Adverse health effects and reduced work ability due to vertical accelerations in high-performance marine craft personnel

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ABSTRACT

Human factors engineering is a key parameter in High-Performance Marine Craft (HPMC) design since the human tolerance to working conditions aboard, in fact, decides the operational limits. So far, the deficiency of the knowledge on how the crew is influenced by the working conditions in terms of health risk and work performance has lead the designing process to exit before incorporating the human element when determining these operational limits. Knowledge, on the relationship of the physical and perceived exposure conditions and on risk factors for health and work performance impairments, would open up possibilities for drawing the operational limits at the design stage and providing feedback to the crew during operations. This is investigated in a research program and the current study pilot test a set of High-Performance Marine Craft Personnel (HPMCP) in order to collect data on their work exposure, health and performance impairments. The study collects subjective and objective data and investigates their correlation and the potential risk factors. Although the amount of data collected is too limited to draw direct conclusions, the pilot test confirms the feasibility of the set-up and the method giving good inputs and experience to the research crew.

Keywords: *Whole-body vibration, Epidemiology, High-Speed Craft, Human Factors.*

1. INTRODUCTION

In attempts to incorporate human factors in the design of High-Performance Marine Craft (HPMC), it has become evident the deficiency of the knowledge on how the crew is influenced by the working conditions in terms of health risk and work performance. The latter is expected to jeopardize the system performance as well as safety at sea, where crews and passengers are demanded for physical fitness in order to successfully complete their missions. In the context of simulation-based design, the present study constitutes a pilot test of a longitudinal investigation of work exposure, health, and performance in High-Performance Marine Craft Personnel (HPMCP). The study has been started by KTH Royal Institute of Technology in collaboration with Karolinska Institutet, the Swedish Coast Guard and Institute of Aviation Medicine Norway, which is a part of an ongoing program investigating relationship between working conditions aboard HPMC and the outcomes in terms of systems performance and occupants' health.

The pilot test is designed to correlate physical and perceived working conditions identifying performance and health related risk factors by collecting objective and subjective work-exposure data and subjective performance indicators and heath data. In the event objective and subjective data correlate, either can be used to level the severity of the working conditions aboard. Moreover, if risk factors can be linked to condition severity it will be possible to depict risk related to the conditions perceived and measured onboard or predicted at the design stage. The latter can be used to adopt the speed reduction curve to human health and performance while the former to crew guidance during operation.

The paper attempts to identify the correlation between subjective and objective data while discussing the lessons learnt from the process.

2. METHODS

Study design

The set-up is designed as a field research on HPMC crew in operation, a sample of eight Norwegian Special Operations Command officers during an eight weeks exercise where HPMC are operated as a part of the program. Craft acceleration and GPS data is objectively recorded by vibration measurement systems installed onboard while work related exposure, performance and health data is subjectively collected via web-based questionnaires.

Instrumentation and data collection

Four HPMC, 11.25m rigid inflatable boats (RIBs), are instrumented as shown in Figure 1. Two craft are fitted with two measurement systems, one in the driver and navigator area and the other one in the passenger area. The remaining two craft are installed with one measurement system on each due to the limited availability of the instruments. The six measurement systems, Figure 2, specifically designed for the purpose, are prototypes consisting of one tri-axial accelerometer, two single-axis accelerometers, GPS antenna and a data acquisition unit with eleven input channels. The system records acceleration and GPS data at 600Hz and 1Hz respectively and stores on a local memory.

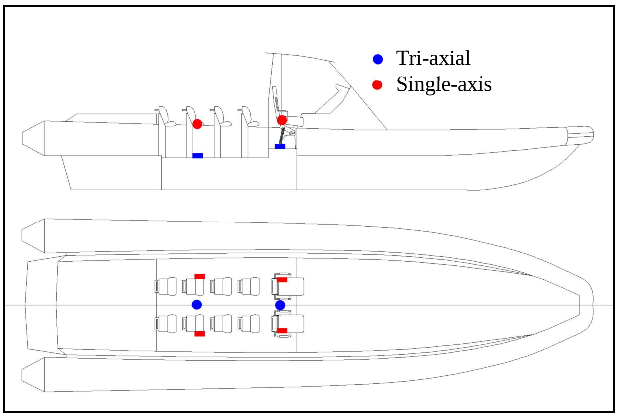

Figure 1: Instrumentation of craft.

