INTERNATIONAL SYMPOSIUM ON NAVAL MEDICINE 2018

# HUMAN IMPACT EXPOSURE
# ONBOARD HIGH-SPEED BOATS
# WHAT IS DANGEROUS?
# AN INTERNATIONAL MULTI-AGENCY STUDY

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## ABSTRACT

Operating high-speed boats is dangerous. Impact induced injuries are sometimes severe and cause permanent disabilities. It is however NOT known which levels of impacts are dangerous and which are safe. The purpose of this study is to establish what levels and what characteristics of impact exposure cause injuries. To prevent injuries and to reduce fatigue onboard high-speed boats, this knowledge is crucial. The slamming-impact exposure causes more injuries per workday than seen in most other peacetime work[12]. Current standards and regulations lack relevance. They are based on mean values of vibrations, and they state exposure limit values impossible to comply with. To establish the connection between impact exposure and the risks of injury, a prospective study will measure and compare human impact exposure to occurrence and development of pain indicating the risk of injury.

**Keywords:** human impact exposure; high-speed boats; injuries; injury prevention

Photo Johan Ullman, Coxswain Carl Magnus Ullman

## 1. INTRODUCTION

**Human impact exposure** on board high-speed boats causes pain, physical fatigue and severe injuries. With increasing numbers of high-speed boats used in professional operations, these problems seem to increase in both numbers and severity all around the world.

**Agencies in several countries**, operating high-speed boats, have expressed a wish to be able to find out how severe impacts their personnel is being exposed to, and to what levels are dangerous. Many also wonder **what is relevant to measure and how to measure and how to analyse the data**.

**Current rules** regulating dangerous exposure are irrelevant for exposure to impacts onboard high-speed boats. They are all based on vibration standards, quantifying the effect on comfort, by exposure to continuous vibration. E.g. the EU directive, 2002/44/EC, which is legally binding in many countries lays **significant but irrelevant restrictions on marine operations**.

Vibration standards are based on mean values of vibration and not relevant for exposure to impact.

**It is still unknown which levels and characteristics of impacts are dangerous and which are safe**. To find out what is dangerous it is necessary to conduct a prospective longitudinal study on humans being subjected to the relevant actual exposure.

**A new way of quantifying impact exposure is needed.** A new measuring unit needs to be defined, related to the forces challenging anatomical structures subjected to impact. Data resulting from the study may lay the basis for a new measuring unit **correlated to injury risk** and based on the characteristics of impacts.

**Lab testing cannot be used to evaluate risks** of injury, nor effectiveness of impact mitigation seats. Exposure to whole body impacts has significant physiological effects, which cannot be tested in a lab.

**In order to gather relevant data**, it is necessary to monitor a large number of subjects, over a sufficient period of time, for exposure and a physiologic response indicating risk of injury.
To achieve these volumes, **a number of agencies** operating high-speed boats, in all kinds of missions and sea states, around the world will join effort.

**The overall purpose** of the study is to establish the knowledge needed **to protect people**, from boat-slamming impact-induced injures, by establishing the appropriate limits for human impact exposure.

## 2. BACKGROUND

The EU-directive 2002/44/EC[3] is in some countries applied to set limits for impact exposure. This directive is based on the ISO-standard 2631:1[4], which has limits defined for exposure to continuous vibration, but never was intended to apply for exposure to impacts. The ISO-standard is based on mean values of continuous vibration and contains advanced algorithms quantifying energy transferred to the human body as vibration.

Existing rules and standards are hence not relevant for exposure to impacts onboard high-speed boats. The EU directive 2002/44/EC, Specifies "*Minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration)*", (Sic!).
Its defined exposure limits, are legally binding, but impossible to comply with, while performing normal SAR, search and rescue or military training. The exposure limits are defined in terms of mean vibration values, not in any terms related to the forces arising from exposure to severe impacts.

So, without protecting people from the most dangerous injuries, this legislation restricts normal operations. In most countries, this directive is not taken seriously. In some much effort is focused on trying to comply with it, primarily by reducing exposure to vibration.

