleration of the deck (October 2003 dataset)

In Figure 10, the peak acceleration from the isolated seat of the January dataset yields a similar histogram to that seen with the isolated seat from the October dataset though the January dataset contains a large number of impacts per bin. So, though the sample sizes are different, the acceleration peak results from the October dataset are quantitatively similar to those from the January dataset.

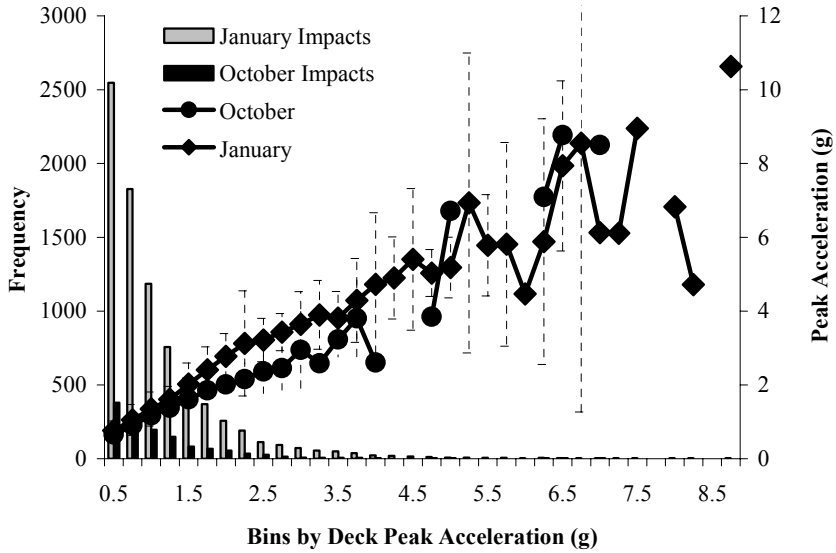

Figure 10. Histogram relating the peak acceleration of individual impacts at the seat pad of the isolated seat of the January and October datasets to the peak acceleration of the deck.

NUMERICAL MODELING: The non-isolated seat was modeled using a human model in Madymo. The Madymo calculation was validated using four cases representative of a range of impacts seen in the sea trials. These cases are a ~2 g vertically dominated impact, a ~4 g vertically dominated impact, a ~10 g vertically dominated impact and a ~10 g impact with the largest rotational acceleration seen in the available data. For each case, the predicted acceleration in the lumbar spine/pelvis is compared to that of the experimental data, discussed above, taken from volunteer subjects under way in a Mk V high speed craft.

For the large heave (10 g) validation dataset, the pelvis center of gravity resultant acceleration is shown in Figure 11. The experimental data and Madymo simulation show very similar acceleration peaks and phasing. The peak amplitudes are comparable with approximately 115 m/s^2 for the simulation and approximately 117 m/s^2 for the high speed craft occupant data. The other three validation impacts show similarly good correspondence between simulation and boat occupant data for both pelvis and head accelerations.

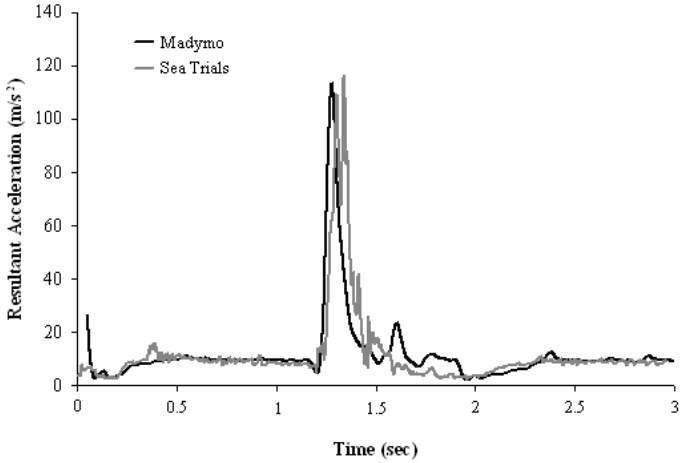

Figure 11 Large heave validation - Pelvis center of gravity resultant acceleration.

Effect of Restraints – Madymo Calculations: As the use of restraints in high speed planing craft is sporadic and the effect of the substantial head supported mass (helmet, communications equipment, and night vision goggles) is unknown, the effect of restraints and head supported mass was explored for three restraint conditions. The

first is a baseline condition of no restraint. The second is a lap belt restraint. The third is a harness restraint in which the occupant wears a helmet with 1.75 kg mass. The helmet was added to the harness restraint to investigate a worst-case condition for neck loading. For the belt and harness restraints, a dynamically loaded finite element belt is pulled across the body to simulate a taut restraint.