Tri-axial accelerometers are fitted on the floor at the center-line, one in between coxswain and navigator seats and the other in the passenger area as shown in Figure 1. The two single-axis accelerometers, measuring vertical accelerations, are mounted each on the coxswain, navigator and passenger seat frames below the cushions. GPS antenna, logging longitudes, latitudes, speed, course over ground and coordinated universal time stamp, is installed on the mast. The data acquisition unit is secured inside a water proof cover on the base of the mast. The accelerometers are calibrated before the installation and considered reliable.

Figure 2: Vibration measurement system.

Although the measurements are intended to be started as the craft ignition key is turned on, in this test, a separate switch is installed due to some technical confidentiality concerns.

Self-reported data is collected by two sets of web-based questionnaires, [de Alwis et al. 2016 and lo Martire et al. 2017], hereinafter referred to as Q1 and Q2 respectively. Q1 collecting demography, life-style, work-exposure and health data, is answered at the beginning of the study by every subject as a base-line questionnaire and considered as a reference data set. Q2 consists of two modules of which one module measuring work exposure and performance indicators is answered daily after each work shift and the other module for musculoskeletal pain is answered weekly during the exercise. The daily module of Q2 is answered regardless their activities, i.e. seaborne or not. All the questionnaires are completed on the subjects' personal smartphones. The data is collected for two months.

Analysis of data

The subjective health impairments are assessed in terms of prevalence and incidence of musculoskeletal pain. Prevalence, i.e. existence of pain, is determined under ten major body areas and expressed as the number of subjects having pain during the past six months and seven days. Incidence, i.e. occurrence of new pain events during a specific time period, is scrutinized weekly and then expressed as the number of subjects incurred new pain events during the entire eight-week exercise program. Musculoskeletal pain data is collected using a high resolution pain areas scheme having 18 different pain areas and the results are merged and presented under ten major body areas.

The subjective performance impairments are evaluated using a fatigue symptoms based aggregated scoring system developed in de Alwis et al. 2016 and lo Martire et al. 2017, and presented as the number of fatigue symptoms. The fatigue symptoms based aggregated score system was developed considering the correlation of five fatigue symptoms: tiredness, concentration difficulties, decision making complications, headache and motion sickness with the perceived ride quality.

The subjective work exposure is mainly measured as perceived ride quality by 4-point ordinal Likert rating scale quantizing perceived ride quality as 1 = Very smooth (good comfort with no or very few bumps, 2 = Smooth, 3 = Rough, 4 = Very rough (considerable discomfort or strain as a result of sea state, vessel speed, or both).

The objective vibration exposure, measured as acceleration, is quantified by daily equivalent static compression dose (S_{ed}), [ISO 2631-5:2004]. This method considers adverse effects on the lumbar spine as the dominating health risks of exposure to vibration containing repeated shocks.

3. RESULTS

All eight subjects have answered Q1 and the daily part of Q2 where only six have answered the weekly part of Q2. The response sequence can be seen in Table 1.

Table 1: Response sequence of Q2.

Respondent ID	Number of Responses			
	Q2 – Daily			Q2 - Weekly
	At sea	Not at sea	%★	
P1	6	0	15.0	1
P2	1	0	2.50	2
P3	1	1	5.00	0
P4	6	0	15.0	3
P5	12	5	42.5	1
P6	2	1	7.50	0
P7	14	11	62.5	2
P8	11	9	50.0	6

★ *Calculated considering Norwegian occupational regulations demanding an average two-day rest per week.*

Of 80 responses, 27 are related to non-seaborne activities.