There is a consensus in the scientific community that the currently applied vibration standards and directives are not relevant for quantifying the risks of injury, caused by exposure to impact.[5],[6]

As there is no proven correlation between exposure to mean values of vibration and risk of acute injury, this use of the EU directive can potentially increase the risks of injuries caused by impacts.[7]

## 2.1 LABORATORY TESTING CANNOT GIVE THE NECESSARY INFORMATION

Lab testing cannot give the relevant, necessary information. Realistic slamming impact exposure cannot be relevantly simulated in a lab test. Real impact exposure is stochastic and multi-directional, reaching levels up to nearly 20g. For ethical reasons, humans cannot be exposed in a lab to the relevant impact levels, where injuries may occur.

Lab testing methods have been developed and suggested to replace testing in real conditions at sea.[8] Suggested lab test methods have severe limitations, making their results irrelevant for assessing risks of injury. These limitations include; testing for impact and motion in only one single axis, while the real dangerous exposure is multidirectional and stochastic, with significant variation in rise times, durations, energy content and slam periods. Lab testing is also done only to up to 10g peak levels, whereas the most severe, real impacts at sea can reach nearly 20g.[9]

It is shown also that some suspension seats and also standing postures can amplify and actually multiply the impacts on the humans up to more than three times.

Lab trials cannot simulate the human physiologic response, with muscular reflexes. They cannot assess the effects of impact on the human posture, which is crucial for the risk of injury. Lab trials can also not test the effect of exposure to lateral forces, which are more dangerous than the pure vertical forces. Still measured impact data is reported in units such as Shock Response Spectrum SRS, Vibration Dose Value VDV, Daily Equivalent Static Compressive Dose, Normalised for 8 hours (Sed(8)), created with advanced algorithms, based on assumptions regarding dynamic properties of segments of human spines.

Lab-testing can give no information about what kinds and levels of impact entail risks of injury.

AS the VDV and Sed8 etc. are defined based on experiments made on cadaver segments of lumbar spines fixed normal positions[10] they should not be used for assessing risks injuries caused by stochastic multidirectional impacts. These impacts when causing injury normally also cause significant uncontrolled deflection of the spine. The dynamic and elastic properties of a severely deflected spine are very different from those of spine in its normal “ balanced ” position. The more a spine is rotated, or ventriflexed, the stiffer it gets and the more dorsiflexed, the less stable it gets. All extreme positions are generally believed to increase risks of injury. No severe slamming induced injury has been reported where impact forces are believed to have caused spinal injuries, without having caused deflection of the spine.

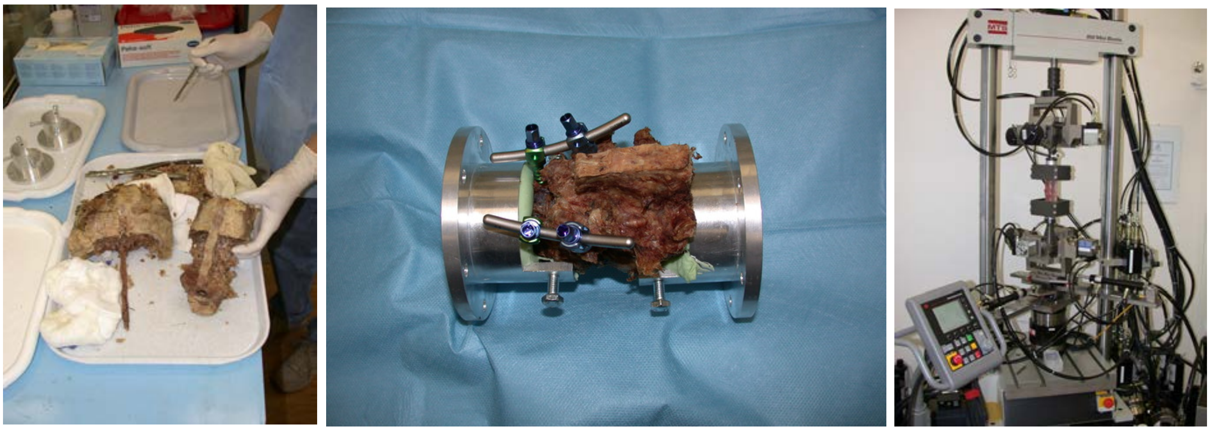

Figure 1 Illustrates the preparation of a human cadaver spine segment and an apparatus exposing this to cyclic compressions. Based on results from this kind of exposure, theoretical models have been created, defining the elastic and dynamics properties of the human body. Based on these assumptions measurement units have defined. These are today used to assess risks of injury on living humans exposed to stochastic multidirectional impacts. The relevance of these assumptions and measurement units are now being challenged.

