Human impact exposure onboard high-speed boats; what is dangerous? - An international multi-agency study

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Dr. Johan Ullman är specialist in anestesi och intensivvård samt företagshälsovård. Han är även forskare och uppfinnare och i den senare rollen känd som upphovsman till bl.a ergonomiska arbetsstolar, portable handsfree och Bluetooth. Dr Ullman, som är Marinläkare (RO/Kapten) vid Försvarsmedicincentrum, tjänstgjorde på tidigt 80-tal som Flottiljläkare vid 1.Ytattackflottiljen och upptäckte vid friskmönstring av värnpliktiga att, efter 9 månaders tjänst ombord på MTB klagade drygt 80 % av vpl på ryggbesvär som de skyllde på stötexponering. Ullman började forska på ämnet på Yrkesortopeden Sahlgrenska och utvecklade både metoder att mäta stötexponering på människor ombord och efterhand stötupptagande säten och styrsystem ad modum motorcykelstyre. Ullmans båtsäten finns nu i fler än 70 länder.

Human impact exposure onboard high-speed boats; what is dangerous? - An international multi-agency study

Abstract: Operating high-speed boats is dangerous. Impact-induced injuries are sometimes severe and cause permanent disabilities. However, it is not known which levels of impacts are dangerous and which are safe. The purpose of the 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. This impact exposure causes more injuries per workday than most other peacetime work.[1,2] 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 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.

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.

Figure 1. Photo: Johan Ullman. Coxswain: Carl Magnus Ullman.

Agencies in several countries, operating high-speed boats, have expressed a need to find out how severe impacts their personnel is being exposed to, and what impact levels are dangerous. Many also w**hat is relevant to measure, 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 aquire sufficient amounts of data, it is necessary to monitor a large number of subjects, over several months, for exposure and a physiologic response indicating risk of injury.

To achieve this, **a number of agencies** operating high-speed boats, in all kinds of missions and sea states around the world **will join efforts**.

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 exposure limits**.

Background

The EU-directive 2002/44/EC[3] is in some countries applied to set limits for impact exposure. It specifies the "*Minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration)*", (Sic!).

This directive is based on an ISO-standard, ISO 2631:1[4], which states limits for exposure to continuous vibration, but never was intended to be applied to exposure to impacts. The standard is based on mean values of continuous vibration and contains advanced algorithms quantifying how much energy transferred to the human body as vibration. 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

Existing rules and standards are hence not relevant for exposure to impacts onboard high-speed boats. The exposure limits are legally binding, but impossible to comply with while conducting normal SAR (search and rescue) or military training.

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 countries, however, much effort is focused on trying to comply with it primarily by reducing exposure to vibration.

The consensus within the scientific community today is 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 risk of injuries caused by impacts.[7]

Lab testing cannot produce the needed information

Real slamming impact exposure cannot be realisticly simulated in a lab test. Real impact exposure is stochastic and multidirectional, reaching levels up to nearly 20 g. For ethical reasons, humans cannot be exposed to relevant dangerous impact levels in a lab.

Lab trial methods are being 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, whereas 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 10 g peak levels, whereas the most severe real impacts at sea can reach nearly 20 g.[9]

It is also shown that some suspension seats and also standing postures can amplify and actually multiply the impacts on humans by more than 3 times.

Lab trials cannot simulate the human physiologic response, or muscular reflexes. They cannot assess the effects of impact on the human posture, which is crucial for the risk of injury. Also lab trials cannot assess 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 (Sed8), created with advanced algorithms, based on assumptions regarding dynamic properties of segments of human spines.

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

As VDV and Sed8, etc. are defined based on experiments[10] on cadaver segments of lumbar spines fixed in their normal unbent positions, they should not be used for assessing risks injuries caused by stochastic multidirectional impacts.

When real impacts cause injury they almost inevitably also cause uncontrolled deflection of the spine. The dynamic and elastic properties of a severely deflected spine are very different from those of a spine in its natural "balanced" and slightly S-curved shape. The more a spine is rotated, or ventriflexed, (bent forward) the stiffer it gets and less apt to absorb shocks, and the more dorsiflexed, the less stable it gets as disks are pulled apart. 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 also having caused deflection of the spine. Pure symmetrical failure is rarely seen in high-speed boat injuries.

