# Monitoring and Assessing Crew Performance in High-Speed Marine Craft – Methodological Considerations

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**Abstract.** This paper proposes a method to monitor and assess human performance specific to high-speed marine craft operation. The high-speed craft crew's ability to efficiently perform their allotted tasks is affected by the manner in which the vessel responds to the variable sea conditions. In general, the reaction of human body to high-speed boat motion and vibration is recognized as the main cause of fatigue during and post transits; whereas random shock represents the most likely cause of injuries during transits. The pilot experiment introduced in this paper was designed and performed with the intention to identify and evaluate measures of crew performance during and after a transit in a marine environment that can serve to indicate increasing fatigue, decreased functional capabilities and thus possible increased risk of injury.

**Keywords:** Human performance, Whole body vibration, Muscle fatigue, Surface EMG analysis.

## 1 Introduction

The crew and passengers of high-speed marine craft, such as rigid-hull inflatable boats (RIB), are often exposed to continuous vibrations and shocks and experience high levels of fatigue during and post transits as well as an increased risk of injuries [1]. A study examining the reduction in physical performance post transit demonstrated that performance was reduced by ~30 % for manual dexterity and ~20 % in a step test [2]. As high-speed craft are often used as transit vehicles to delivery personnel undertaking activities such as search and rescue, it is important that they arrive at the destination in the best possible condition as peoples lives are dependant on their performance. Thus, it is of great importance to identify and examine possible causes of the fatigue and provide effective methods to reduce them.

This paper proposes a method to monitor and assess human aspects during and post high-speed transits at sea. The pilot experiment has been designed and performed with the intention to evaluate measures of fatigue that could be used to assess possible degradation of crew performance. To achieve this, sea trials were undertaken with a RIB instrumented with tri-axial accelerometers and rate gyros to record shocks and boat motion, respectively. In addition, physiological data – surface electromyography (EMG) and electrocardiogram (ECG) – were measured simultaneously during transits

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to investigate any effect that could be in association with the exposure to vibration. EMG and ECG signals were also collected during muscle fatigue tests performed instantly before and after each trial to examine the characteristics and effect on theses outcome measures of the high speed transit. Rate of perceived exertion (RPE) using the Borg scale [3] was used to assess subject's level of perceived exertion rated at the point when, during the transit, they perceived they were working hardest.

The paper is organized as follows. A proposed methodology used to measure, process and analyze both physical and physiological data is explained in details in section 2. The results of the experiment are presented and discussed in section 3 followed by the conclusions in section 4.

## 2 Method Description

### 2.1 Experimental Procedure

The experiment consisted of a sea trial preceded and followed by a muscle fatigue test. Physical data measured during the trials were: boat LCG (longitudinal centre of gravity), seat and head accelerations and boat motions. Measurements of physiological data were: ECG and surface EMG activities of four spinal muscles (upper fibers of *Trapezius* and *Multifidus* in the lumbosacral region), performed during all phases of the experiment. A scheme of the performance measurement system is depicted in Fig. 1.

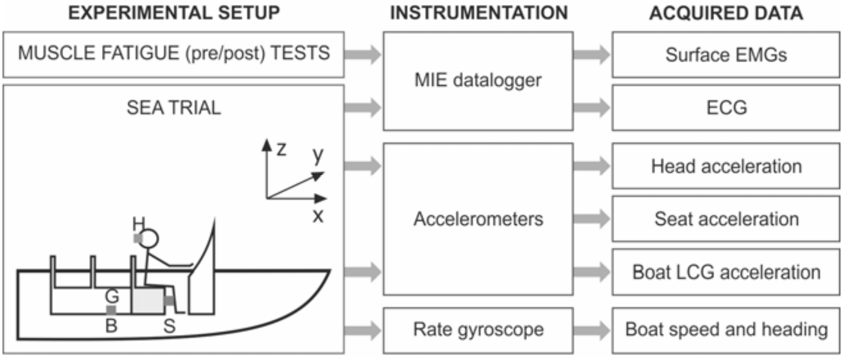

**Fig. 1.** Performance measurement system (B, H, S and G correspond to the positions of the accelerometers placed at the boat LCG, head and seat and rate gyroscope respectively)

**Sea Trials.** Three sea trials, each approximately 33 minutes long, were carried out with a RIB-X Expert XT650 at the south coast of England. Each trial was run with one subject sitting on the front left seat next to the driver. Three physically fit male subjects (83±9.6 kg weight, 182±12 cm height, 28.3±3.2 age) participated in this study. The sea conditions were *slight* (sea state 3). The average and maximum boat speed estimated from the GPS recordings for each trial are reported in Table 1 (1 knots≈0.5144 m/s).