## 2.2 FILTERING OF IMPACT DATA COMPROMISES BIOLOGICAL RELEVANCE

By filtering out the frequency content above 20 Hz in measured impact data, results from lab testing can lose even more relevance. Historically, filtering was necessary due to limitations of the available hardware and software. With significantly increased processing power and storage media, filtering is no longer required. Justifications for the low-pass filtering include cost efficiency and reduction of noise and structural vibrations, as well as making simulation in the lab easier, when not having to replicate the true characteristics of real impacts. With this hard, Low-Pass filtering, energy with higher frequency content, potentially highly relevant for causing structural failure in hard tissue, fractures, can be hidden away. Low pass filtering changes the peak acceleration values. Also, rise-times of the impacts cannot be identified.

To understand why rise-time is relevant for the physiological response and the risk of injury, the following example with a fighter-jet pilot is relevant. Going into a sharp turn, acceleration (g-forces) on the platform and pilot increase gradually, during almost a second, up to 7g or even above. This causes significant physiologic effects, but no structural anatomical failure. In wave-slam events, acceleration can go from 0g to 7g in a few milliseconds. There are obvious reasons to believe that this is more challenging to anatomic structures. Sudden experience of pain is one significant reason.

A special case of uncontrolled movement is the deflection of the cervical spine caused by head jolts. Anecdotal information suggests that standing subjects exposed to slamming report relatively more neck injuries than low spinal injuries. These, just like traditional whiplash injuries, often give severe and long-lasting problems, with pain and impaired function, often without any objective findings in currently available diagnostics, such as X-ray, CT or MRI.

Claims that energy content above 20 Hz in the impacts lack relevance for these injuries remain unsubstantiated.

## 2.3 RISKS OF INJURY

The risk of injury - structural failure in anatomical structures - depends on the forces acting on the human body, and these forces depend on the amount of energy transferred to the human body by the impacts. While injuries occur in all parts of the body, most of the severe and permanent injuries affect the spine. The risk of injury depends on several factors related to impact forces.

Impacts containing horizontal forces are more dangerous than purely vertical impacts. Oblique and lateral impacts cause not only compression forces, but also shear forces, bending forces, rotational forces and unpredictable and uncontrolled defections of the spine. A contributing cause of cervical spine injuries is the head jolts, seen both in seated and not least in standing subjects. Documented injuries include vertebral fractures, ranging from wedge-shaped compression to complete shattering of vertebrae, disk ruptures, traumatic olisthesis and ligament ruptures. Some impact-induced injuries result in permanent disabilities; paralyses and disabling chronic pain conditions.

Figure 2 Showing a vertebra shattered and fragmented by a slamming impact onboard a high-speed boat. This kind of injury alters the geometry and may result in neurological damage and permanent disability.

When stabilising structures are damaged, neurological symptoms may occur instantly or develop over time, and also come as results of a repeated impact. In any case pain is present as indicator of acute injury, and acute pain should be considered as a sign of possible injury - damage to anatomical structures. Pain can be present without injury, but acute injuries rarely occur without causing pain.

## 2.4 IMPACT EXPOSURE HAS MEASURABLE PHYSIOLOGICAL EFFECTS

A study of human impact exposure, comparing suspensions seats to fixed seats,[11] showed twice the number of impacts and three times the peak impacts levels when using the fixed seats.
After 3 hours of exposure at sea, the physical performance, measured by shuttle run test, was reduced by more than 30% in the more exposed group.