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, bone and cartilage, 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. When going into a sharp turn, the acceleration (g-forces) on the platform and pilot increase gradually, during almost a second, up to 7g or even above. This causes significant physiological 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.

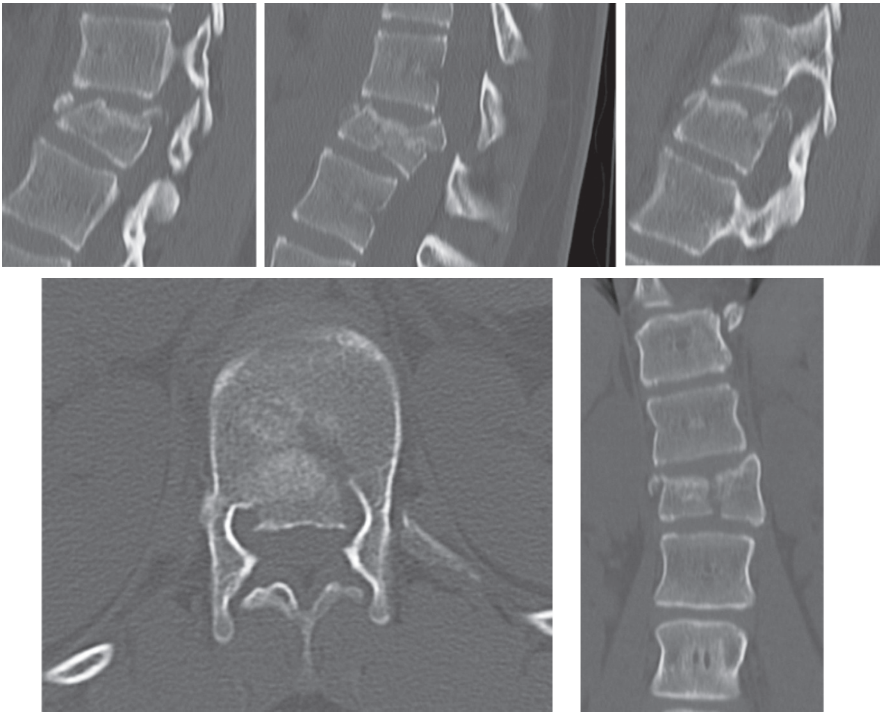

Figure 2. Shows a vertebra shattered and fragmented by a slamming impact onboard a high-speed boat. This kind of injury alters the geometry and may result in neurological damage and permanent disability.

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.

One cause of cervical spine injuries is the head jolts, experienced by both seated and, not least standing subjects.

Documented injuries include vertebral fractures, ranging from wedge-shaped compression to complete shattering of vertebrae, disc ruptures, traumatic displacements and ligament ruptures.

Some of these result in permanent disabilities; paralyses and disabling chronic pain conditions.

When stabilising structures are damaged, neurological symptoms may occur

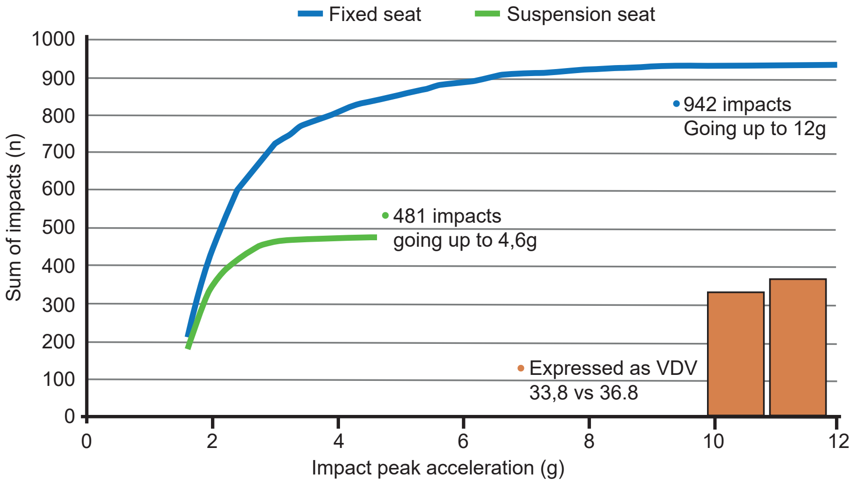

Figure 3. This graph shows significant difference in impact exposure onboard two identical boat, fitted with different types of seats and run side by side over three hours. Measured as peak acceleration plotted as (g), 9.81 m/s^2, the number of impacts was double (481 vs 942 impacts), and the difference in amplitude of the highest peaks was 2.6 times higher (4.6 g vs 12 g) for the fixed seats.The overlaid brown columns illustrate the same data measured as VDV, showing almost no difference in exposure, just 9 % (33.8 vs 36.8)[11]

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 biological structures. Pain can be present without injury, but acute injuries rarely occur without causing pain.