Little difference is seen in lumbar force and acceleration values with the addition of a restraint condition. The effect of restraint conditions is most pronounced on head and neck dynamics. Head center of gravity acceleration for the three restraint conditions is shown in Figure 12. The lap belt increases the head center of gravity acceleration about 10% relative to the baseline case. Adding helmet mass tends to lower the head accelerations because of increased mass above the neck. The addition of restraints increases the shear load, axial load, and flexion/extension moments. It was found that the shear force on the neck nearly doubles from no restraint to harness restraint with added helmet mass. However, these increases are small compared with impact force and moment reference values (c.f. Bass, 2004) and should not restrict restraint use.

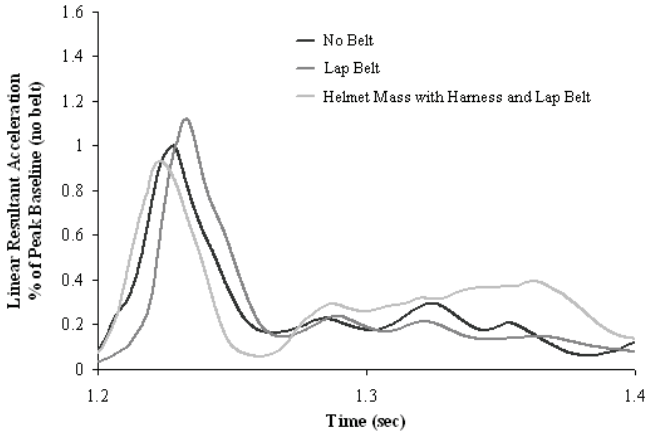

Figure 12 Head linear resultant acceleration relative to baseline simulation for various restraint conditions with an emphasis on the time history around the peak acceleration.

ISO 2631 Part 5 Spinal Model vs. Madymo Calculation: The heave direction (vertical) spinal dynamics neural net model within ISO 2631 Part 5 was trained on seat pad impulses and responses that ranged from approximately – 4 g to +4 g. As a recursive neural net model, the physical meaning of the 99 coefficients that comprise the ISO 2631 Part 5 heave axis biomechanics model is uncertain. So, it is instructive to compare the lumbar dynamics predictions of the Madymo model, relative to those of the ISO 2631 Part 5, based on measured seat pad accelerations that exceed +/- 4 g.

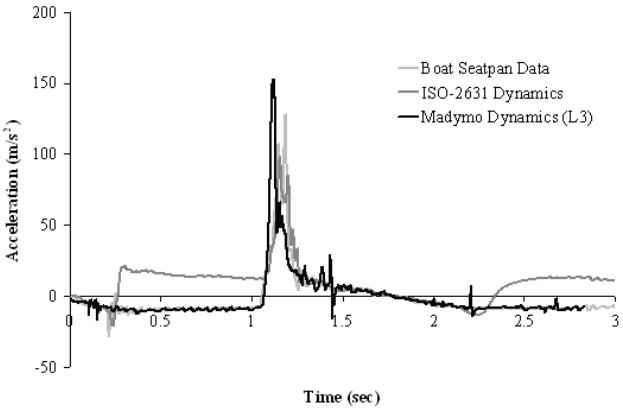

Figure 13 Madymo model lumbar resultant acceleration plotted against that predicted by ISO 2631 Part 5 dynamics. Boat seat pad data included for comparison.

The unfiltered results using both models with the large heave axis dataset used for validation studies are shown in Figure 13. In this figure, the boat seat pad data is provided for comparison. A substantial difference is seen between the peak acceleration at the L4 vertebral body for the Madymo model relative to that of the ISO 2631 Part 5 lumbar biomechanics model. The peak acceleration at the L4 position predicted by Madymo is approximately 150 m/sec^2, while that predicted by the ISO 2631 Part 5 is 100 m/sec^2. This result suggests the

possible need for replacing the ISO-2631 Part 5 neural net model with a model based on the Madymo simulation to more accurately predict lumbar dynamics associated with large high speed craft loading.

DISCUSSION

This investigation is not without limitation because controlled sea tests, during which injuries are unlikely, cannot provide sufficient statistical injury data with which to fully evaluate relative injury model performance. That is the role of an epidemiological investigation. Further, the results are interpreted based primarily on operator feedback related to comfort. For example, the investigated standards are expected to show improvement in injury assessment values for an isolated seat relative to a non-isolated seat, but this does not necessarily indicate reduced probability of spine injury. Positive sensitivity of a candidate models to two craft-seat configurations is viewed as a necessary but not sufficient condition for indication of the particular model for use as an impact injury design rule. Thus, the results of this performance assessment that is based on specific craft-seat sea test measurements must be tempered with the body of impact biomechanics knowledge and experience.