**Table 1.** Boat speed during the sea trials

| Trial No. | Trial Duration | Average speed [knots] | Average speed [m/s] | Maximum speed [knots] | Maximum speed [m/s] |
|---|---|---|---|---|---|
| 1 | 35 min 20 s | 20.84 | 10.72 | 27.58 | 14.19 |
| 2 | 27 min 0 s | 25.17 | 12.95 | 37.73 | 19.41 |
| 3 | 38 min 50 s | 25.58 | 13.16 | 36.54 | 18.80 |

**Muscle Fatigue Test.** Before and after the sea trial, a subject performed a standardized isometric back extension test until fatigue [4]. The subject, lying prone, was instructed to maintain the upper body above the floor as long as possible, with his arms aligned with the body and the head in a neutral position looking downward. The test ceased when the subject was no longer able to maintain the trunk in the test position, the time for each test was recorded.

### 2.2 Instrumentation and Data Acquisition

Tri-axial accelerometers (Crossbox CXL100HF3, range ±100 g) were used to measure boat and human vibrations. The accelerometer positions, denoted as B, H and S in Fig. 1, correspond respectively to: the boat's LCG (accelerometer attached at the floor of the boat), the subject's head (accelerometer attached at the back side of the helmet), and the subject's seat (accelerometer positioned at the front side of the seat). The axes of each accelerometer were referenced according to recommended method such that the $x$-axis measured fore-aft acceleration, the $y$-axis measured lateral acceleration, and the $z$-axis measured vertical acceleration [5]. Acceleration signals were recorded at sampling frequency of 2.5 kHz using a 16-channel logger (IOTECH Logbook 300).

Surface EMG signals were recorded using a differential pair of pre-gelled electrodes attached 3 cm apart over and parallel to the fibers of each muscle using standard SENIAM guidelines [6]. A reference electrode with a built-in 1k gain preamplifier was attached at the same distance from the electrodes. Pre-amp cables were fixed to the skin with adhesive tape to reduce potential artifacts caused by movement. Raw signals were amplified, band-pass filtered (3 dB bandwidth: 6-6000 Hz) and recorded with a 1 kHz sampling frequency using a portable data logger (MIE Medical Research ltd).

To synchronize data acquired by two data loggers, tri-axial accelerometer transducers (ranges ±25 g and ±100 g) used by each data logger were mounted close to each other on the back of subject's helmet with the corresponding axes of detection aligned. Thus, the head acceleration signals acquired by two transducers were used in the processing stage to establish an exact match between time scales of the measured signals. All data were stored on memory cards and converted later into a MATLAB format for processing purpose.

### 2.3 Vibration Data Analysis

In this study, the assessment of the level of exposure to vibration is based on the calculated vibration dose value (VDV). VDV is commonly used as an assessment method when a person is exposed to numerous shocks and represents a cumulative dose of vibration during a total exposure [7],[8]. Two weighting filters – $W_d$ for the horizontal $x$ and $y$-axes and $W_b$ for the vertical $z$-axis, were initially applied to the vibration signals measured at the passenger's seat and the boat's LCG in order to estimate exposure level associated with the two positions [5]. In accordance with BS 6841 [7], VDV for each axis is calculated according to the following formula:

$$\mathrm{VDV}_i = \sqrt[4]{\int_0^T a_{iw}^4(t)\,dt},\ i = x, y, z\,, \tag{1}$$

where $a_{iw}(t)$ is frequency-weighted acceleration along the $i$–axis and $T$ is the duration of exposure in seconds, i.e. total period during which vibration occurs.

Total vibration dose in all axes is obtained by summing individual vibration doses for each axis:

$$\mathrm{VDV}_{tot} = \sqrt[4]{\sum_{i=x,y,z} \mathrm{VDV}_i^4},\ i = x, y, z\,, \tag{2}$$

where $\mathrm{VDV}_i$ is the partial vibration dose value calculated for the $i$–axis using Eq. (1).

Furthermore, the calculated VDVs can be compared with limit values of vibration exposure standardized to an eight-hour period above which vibration exposure must be controlled or completely stopped. According to [8], exposure action value (EAV) and exposure limit value (ELV) are 9.1 m/s$^{1.75}$ and 21 m/s$^{1.75}$ respectively.

# 3 Results and Discussion

## 3.1 Boat Speed and Vibration

Frequency-weighted peaks and root mean squared (rms) amplitudes of the LCG and seat accelerations calculated for each trial are reported in Table 2. For all three trials, the highest impact magnitudes occurred in the vertical direction ($z$-axis) at the boat's LCG and in the longitudinal ($x$-axis) or lateral ($y$-axis) directions at the seat front. (The magnitude and frequency of impacts increased significantly in the second half of each trial.) Overall frequency-weighted rms seat acceleration magnitudes were found to be considerable larger than the rms magnitudes of LCG acceleration. In accordance with BS 6841 [7], vibrations with such frequency-weighted rms magnitudes are indicated as being *uncomfortable*.