Impact exposure has measurable physiological effects

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

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, with this same exposure data, processed and presented as VDV, there was 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, just comparing the highest peak values to the mean of all

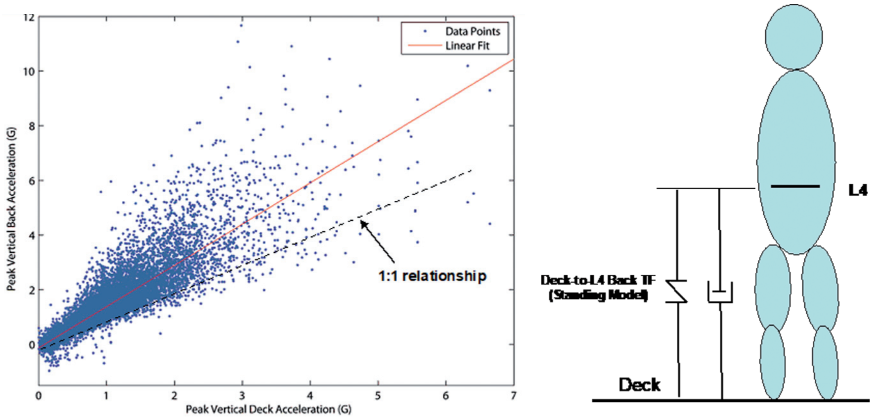

Figure 4. Deck-to-L4 Standing Transfer Function. The graph created using deck and back data from sea tests of NSW 11M RIB, showing an average of 50 % amplification and a maximum 4 times higher impacts on the human than on the hull/deck.

peaks and thus does not indicate injury risks.

Many suspension seats type, 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 its end of stroke and comes to an abrupt stop. Such events have caused severe injuries and overboard ejections. Amplification can also be caused by linear suspensions locking up under exposure to oblique impacts with and lateral forces.

Even standing positions aboard high-speed boats 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 freefall until heels impact with the deck. At least no other explanation has been suggested.

Standing seems especially challenging for the necks, as cervical injuries reported from boats, fitted with standing bolsters seem to dominate over lumbar injuries. This is still an anecdotal observation.

Methods

The method is developed to record impact exposure on both hulls and on humans, onboard high-speed boats, while 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 contentment, slam period (time between slams) and force vector (the direction of impact), etc. This

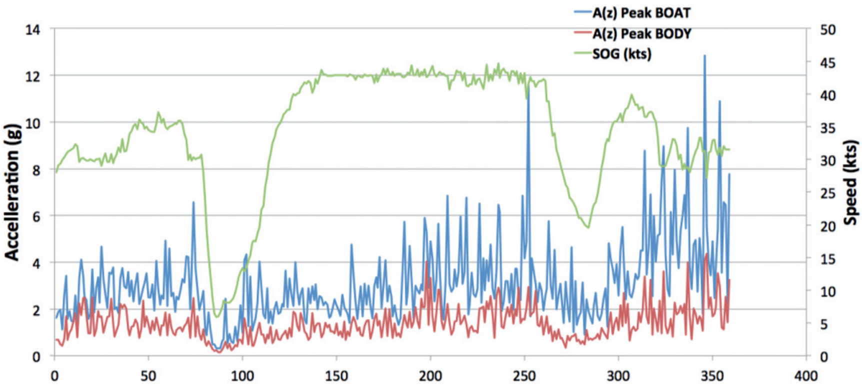

Figure 5 . This illustrates one way to present exposure data from the Marec. Graphs can be zoomed from one entire day in to seeing the detailed shape of single impact. Here, we see 400 seconds on the X-axis. On the Y-axis left, acceleration is measured in g = 9.81 m/s2 with red for 'driver' and blue for 'boat hull'; and on the Y-axis right, boat speed, with green line.

will also make the results transparent and possible to scrutinise.

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 various agencies, and eventually sharing the relevant parts of the resulting data in a common database.