The injury criteria were evaluated based on applicability, background in biomechanics (particularly the lumbar spine), and ability to discriminate between the isolated seat and the non-isolated seat. The RMS was the only injury criterion that was unable to distinguish the difference between the two seats. All the other criteria were able to discriminate between seating conditions with ISO 2631 Part 5 and the PSD showing the least amount of high-level improvement and ISO 2631 Part 1 VDV showing the most improvement in the performance of the isolated seat over the non-isolated seat. From the analysis, it cannot be determined whether ISO 2631 Part 5 and the PSD is underestimating the improvement or if ISO Part 1 is overestimating the improvement. The basis of the injury criteria and the applicability must be examined.

The basic RMS and ISO 2631 Part 1 from 1985 are vibration methods of analysis, and, along with the PSD, they give a measure of the power in the acceleration profile. The RMS of a signal does not account for human spine dynamics, nor does it accurately account for single severe events within an acceleration profile (Payne 1978). The 1985 ISO 2631 Part 1 standard was designed to predict fatigue and discomfort in the presence of vibration, and its ability to predict injury from severe repeated impacts has been questioned (Village *et al. 1*995, Bass *et al.* 2003). ISO 2631 Part 1 from 1997 uses a VDV value, which gives more emphasis on the higher peaks within an acceleration profile, for acceleration profiles with high Crest factors. The peak acceleration is a measure of the shape of the waveform for each impact within the acceleration profile. While a waveform with larger acceleration would more likely lead to injury, it is not necessarily the case.

One of the difficulties in the field of planing boat impacts is that the 'traditional criteria', as discussed above, that are used to assess injuries are often not based on injury criteria. For example, RMS vibration in high speed boat impact has not been associated or correlated with injuries in the biomechanics literature. In a similar vein, ISO-2631 Part 1 is based on discomfort boundaries, not injury boundaries and the PSD has been associated with discomfort, not injury. However, most of these have been used as injury indicators in the design of craft. There are, however, two existing spinal injury criteria that may be appropriate for repeated vertically dominated impacts at levels, DRI and ISO 2631 Part 5.

The DRI and ISO 2631 Part 5 are the only injury criteria within those examined that are based on the biomechanics of the human spine. The DRI has shortcomings when used to predict spinal injuries in high speed planing craft because it does not account for and has not been validated for repetitive loadings. Spinal injuries occurring during high speed planing craft operation are often the result of many impacts occurring over an extended period of time. The biomechanics of the DRI is based on compressive spinal fracture and columnar spinal loadings, while high speed planing craft injuries are usually related to intervertebral disc injuries (Bass *et al.* 2003). . It is also important to note that for reasonable assumptions of boat use during operator careers that injury reference values computed ISO 2631 Part 5 predict large risk of injury ($R > 1.2$ for ISO 2631 Part 5).

ISO 2631 Part 5 is likely the best injury criterion available to assess spinal injury and fatigue on high speed planing craft (Bass *et al.* 2004). ISO 2631 Part 5 includes a superior spine model relative to the DRI, and is the only injury criterion discussed that incorporates the surge and sway accelerations along with the heave acceleration. The standard was also developed for evaluating repeated impacts; however, it is not validated for impacts greater than 4 g. The data analyzed has 119 impacts at or above the 4g level. The standard assumes the occupant is securely belted; however there is evidence that lap belts are generally not used in the craft. The ISO 2631 Part 5 model also does not account for spinal rotational modes and moments that may increase the occurrence of lumbar spine injury (Bass *et al.* 2003).

The Madymo numerical model has indicated that the neural network may not perform well outside of its design range of +/- 4 g. The four different representative impact conditions were numerically modeled within Madymo to produce an acceleration response in the L4 lumbar spine. These responses were compared to the respective response of the ISO 2631 Part 5 dynamics model. The Madymo model and the ISO 2631 Part 5 dynamics model correlated well for the two impacts within the +/- 4 g range. For the two impacts outside of the

design range, ISO 2631 Part 5 produced much smaller peak acceleration values, one of which is shown in Figure 13. This suggests that ISO 2631 Part 5 may not be valid outside of its design range.

