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# Multidisciplinary study of biological parameters and fatigue evolution in quay crane operators

P. Fadda[a,d], M. Meloni[d], G. Fancello[a,d], M. Pau[c], A. Medda[a,d], C. Pinna[a,d], A. Del Rio[d], L. I. Lecca[b,d], D. Setzu[d], B. Leban[c]

[a]*DICAAR, University of Cagliari, via Marengo, 2, Cagliari 09100, Italy*
[b]*Department of Public Health, Clinical and Molecular Medicine, University of Cagliari,Cagliari, Italy.*
[c]*DIMCM, University of Cagliari, via Marengo, 2, Cagliari 09100, Italy*
[d]*CenTralabs - Medical Section - Monserrato 09042, Italy*

**Abstract**

In intermodal terminals the handling of containers and the number of accidents still depends on a wide range of human errors due to fatigue despite the automation level reached nowadays. For this reason it is very important to increase knowledge about the factors affecting the propensity of operators to make errors, increasing the chance of accidents happening. The aim of this work is to propose a novel approach to assess fatigue and performance levels in quay crane operators as a function of physiological parameters and of the many varying boundary conditions encountered in daily work. During their work, quay crane operators have to deal with variable environmental conditions, such as task type, wind speed and direction, lighting conditions that reduce visibility that can require an exacting level of attention. In the trial eight operators have been examined in a session lasting four hours. All actual conditions are reproduced through a fully immersive quay crane simulator. The operator completes the assigned task (the same for each one) and can see through four wide monitors a high quality virtual reality view of the simulation. Most biological parameters are acquired using different devices including a Holter ECG monitor, electromyographic monitoring the four trunk muscles most involved in the test, eye tracker and seat-body pressure interface for both seat pan and backrest. Changes in physiological parameters have been monitored during the trial and interesting correlations with performance levels and boundary conditions have been found for each operator, in accordance with their age and skills. The present study can form the basis for further investigations aimed at developing a cost effective, reliable and robust system for monitoring increasing fatigue and for predicting the critical conditions that may result in an accident.


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*Keywords:* Quay crane operator; Simulator; Fatigue; Biological parameters


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## 1. Introduction

In maritime transport fatigue, impaired performance and human error in general, are the primary causes of a large percentage of accidents occurring in all transport systems [1].

Operators and human factors continue to play a central role, in spite of the high degree of automation achieved in recent years in the port sector, especially quay crane operation.

For this reason the human being becomes the pivot around which the system revolves in terms of safety. The *human factors* discipline is central to the design of the system and to the development of its components [2].

It has been ascertained that alertness, vigilance, fatigue, stress and performance all have physiological roots; these have a direct consequence on errors and on safety levels [3,4].

Previous research conducted on human fatigue prevention have focused on both the physiological mechanism and methods for measuring fatigue levels [5,6]. Current operator fatigue monitoring systems can be divided into two groups [7]: measurement of the extent and length of reduced alertness and real time development of drowsiness control and alarm systems [8].

Research efforts are currently focused on investigating the complex phenomenon of fatigue, the underlying internal and external factors and their interaction and most of these studies are based on simulation techniques [9]. .

Recently a cognitive definition of the factors causing work-related stress has been provided [10] distinguishing two macro areas, 1 physical (heat, cold, noise, vibrations, etc.) and physiological (lack of sleep, dehydration, muscle fatigue, etc.) and 2 mental: cognitive (too much or too little information, judgement difficulties, etc.) and *emotional* (pressure, frustration, boredom, monotony, etc.).

Physiological measurements are used to evaluate the early onset of fatigue and drowsiness, the most common being the electroencephalogram (EEG). Behavioural measurements, that have recently gained credibility, are used to gauge fatigue and are based on the frequency of body movements: the number of movements recorded during task performance over a specific time interval is significantly correlated with the EEG [11].