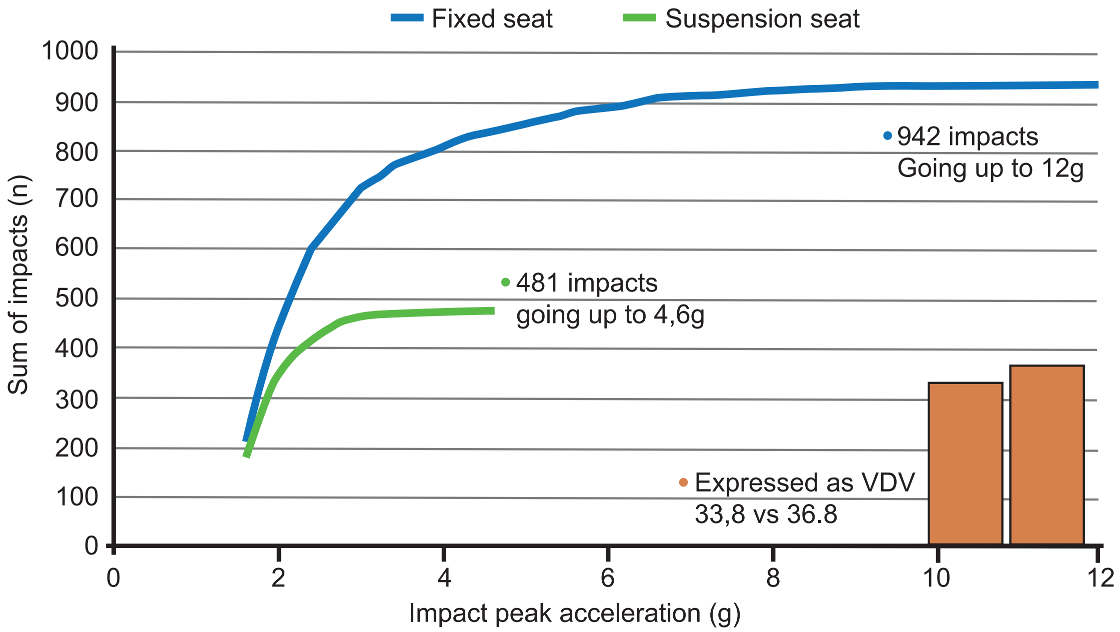

Figure 3 This graph shows significant difference impact exposure onboard two boat of the same kind, fitted with different types of seats, run side by side over three hours. Measured as peak acceleration plotted as (g), 9.81 m/s2, the number of impacts was double (481 vs 942 impacts), and the difference in amplitude of the highest peaks was 2.6 times higher (4.6 g vs 12g) for the fixed seats. The overlaid blue columns illustrate the same data measured as VDV, showing an insignificant difference in exposure, just 9% (33.8 vs 36.8) [11]

Impact exposure differed significantly between the two groups.
Those in the fixed seats received twice as many impacts as those in the suspension seats.
The impacts were also almost three times as high on the fixed seats as on the suspension seats. This difference in exposure correlates to the physiological effect on physical fatigue.

However, this same exposure data, processed and presented as VDV, shows no significant difference, 33.8 versus 36.8.
Data, presented as Crest factor, showed a 50% reduction (of Crest factor) on the suspension seats vs hull exposure, and a slight increase on fixed seats. Crest factor, however, is not an absolute-, but a relative measure, comparing the highest peak values to the mean of all peaks and thus does not indicating injury risks.

Many types of suspension seats, often called “shock mitigation” seats have been shown to increase impact levels on humans as compared to the impact on the hulls. This is normally caused by a phenomenon called bottoming out, meaning that a suspension reaches end of stroke and comes an abrupt stop. Such events have caused severe injuries and overboard ejections. Amplification can also be caused by single-direction suspensions locking up when exposed to impacts containing oblique or lateral forces.

Even standing positions onboard H-S boat have been shown to amplify human impact exposure,[12] potentially up to more than three times higher than the impacts on the hulls. The reason seems to be that impacts, taken on straight or almost straight legs, occur after the downward movement of the hull has stopped, while the human is still accelerating in free fall until the heels impact with the deck. Standing seems especially challenging for the neck, as cervical injuries reported from boats, fitted with standing bolsters seem to dominate over lumbar injuries. This is still an anecdotal observation.