General health status

According to the data collected by Q1, 7 out of 8 subjects got musculoskeletal pain in different body areas considering the past six months period whereas majority of them, 5 out of 7, having neck and lower back pain. Prevalence of musculoskeletal pain in different body areas considering past 6 months and 7 days is provided in Table 2.

Table 2: Prevalence of musculoskeletal pain in different body areas considering past 6 months and 7 days.

Pain Area	Number of Subjects	
	6 months	7 days
Neck	5	0
Lower back	5	0
Head	2	1
Knee	2	0
Lower leg	2	0
Shoulder	1	0
Upper back	1	0
Elbow	0	0
Forearm and wrist	0	0
Hip and thigh	0	0

It can be seen from the results that only one person was having head pain during the past 7 days period. The occurrence of new pain events during the eight-week exercise program are shown in Table 3.

Table 3: Occurrence of new pain events during eight-week exercise program

Pain Area	Number of Subjects
Neck	5
Lower back	4
Head	1
Knee	2
Lower leg	0
Shoulder	1
Upper back	4
Elbow	1
Forearm and wrist	2
Hip and thigh	0

Four subjects believed that the cause for their pain events was work at sea.

Table 4 shows the measured and perceived vibration exposure and the performance indicators during the first four weeks of the exercise. Subjective data is not available on certain days. Vibration levels on the craft floor indicates about the exposure without a shock mitigation seat.

Table 4: Measured and perceived vibration exposure and the performance indicators during the first four weeks.

Week and Day★	Craft ID	Analyzed Duration [Hours]	S_{ed} [MPa] Craft Floor	On Seat	Respondent ID	Task	Ride Quality	Fatigue Score+
W1-D1	C2	1.6	0.6	0.5	P7	D	VS	1
				0.5	-	N	-	-
W1-D1	C5	2.2	0.7	0.8	P5	D	S	1
				0.5	P8	N	VS	2
W1-D5	C2	0.6	2.1	1.9	P7	D	VS	0
				1.7	-	N	-	-
W1-D5	C5	0.5	2.2	1.8	P5	D	R	1
				1.9	-	N	-	-
W1-D6	C5	0.4	0.8	0.8	-	D	-	-
				0.9	-	N	-	-
W1-D7	C5	0.3	0.3	0.2	P7	D	VS	1
				0.3	-	N	-	-
W3-D3	C1	8.2	6.5	5.4	P5	D	VR	2
				6.9	P8	N	R	3
W3-D4	C1	5.3	5.4	4.2	P5	D	VR	2
				5.5	P8	N	R	3
W4-D2	C3	1.3	1.7	1.1	-	D	-	-
				1.2	-	N	-	-
W4-D5	C3	3.0	1.1	0.7	-	D	-	-
				0.7	-	N	-	-
W4-D6	C5	1.5	1.2	1.2	-	D	-	-
				1.2	-	N	-	-

★ *W – Week, D – Day of the week*
+ *Fatigue score - Number of fatigue symptoms*
D – Driver, N – Navigator
S – Smooth, VS – Very smooth, R – Rough, VR – Very rough
– Data not available

Perceived ride quality shows a correlation with the measured acceleration exposure as can be seen in Figure 3.

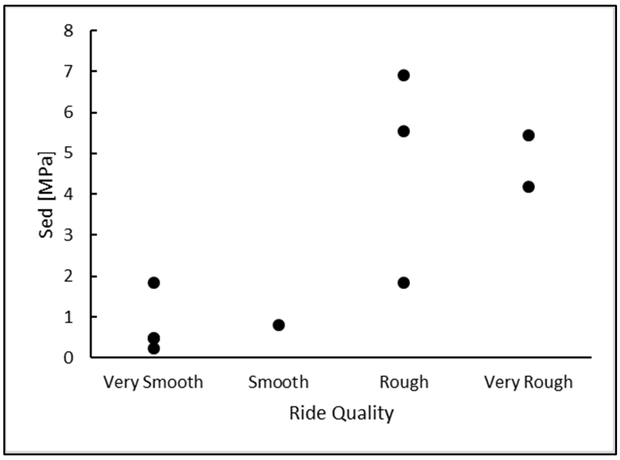

Figure 3: Acceleration exposure relative to self-reported ride quality.