**Table 2.** Vibration parameters of the sea trials

| Trial | peak [g] | | | rms [m/s$^2$] | | | |
|---|---|---|---|---|---|---|---|
| No. | $x$-axis | $y$-axis | $z$-axis | $x$-axis | $y$-axis | $z$-axis | total |
| LCG acceleration (weighted) | | | | | | | |
| 1 | 0.119 | 0.109 | 0.866 | 0.124 | 0.083 | 0.324 | 0.357 |
| 2 | 0.148 | 0.162 | 2.165 | 0.188 | 0.103 | 0.457 | 0.505 |
| 3 | 1.740 | 0.212 | 2.292 | 0.281 | 0.191 | 0.551 | 0.647 |
| Seat acceleration (weighted) | | | | | | | |
| 1 | 0.186 | 0.708 | 0.799 | 0.119 | 0.653 | 0.248 | 0.709 |
| 2 | 0.231 | 1.538 | 1.363 | 0.181 | 1.005 | 0.347 | 1.079 |
| 3 | 0.452 | 1.359 | 1.490 | 0.200 | 1.060 | 0.352 | 1.135 |

### 3.2 Vibration Dose Values

Partial and total VDVs calculated according to Eqs. (1) and (2) for all three sea trials performed in this study are listed in Table 3. The largest VDVs were reported for the third trial where a higher number of impacts were encountered, especially in the second half of the trial. It can be also seen that the total VDVs calculated at the seat (seated posture) are larger than the total VDVs calculated at the boat's LCG (standing posture) for all three trials. Moreover, a main contribution to the seat's total VDVs is from impacts in lateral direction; while in the case of the boat's LCG it is predominantly the result of vertical impacts. In the second and third trial, even thought the sea state was *slight*, the total VDVs calculated at the seat exceed the EAV of 9.1 $m/s^{1.75}$ standardized for an eight-hour period within 20 minutes.

**Table 3.** Vibration dose values derived in case of seated and standing postures

| Trial | VDV (standing posture) [$m/s^{1.75}$] | | | | VDV (seated posture) [$m/s^{1.75}$] | | | |
|---|---|---|---|---|---|---|---|---|
| No. | *x*-axis | *y*-axis | *z*-axis | total | *x*-axis | *y*-axis | *z*-axis | total |
| 1 | 1.54 | 1.19 | 4.12 | 4.15 | 1.40 | 7.54 | 3.13 | 7.60 |
| 2 | 1.92 | 1.37 | 8.41 | 8.41 | 2.08 | 12.20 | 4.92 | 12.28 |
| 3 | 6.43 | 2.65 | 11.37 | 11.66 | 2.98 | 14.73 | 6.23 | 14.85 |

As an example, cumulative effects of the total VDV relative to the frequency-weighted LCG and seat acceleration magnitudes during the third trial are illustrated in Fig. 2 where the exposure action and limit values are marked with the horizontal dotted lines. The EAV is exceeded approximately 18 minutes from the beginning of the trial whilst the magnitude and frequency of impacts increased significantly resulting in a rapid increase of the acceleration magnitudes.

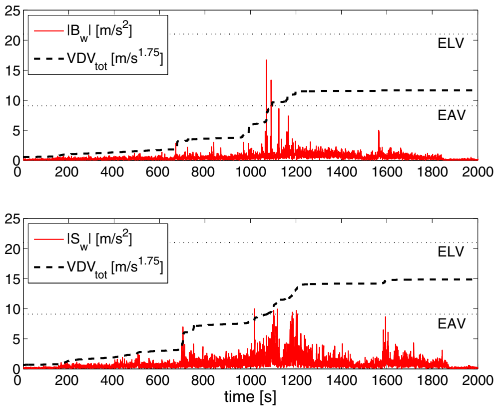

**Fig. 2.** Frequency-weighted acceleration magnitudes and total vibration dose values calculated from the LCG (top) and seat (bottom) accelerations in the third trial

### 3.3 Physiological Data

The EMG variables considered in this study are the root mean square (rms) value and median frequency (MDF) [9],[10]. These parameters are calculated from the consecutive 1 s time windows of the bandpass-filtered (10-300 Hz) EMG signals.

All three trials reveal very high correlation between EMG and acceleration rms values. As an example, the normalized running rms values for *Left* and *Right Multifidus* muscles at the level of the lumbar 4th and 5th vertebrae and seat acceleration are shown in Fig. 3, this is zoomed in at the time interval where most impacts occurred. An increase of the EMG magnitudes caused by large impacts in seat acceleration is evident.