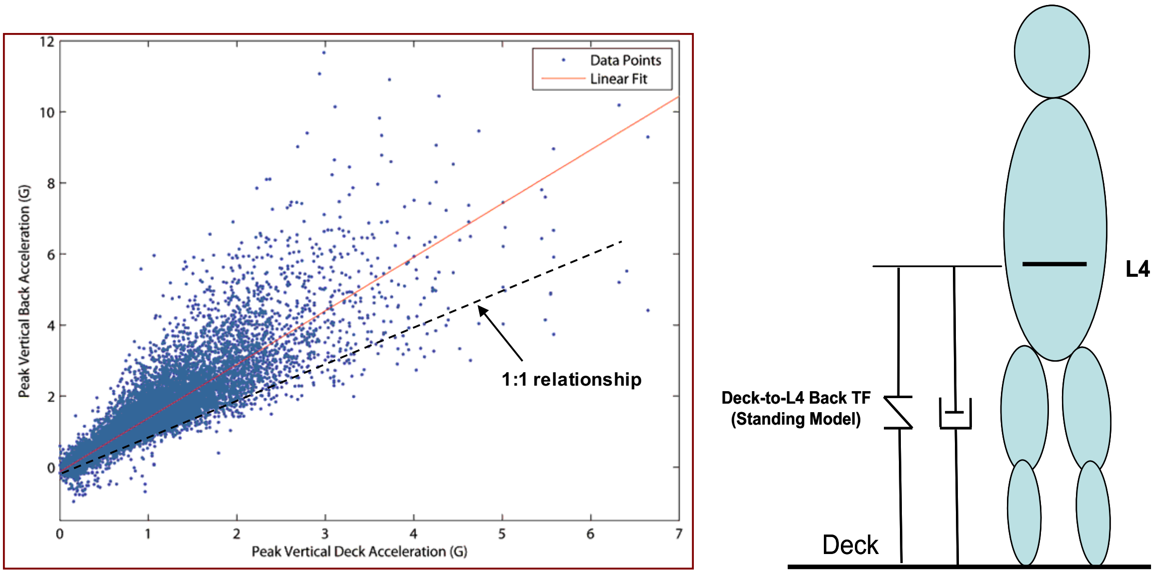

Figure 4 Deck-to-L4 Standing Transfer Function. The graph created using deck and back data from sea tests of NSW 11M RIB, showing an average of 50% amplification and a maximum 4 times higher impacts on the human than on the hull/deck.

## 3. METHODS

The research method is designed to record impact exposure on both hulls and on humans onboard high-speed boats operating in their real sea conditions. Accelerations will be recorded as unfiltered, raw data. This will allow for analysis of all the characteristics of impacts, potentially relevant for physiological effects and risks of injury. This shall make it possible to assess the significance of other factors than only peak acceleration values, such as rise-time (time form 0 g to peak g), impact duration, energy content, slam period (time between slams) and force vector, (true direction of impact) etc. This will also make the results transparent and possible to scrutinise.

### 3.1 MULTI-AGENCY STUDY DESIGN

The purpose of the Multi Agency Study design is to gather sufficient volumes of data, to allow for the identification of correlations between human impact exposure and the occurrence of pain. This can be done in a scientifically valid way, by using the same study design, protocols, hardware and software, in all the agencies and eventually sharing the relevant parts of the results in a common database.

By sharing results, enough data can be aggregated to achieve significant results, indicating what levels and kinds of impact exposure cause pain. By sharing costs, data and results, great synergies can be achieved and the number of boats, subjects and wave slam events can be sufficient to achieve statistically significant results. Also, the large variation in sea conditions around the world will contribute to the quality of the investigation.

The target is to have at least 10 agencies participating, with at least 4 boats each, all wired with data loggers and acceleration sensors and monitoring over a period of 4-5 months.
Agencies in 16 countries around the world have already expressed their interest in participating.

All subject data will be anonymous and boat data stripped of potentially sensitive information regarding coordinates and whereabouts of operations, before being submitted to the common database.

## 3.2 MEASURING IMPACTS ON HUMANS AND HULLS

Whole body impact will be monitored, on two people, on board each boat, at all times. Each boat will have a data logger installed for the entire period of the study. This will be connected to a 3-axis accelerometer attached to the hull close to the centre of gravity, COG. Acceleration sensors mounted to kidney belts, will be worn by two crew, preferably the coxswain and navigator, and connected to the data logger. Recorded data will indicate the actual, real-life impact exposure and hence the forces acting on the hulls and humans. This data will show the actual exposure and the relation between hull impacts and human impacts for each boat type.