Fatigue can also be readily detected by observing facial behaviour: changes of facial expression, eye, gaze and head movements are all indicators of increasing fatigue. Others parameters such as eye movement and saccades are indicative of the level of alertness.

Many physiological and neurological modifications are induced by fatigue: in the literature the pupillary response is a widely used parameter for monitoring this phenomenon.

The pupil has the function of regulating the amount of light that reaches the retina by maintaining a constant lighting level but it also depends on emotional stimuli, mental workload and muscular fatigue. The autonomous regulation of pupil size provides an objective measure of alertness. In fact as alertness decreases, pupillary size becomes gradually smaller [12].

Increases in baseline pupil diameter are associated with decreases in task utility and disengagement from the task, whereas reduced baseline diameter is associated with task engagement [13].

In order to cope with the new challenges posed by globalization, job tasks such as mental and physical workloads have to be studied and re-designed to maintain workers health and improve their well-being and to achieve high productivity levels [14].

Most of the time quay crane operators work in harsh weather conditions or strong sunlight and prolonged awkward posture due to poor vision during part of the operations, working in isolation, tight deadlines and shift work may adversely affect their health.

Moreover the neck, shoulders, vertebral column, especially lower lumbar vertebrae, may be affected by musculoskeletal disorders and work related stress can affect the cardiovascular system.

Lastly, contact pressure at the body-seat interface has been found to be the parameter most clearly related to subjective ratings [15] and thus is widely used to characterize comfort levels in the automotive industry [16-20] as well as in office chairs [21].

## 2. Materials and methods

### 2.1. Sample

The quay crane operators tested work in two different Italian ports. In the following table their characteristics such as age, anthropometric characteristics and job seniority are shown (Table 1).

Table 1.Sample characteristics.

| | Age (years) | Height (cm) | Weight (kg) | Length of employment (years) |
|---|---|---|---|---|
| Operator 1 | 36 | 173 | 89 | 11 |
| Operator 2 | 29 | 187 | 108 | 11 |
| Operator 3 | 39 | 175 | 72 | 5 |
| Operator 4 | 27 | 199 | 116 | 8 |
| Operator 5 | 48 | 175 | 72 | 5 |
| Operator 6 | 35 | 175 | 77 | 8 |
| Operator 7 | 40 | 177 | 71 | 10 |
| Operator 8 | 40 | 183 | 78 | 13 |
| Average | 36,75 | 180,50 | 85,38 | 8,88 |
| SD | 6,67 | 8,86 | 17,53 | 2,90 |

### 2.2. Simulator

The quay crane simulator “CHAMELEON”, is an innovative system designed for the purpose of solving human factor related problems (sight, ergonomics, anthropometrics etc.) associated with quay crane operator tasks, as well as for conducting advanced training activities. The Chameleon simulator is located in a 40 ft. High Cube container (purposely chosen for its internal height of 2.70 m, higher than a standard ISO container, allowing more space for designing the main platform). This minimizes the time required to prepare training and research sessions, providing on-site training services for container terminal operators.

Like many training simulators, the “Chameleon” crane simulator consists of 4 main components:

1. cabin interface (cockpit): composed of seat and cockpit (commands, two manipulators, one for movement and the other for elevation of the spreader-container system). It is positioned on a motion platform (3 degrees of freedom) to perceive motion sensation.
2. the virtual image is reproduced by four display screens/drapes, that provide the trainee with 270° horizontal and 120° vertical field of vision.