By joining efforts and sharing results, it is intended to gather sufficient volumes of data 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 ten agencies participating with at least four boats each, wired with acceleration sensors and data loggers, and monitored over a period of four -five months. Agencies in 15 countries around the world have expressed interest in participating.

All subject data will be anonymised and all boat data stripped of any potentially sensitive info regarding coordinates and whereabouts of operations carried out before being submitted to the common database.

Measuring impacts on humans and hulls

Whole body impact will be monitored, on two people, on board each boat all times. Each boat will have a Marine Acceleration Recorder (Marec) 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

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. A kidney belt is attached with the sensor as close as possible to crista iliaca (top of the upper edge of the pelvis) on the axillar line (side line).

platform's 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 hulls and humans. This data shall show the actual exposure and the relation between hull impacts and human impacts for each boat type.

Data logger and sensors

The bespoke Marec was designed specifically for this study, optimised for ease of use and ease of installation. Once installed onboard and connected to 12V/24V DC, it will automatically start recording, as soon as the boat makes speed over 3 knots, with a sampling rate of 600 Hz.

It has 10 analogue channels. In the standard configuration five are used for accelerometers. These have a range of ± 20 g. One 3-axis accelerometer, monitoring hull impacts in x, y and z and two 1-axis accelerometers. The latter 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, data be uploaded to a PC for analysis.

Pain indicates risk of injury

To assess the risk of injury, before it occurs, various physiological parameters can be used. Lab testing of raised levels of creatinine is one. Repeated testing of blood samples is not possible to do in a large population. Instead, pain 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 done using PainDrawing, a smartphone app, 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, that 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 considered 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.

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 Minister Councils pain drawing form, which has been used for decades, to follow development of pain, the other is the Visual Analogue Scale (VAS). PainDrawing can be downloaded for free.

Separate sub-studies are possible

As the data loggers have 10 channels, and only five are occupied in the basic study design, further data can be collected during the same trial period. Separate specific sub-studies can be carried out, without involving other all agencies and without compromising the validity of the main database.

Such studies could involve measuring EMG (electromyography) on muscle groups in extremities, known to produce a protective reflex response to whole body impacts. Specifically the role of reflex response and even voluntary response in M. erector spinae (back stretching muscles) and M rectus abdominis (abdominal muscles "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 for freedom of movement. Alternative kinds of accelerometers can also be connected and accelerometers can be fitted different places along the hull and on seats or seat cushions. This way even the methodology can be further tested and validated. Any sub studies should be designed and conducted so that the collection of base data defined by study is not compromised but done in the same way in all countries and agencies.

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 would indicate "out of boundaries". Then only the hull impacts need to be measured.

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.

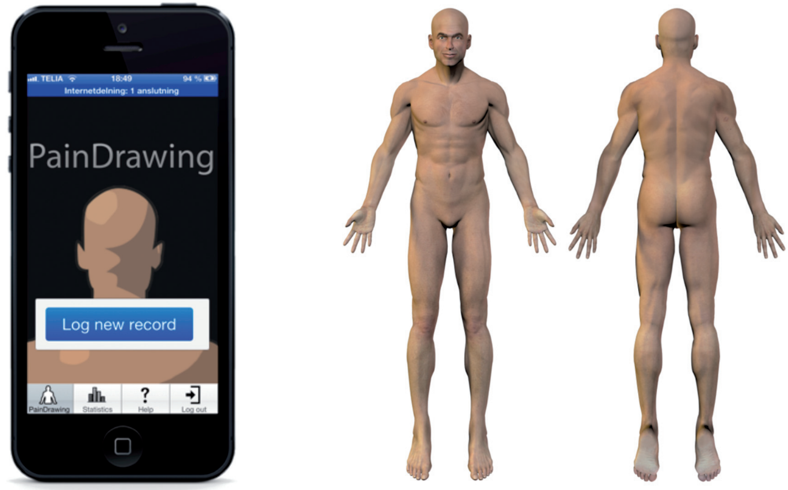

Figure 6. The PainDrawing app is optimised for maximum subject compliance with a self-instructing interface. It prompts subjects for input on pre-set times. Answering takes approximately four to 14 seconds, depending on whether or not there is any pain to report.

Ultimately the results could 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 be able to gather information about how their various boats perform, producing slamming impacts in real use. They will also be able to compare operator skills, in regards to producing smoother versus rougher rides.

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.

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