Figure 4 shows that, although no subject has experienced more than three fatigue symptoms, there is a correlation between the fatigue score and the measured acceleration exposure.

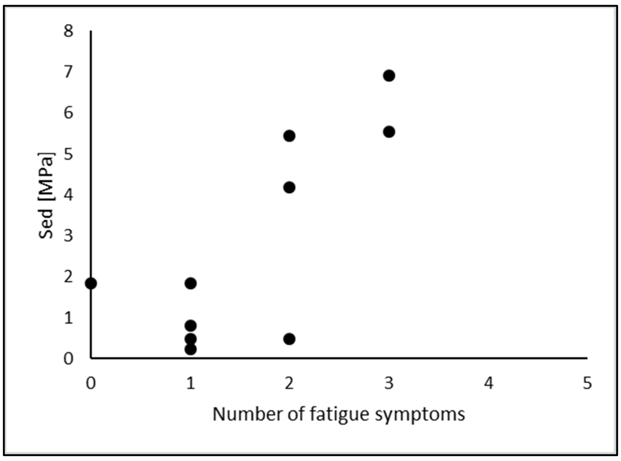

Figure 4: Acceleration exposure relative to fatigue score.

The response of the fatigue symptoms based aggregated scoring system to the perceived ride quality is shown in Figure 5.

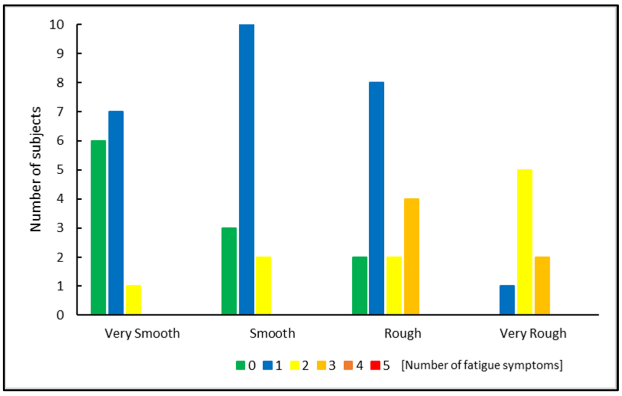

Figure 5: Response of the fatigue symptoms based aggregated scoring system to the perceived ride quality.

The results show that the number of subjects with 0-5 fatigue symptoms scores is proportional to the self- reported ride quality.

4. DISCUSSIONS

Eight Norwegian special operations command officers answered two web-based questionnaires providing data mainly on work exposure, musculoskeletal pain and performance indicators during a period of two months. Simultaneously acceleration data was also measured aboard the craft they operated.

Pain prevalence data during past 6 months shows that the body area based pain prevalence distribution differs from the general population, [Brattberg G et al. 1989, Fejer R et al. 2006 and Hoy D et al. 2012]. Prevalence of neck and lower back pain is higher than that of the general population. Since in Q1, the subjects reported that they had not experienced any pain during the past 7 days, it was decided that they had no prevailing pain, except head pain, at the time of starting the exercise. Most of the subjects got neck pain during the exercise followed by upper and lower back pain.

Since Figure 3 and 4 indicates that the subjective ride quality and the performance indicators (fatigue score) correlate with the measured acceleration exposure, the perceived ride quality can be used to grade the exposure severity as well as performance degradation, in the absence of measured vibration data.

It is observed, in Table 4, that in most occasions, despite the fact that driver and navigator had used shock mitigation seats, their vibration exposure levels (S_{ed}) exceed the upper limit for the lifetime exposure, i.e. 0.8 MPa, [ISO 2631-5:2004]. This tends one to think that there might be a relationship between vibration exposure and the health impairments in HPMCP, since the pain incidence is high. This relationship could further be investigated using a summary score of weekly vibration exposure with pain incidence or pain intensity data.