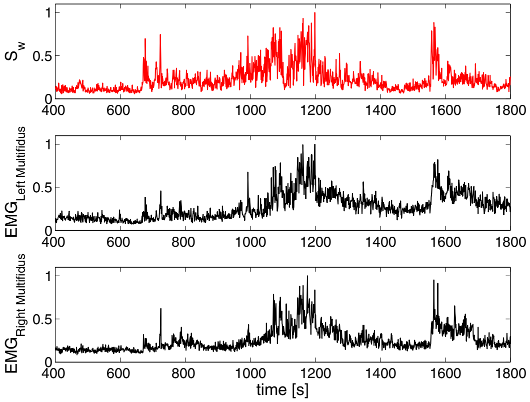

**Fig. 3.** Normalized rms amplitudes of frequency-weighted seat acceleration (top), *Left Multifidus* EMG (middle) and *Right Multifidus* EMG (bottom)

Median frequencies calculated for the whole duration of the third trial are given in Fig. 4. It can be seen that the MDFs of the *Left* and *Right Multifidus*, decrease by more than 8 Hz when the majority of impacts occurred (in time period between 1070 s and 1200 s from the beginning of the trial) demonstrating a similar effect to that seen when muscle fatigues during an activity [9]. Similar trend is not detected in the upper fibres of *Trapezius*.

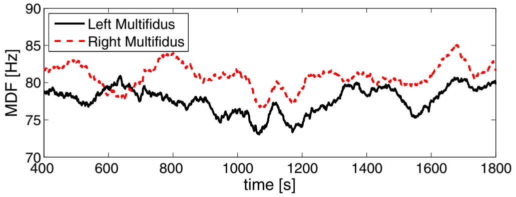

**Fig. 4.** Median frequencies of *Multifidus* muscles

The results of the Borg RPE test for each trial respectively are 11.5, 12 and 17 indicating that the subjects perception of the sense of effort during the sea trial, when they perceived that they were working at their hardest, was rated between *somewhat hard* (>11) to *very hard* (>15). These results concur with vibration data which illustrates the severity of the trial – as can be seen from Table 2, the vibration parameters increased from the first to the third trial.

The heart rate and MDF values calculated for the EMG and ECG measurements conducted before and after the first trial are given in Tables 4 and 5 respectively. In this pilot study, the results of the muscle fatigue test have not demonstrated general increase of heart rate or decrease of MDF values after the trials. It could be speculated that the effect of the vibration exposure on the muscle fatigue was not significant due to *slight* sea conditions and good fitness levels of the subjects.

**Table 4.** Comparison of heart rate values for the pre- and post-trial muscle fatigue tests

| HR [beats/min] | min | | max | | mean | | st. deviation | | range | |
|---|---|---|---|---|---|---|---|---|---|---|
| | pre- | post- | pre- | post- | pre- | post- | pre- | post- | pre- | post- |
| | 63.8 | 59.6 | 95.8 | 93.1 | 83.6 | 77.3 | 7.2 | 8.5 | 32 | 33.4 |

**Table 5.** Comparison of MDF values for the pre-trial and post-trial muscle fatigue tests

| MDF [Hz] | min | | max | | mean | | st. deviation | | range | |
|---|---|---|---|---|---|---|---|---|---|---|
| | pre- | post- | pre- | post- | pre- | post- | pre- | post- | pre- | post- |
| L. Upp. Trap. | 64 | 68.6 | 75.6 | 89.2 | 68.7 | 79.2 | 2.6 | 5.6 | 11.6 | 20.6 |
| R. Upp. Trap. | 58.8 | 65 | 76 | 88 | 64.9 | 73.6 | 2.4 | 3.4 | 17.2 | 23 |
| L. Multifidus | 76.2 | 84 | 101.7 | 104 | 88.3 | 94.4 | 6.7 | 4.9 | 25.5 | 20 |
| R. Multifidus | 73 | 83.8 | 110 | 115 | 91.1 | 99.1 | 9.3 | 7.3 | 37 | 31.2 |

## 4 Conclusions

In this paper, a method to monitor and assess crew performance in high-speed marine craft transits at sea is proposed and preliminary results of the pilot study are presented. The vibration dose values obtained in this pilot experiment are compared with limit values set by current standards and legislation demonstrating the VDV that can be expected onboard high-speed marine craft. Values would be even larger in more severe sea states and compounded by wind and tide effects. It is shown that the physiological data are highly correlated with vibration magnitudes during sea transits. A decrease in median frequencies of the EMG signals due to an increase in vibration amplitude is demonstrated for lower back muscles. For more thorough analysis of the effects of the trials on the subject's performance during the muscle fatigue tests conducted before and after trial, it would be of interest to collect more experimental data in higher sea states.

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