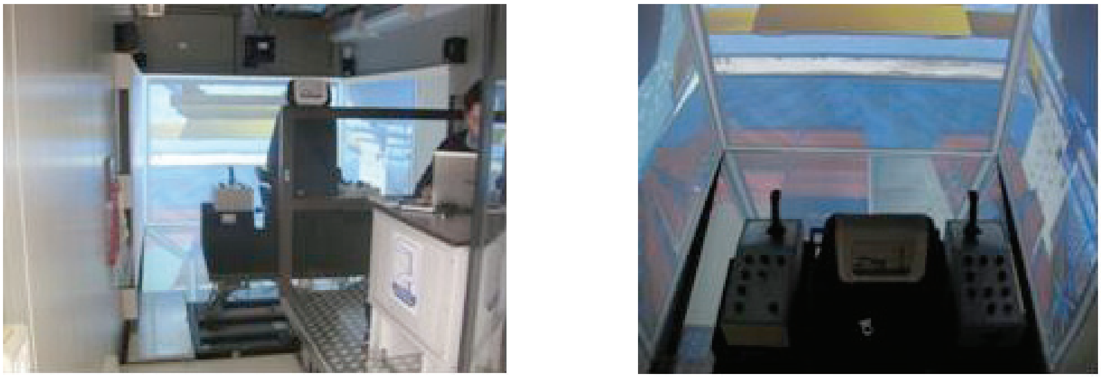

Fig. 1. Photo of (traditional) dynamic cockpit and graphic interface of the quay crane simulator.

3. the trainer observatory is external to the cabin and reproduces different simulation scenarios through the central operating system, varying weather conditions (wind, rain, sun, etc.), lighting (daytime with sunlight, night-time with artificial light) and tasks (import and export).
4. the visual system reproduces the real environment by means of projection screens and the audio system creates sounds effects due to vibrations (movement of the crane cabin on the portal), collisions, wind.

The simulator has been designed so as to allow the installation of different types of seats and cockpits, in order to test different ergonomic postures and suggest arrangements for improving the man-machine interface.

In our research project the dynamic Brieda® seat, provided with specific ergonomically designed seating arrangement has been used in each test.

All the events that occur during simulation are acquired, those imposed by the simulation (weather and lighting conditions) and those created by the operator (TEUs handled, errors).

The sample of eight quay crane operators with different expertise and job seniority undergo the same task. The test (lasting four hours) starts with relatively good weather in daylight, with wind blowing and good lighting conditions that at hourly intervals become gradually more challenging.

The simulator provides the following data:

- number of TEUs handled;
- number of errors (i.e. crashes of containers or moving parts of the crane with other elements);
- error severity (proportional to impact speed)

Moreover we propose a derived value of the number of TEUs handled, weighted to error severity, defined as the number of handled TEUs over error severity. Using this parameter operator productivity takes into account the operators' ability to handle containers carefully, as it increases with the number of handled TEUs and decreases as damage (error severity) increases.

Each worker was examined at rest (medical history, medical examination, ECG) before the test and during the test by means of a Holter ECG (Cardiette – giOtto Holter system) and an electro-myographic test (mega ME6000) on the trapezius and lumbar paravertebral muscles (spinal erectors). Heart rate (HR) and heart rate variability (HRV) were recorded throughout the test and under the different environmental conditions imposed by the simulator each hour.

The eye movements, the elements observed during the manoeuvres and the fixation times of each element in the visual field were recorded for each operator during the tests, using an eye tracker.

The eye tracker is an electro medical instrument, which allows that identifies the observed points and measures the fixation time and pupil size.

The instrument consists of a pair of glasses, where two cameras are installed, one focusing on the eye through a glass slide which reflects the cornea, the other on the external environment. The instrument uses a technique known as dark pupil tracking and it records the parameters every 0.03 seconds.

Body-seat interface pressure measurements were performed by means of two pressure sensitive mats (Tekscan 5330E 471.4 x 471.4 mm active area, 1024 sensing elements arranged in a 32 x 32 matrix, sensor pitch 14.73mm) that were placed in the seat pan and backrest. The sensors were connected to a two-port hub (Tekscan Versatek) using RJ-45 cables and then to a PC via USB connection. Prior to the tests, each mat was calibrated according to the manufacturer's instructions.