There are two likely sources for the differences in the Madymo and ISO 2631 Part 5 dynamics models for impacts with peak accelerations above 4 g. First, the ISO 2631 Part 5 model assumes that the occupant is always in contact with the seat. This may not be generally true for planing boat occupants and is not true for this acceleration profile. Second, the amplitude of the acceleration input is well outside the input data used to train the neural network.

ISO 2631 Part 5 assumes the occupant is belted. There is evidence that this is not the case during typical operations of the MK V SOC. Video data of MK V occupants underway suggest that occupants may separate up to several inches from the seat during the typical free fall before a large impact when the occupant is unbelted. From Figure 14 it is seen that the hip acceleration history predicted by Madymo is similar to that of the seat pad for belted occupants. Further, it is believed that belts should be used in isolated seats because the differential velocity that develops from this initial separation between unbelted occupants and the seat pad may be detrimental to the proper operation of the isolator.

With basic career information such as starting age, years of exposure, and days of exposure per year, an R-value from ISO 2631 Part 5 can be calculated and referenced to injury prediction thresholds given in the standard. However, the high injury risk value of 1.2 set in the standard is much lower than has previously been accepted in planing craft occupations, even with shock isolated seats. This standard, as currently specified, may be too restrictive to be used practically in the design of new high speed planing craft and the evaluation of current craft. Anecdotal information from the crew seated in the shock isolated seats suggests such a ride is tolerable and provides an acceptable tolerance boundary. Based on the January 2003 sea trials an ISO-2631 Part 5 $S_{ed}(8)$ value of 5.87, corresponding to R = 3 (assuming a career of 52 days a year of impacts similar to the days of the January 2003 sea trials and a career of 20 years from age 25) is an acceptable tolerance boundary. This tolerance is substantially higher than that given in the standard of R = 0.8 for a low risk of injury and R = 1.2 for a high risk of injury.

CONCLUSIONS

ISO 2631 Part 5 is considered the best injury prediction criterion available at this time because of its development for use in repeated impact situations and its basis in the biomechanics of the spine (c.f. Bass *et al.* 2004). ISO 2631 Part 5 discriminates well between the isolated seat and the non-isolated seat. However, using reasonable military career assumptions, it appears that the injury reference values given in ISO 2631 Part 5 are too low for planing boat operators. Mk 5 craft have been operating for years with rigid seats in conditions that suggest injury assessment values substantially higher than R = 1.2 for ISO-2631 Part 5. So, though many operators have been injured, not all are injured, even with rigid seats. Anecdotal information from the crew seated in the shock isolated seats suggest that rides with much higher injury values than R = 1.2, such as the January 2003 sea trial, are acceptable. The use of the usual ISO 2631 Part 5 injury assessment value may result in substantial limitations of high speed planing craft operations; it is recommended that the injury reference value be increased to reflect the increased fitness level of the military operators.

ISO 2631 Part 5 is acceptable as an interim injury evaluation tool for high speed craft design contractors. The contractor would either develop a model of the suspended seat with a seat cushion and would process deck accelerations with this model, or the contractor could simply outfit accelerometers on the seat cushion during sea trials, similar to the tests evaluated in this paper. The acceleration time history obtained would be used to produce a value for the ISO 2631 Part 5 spinal stress dose, which can then be compared to a specified injury limit. If this limit is exceeded the contractor would have to modify either the seat or the hullform until the Spinal Stress Dose obtained is under the specified injury limit. Investigators have proposed developing an improvement over ISO 2631 Part 5, in which the nonlinear neural network spine model is improved to reflect the larger impacts associated with planing boats (Bass 2002).

This study included the development of a numerical model of a human in Madymo to simulate a seated occupant of a Mk V Special Operations Craft. Validation of this model was based on experimental data taken from volunteer subjects under way in a Mk V. The numerical results were found to be in good qualitative and quantitative agreement with the sea trial validation data. However, the acceleration peaks from the ISO 2631 Part 5 dynamics model were lower than the Madymo numerical results for impacts outside of the ISO 2631 Part 5 design range. Thus, the ISO 2631 Part 5 dynamics model has the potential to substantially under-predict acceleration time histories for large amplitude impacts. The ISO 2631 Part 5 biomechanics model may not be valid outside the range of +/- 4 g and should be used outside that range with caution.

The Madymo model also predicted hip acceleration profiles that were very similar to the acceleration profiles seen at the seat pad for the four impacts tested. This suggests that ISO 2631 Part 5 can be used with hip acceleration data instead of seat pad acceleration data. The acceleration would be measured at the human, and thus it is unnecessary to assume the occupant is belted.

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