It is interesting to see, in Table 4, that perceived ride quality of the navigator is lower than that of the driver operating the craft. This might be due to individual perception differences or the navigator was concentrating on the navigation panel. A similar trend is observed in the other exposure categories such as sea conditions, wind conditions, noise level, temperature, sea spray and visibility. In certain cases S_{ed} levels on seat are higher than the levels on craft floor, a reason for which could be the varying body posture found by the daily part of Q2, i.e. mainly sitting, but standing in rough sea conditions. This problem could be addressed by introducing a sensor to the measurement system for indicating the occupant's posture, for instance, sitting or standing, which will provide information on another objective and subjective relationship, i.e. body posture.

It was found that the vibration measurement systems lack the requisite robustness to withstand the rugged environments. Some of the devices stopped recording data after experiencing large impacts and two systems completely broken during the first four weeks of operation. The objective data collection was affected by this issue since the craft installed with these defective instruments had been used for the exercises in many occasions. In certain cases self-reported data suggests that the duration of operation was about seven to ten hours per day where the measurement systems have recorded data for less than an hour. Moreover, GPS data confirmed that the subjective data is correct. Furthermore, it was identified that the objective vibration data was not available, in some occasions, as the crew had forgotten to switch-on the measurement system.

Another problem was the confidentiality of the population which hindered identifying the actual reasons for the missing data, for instance, the days when objective data is available but the subjective data is not and vice versa. It was also revealed that the subjects were not allowed to access their phones during several weeks due to which the study lost a large amount of subjective data. Availability of cellular network was also another critical issue with the data collection when the subjects spend multiple days out in the sea or forests.

During the eight-week exercise program, the study subjects had participated not only in HPMC operations, but also in other activities such as running, diving and parachute jumping, which could significantly affect their health and performance. It was difficult to account these effects in the analysis since their training schedules were confidential.

Even though the number of subjects was only eight, the results indicate correlations between the subjective and objective data which could be further improved by studying larger populations. Taking into consideration all the above aspects KTH in collaboration with Karolinska Institutet and the Swedish Coast Guard has now started the main study of investigating work exposure, health and performance of HPMCP and quantifying their association using measured vibration environments. Q1 and Q2 has now been updated based on the inputs received from this pilot study and more robust instruments have been occupied based on the lessons learnt. As a study population coast guards are mainly involved with sea going activities and the other activities affecting their health and performance are comparatively less. The population is sufficiently large and the mission-confidentiality is relatively low. The data collection has already been started with the baseline data set, i.e. Q1.

5. CONCLUSION

Although the amount of data collected is not sufficient to draw direct conclusions on the relationships between subjective and objective data and identification of related risk factors, the pilot study suggests that the set-up and the method are feasible. The inputs received, experiences gathered and the lessons learnt strengthened the main study which has already been started.

Important aspects in need of consideration after the pilot test are;

- Selection of study population.
  a) Size
  b) Activities
  c) Confidentiality
- Modifications to the vibration measurement system.
  a) Robustness in rugged environments
  b) User-friendliness, especially in data retrieval
  c) Start data recoding with craft ignition key
  d) Subject’s posture identification method
  e) Objective craft ID detection method
- Summary score method for the assessment of weekly vibration exposure in order to analyze the correlation between musculoskeletal pain and the vibration exposure levels.
- Mode of answering the questionnaires including the availability of cellular network signals.
- Further improvements to the questionnaires.
  a) More mechanisms for the identification of missingness of data
  b) Introduce memorizing features for one-time data, for instance, anthropometric and demographic data.
  c) Fatigue score system
  d) Resorting the items on priority basis
  e) Rephrasing the pain questions
- Introduce objective performance indicators to the study program, such as cognition, bio-marker and electromyography (EMG) data.

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