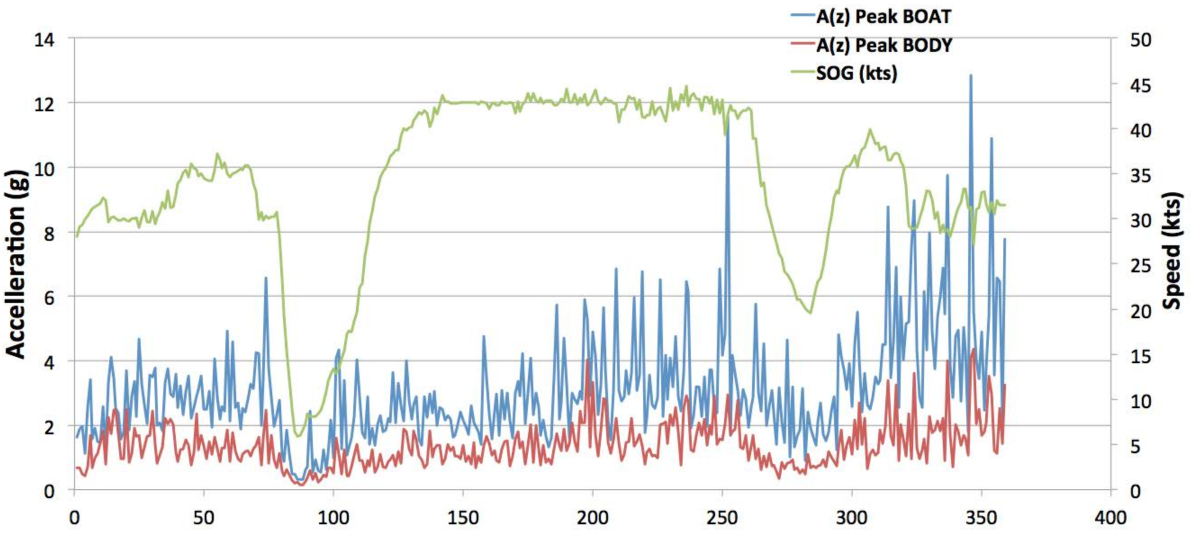

Figure 5 This illustrates one way to present exposure data from the Marec. Graphs can be zoomed in from seeing one entire day, into seeing the detailed shape of a single impact. Here we see 400 seconds on the X-axis. On the Y-axis left acceleration measured in g = 9.81m/s$^2$ with red for "driver" and blue for "boat hull"; and on the right Y-axis, boat speed with the green line.

## 3.3 DATA LOGGER AND SENSORS

A bespoke data logger device has been developed for this study. MAREC, (Marine Acceleration Recorder) is optimised for ease of use and ease of installation. Once installed onboard and connected to 12 or 24 V DC, it will automatically start recording, as soon as the boat is making speed of more than 3kts. It has ten analogue channels. In the standard configuration five are used for accelerometers. with ± 20g range. Sampling rate will be 600Hz. One 3-axis accelerometer, monitoring hull impacts in x, y and z and two 1-axis accelerometers, which will be attached to kidney belts and worn by the coxswain and the navigator at all times. It also has a built-in GPS receiver, logging satellite time, position, heading and speed. The 16 Gb internal USB memory can store the data for the entire period of the study. Afterwards or even during the study, the data can be uploaded to a PC for analysis.

Figure 6 The Marec data logger, connected with (counter-clockwise) two human accelerometers, the hull accelerometer, the GPS antenna, and the red/black power cord. Kidney belt with the accelerometer attached as close as possible to crista iliaca (upper edge of the pelvis) on the axillar line (side line).

## 3.4 PAIN INDICATES RISK OF INJURY

To assess the risk of injury, before it occurs, various physiological parameters can be used. Lab testing for raised levels of creatinine is one. Repeated testing of blood samples is not possible to do in a large population. Instead, pain is used as an indicator of threatening injury. Occurrence and development of pain will be monitored on all personnel serving on board the boats during the entire trial period. This will be using a smartphone app, PainDrawing, daily prompting subjects to report any relevant pain.

Pain is a physiological function provided to protect us from injury by telling us what is potentially harmful. Pain is the only physiological parameter, which can be used as an indicator of risk of injury and be monitored and quantified over time, frequently enough to monitor a sufficiently large population of test subjects. Pain is relevant to use as an indicator, because its primary function is to prevent injury and it has a connection to injury. There can be temporary pain without injury, but very rarely a manifest injury without pain.

Pain is also in itself a relevant symptom, or sometimes a condition, which compromises physical performance and endurance and eventually even mental capacity.

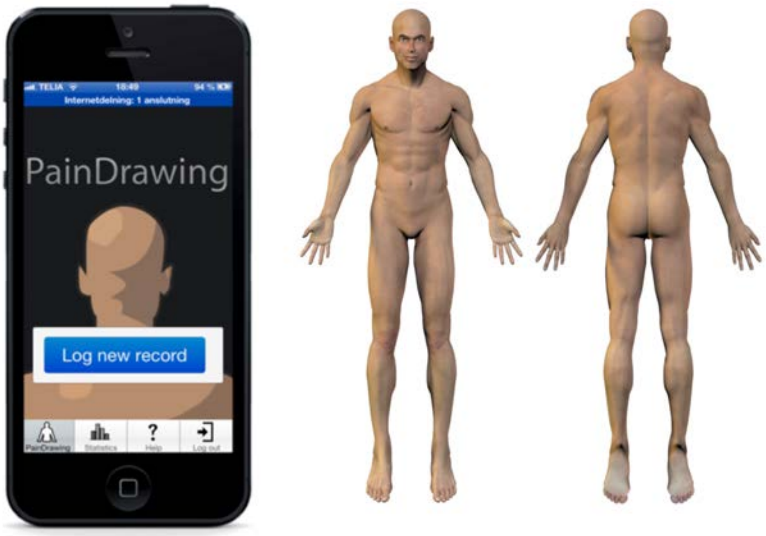

Figure 7 The PainDrawing app is optimised for maximum subject compliance with a self-instructing interface It prompts subjects for input on pre-set times. Answering takes only ≈ 4 to 14 seconds, depending on whether there is any pain to report or not.

It should be obvious that exposure causing pain during demanding operations must be avoided, or limited as much as possible. This is relevant, not only for liability reasons or for the long-term health aspect, but also for enhancing proficiency and effectiveness of the teams operating in adverse environments and challenging conditions.

The PainDrawing app was developed for the purpose of this study. It is built on two scientifically validated methods. One is the Nordic Council of Ministers' pain-drawing form, which has been used for decades to follow development of pain, the other is he VAS Visual Analogue Scale.
PainDrawing app can be downloaded for free for both Android and iPhone.

## 3.5 SEPARATE SUB-STUDIES ARE POSSIBLE

As the data loggers have ten channels, and only five are occupied in the basic study design, further data can be collected during the same trial period, and separate specific sub-studies can be done, without involving all the participating agencies, and without compromising the validity of the large database.

Such studies could involve e.g. measuring EMG, electromyography on muscle groups in extremities known to react by reflex to protect the body during exposure to whole body impacts.
Specifically the role of reflex response and even voluntary response in M. erector spinae (back stretchers) and M. rectus abdominis (the abs) would be relevant to study, as these have a stabilising effect on the torso and spine.

It would also be possible connect gyro sensors to log hull movement in all degrees of freedom of movement. Alternative kinds of accelerometers can also connect and accelerometers place in different places along the hull, or on seats or seat cushions. This way even the methodology can further tested and validated. Any sub-studies should be designed and conducted to be compatible with the collection of base data for the main study.

## 4. RESULTS AND APPLICATIONS

Based on the expected results of the study, it will be possible to calibrate instruments with dashboard-mounted indicators, telling operators when hull impacts exceed safe levels, by green, yellow or red signals, where red should indicate out of boundaries.

The results should also indicate further the significance of horizontal components in the impacts, indicating if they should be weighted for risk of injury differently than the factor of 1.4 higher risk level normally applied.

The results should also indicate the significance of the rise-time, and how the jerk factor (the derivative of the rise-time) should be weighted for risk of injury.

Ultimately the results can lay a base for a new relevant standard, defining limits for allowable versus dangerous exposure to whole-body impact. To protect people from injury, such a standard must consider the forces affecting the human body at sea.

Participating agencies will gather information about how their various boats perform, producing slamming impacts in real use.
They will also be able to compare their operators' skills to produce smother versus rougher rides.

## 5. CONCLUSION

Leonardo da Vinci 1452-1519 based his scientific work on observations of nature, where he identified certain patterns, the relevance of which, he tested by further observations and experiments. He claimed that one's own observations and experiences are superior to old knowledge found in the books. Like a modern scientist, he claimed that, before stating a theory about a phenomenon, it has to be tested several times, to validate if the thesis gives the same result. With this very method Leonardo initiated the dialogue between experiment and theory, that later should start the Scientific revolution. Studying reality is hence neither new nor unique and should not be controversial, even in the third millennium. Especially so in an area where the relevant knowledge sought, has not revealed itself in the published literature.

Current standards and regulations cannot quantify or help control human impact exposure at sea.
**New knowledge is needed and can only be established by studying what happens in real life.**

## 6. CONTACT

For info about the progress or about how to participate contact the author, JohanUllman@me.com

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