Pressure data were recorded for 4 consecutive hours (which is the typical duration of a work shift) setting the sampling frequency to 10 Hz. The original data were then post-processed using the Tekscan Conformat Research Software v. 7.10 to extract the temporal series of the mean body-seat contact pressure calculated on the whole mat area and for 4 sub-regions on the seat pan mat (i.e. left and right buttocks and thighs) and on the whole mat active area only for the backrest. Pressure values were extracted at 30 min intervals from the 'pressure vs. time' curves, so that 8 values were considered overall to define the trends of body-seat pressure throughout the whole shift. Note that as the curves are quite irregular due to the presence of seat vibrations, a linear fitting was performed on raw data before calculating the values of interest.

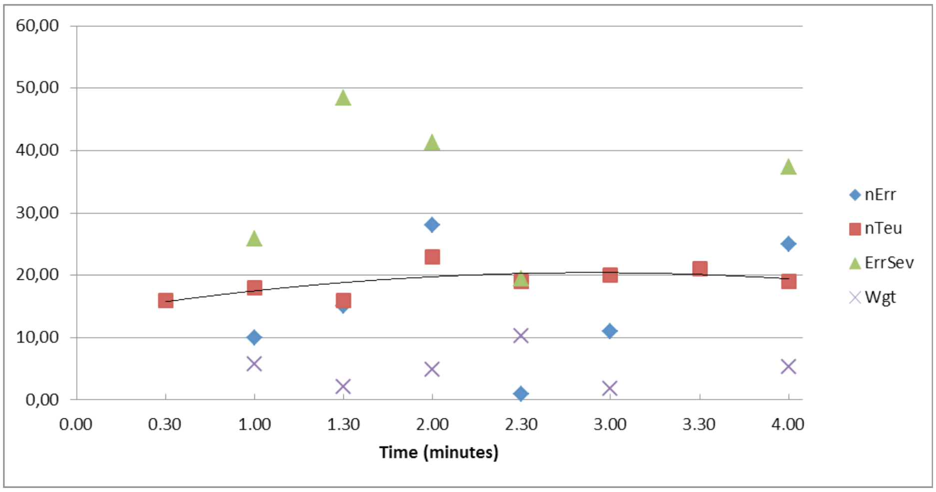


Fig. 2. Average heart rate measured every 30 min.

## 3. Results

### 3.1. Simulator

The simulator records the number of handled TEUs (NT), the number of errors (NE) and their severity (IS). The weighted productivity (WP) can then be derived.

Notwithstanding a sample frequency of 1Hz, in this step of the study the average values per 30 minutes were considered in order to detect the trend.

In figure 2 an example of the simulator parameters is shown, the number of handled TEUs clearly has a reverse U- shape, in agreement with Yerkes-Dodson's law [22]: in fact productivity is lower in the earlier and final phases becoming uniform and higher in the central part of the test.

The number of errors and their severity increases during the test.

### 3.2. Eye tracker

Pupil radius was recorded during the test and fluctuations were analysed each hour, corresponding to changes in lighting conditions imposed by the simulator at each hour of the test.

Average pupil radius of the sample was 78.12 pixels (SD = 8.35).

The largest pupillary size was measured for operator 5, the oldest of the operators tested (48 yrs), the lowest for operator 6 (35 yrs) the youngest blue-eyed operator.

The hourly average values show that pupil size decreases from the first to the second hour, progressively increasing up until the end of the test as the environment becomes darker.

It is widely accepted in the literature that pupil size is larger when the operator has the highest level of alertness and decreases progressively due to fatigue, down to a minimum size before drowsiness. In this test the reduction in pupil size due to fatigue was offset by the environmental lighting that was gradually reduced over the four hours.

Regression curves were separately estimated for each hour, in order to detect the change in pupil size caused by fatigue and not due to the reduction in environmental lighting.

In some cases, the trend is more marked and assumes the U-shape (as shown in Fig. 3 for operator 2), in other cases the variation is less evident (operator 1).

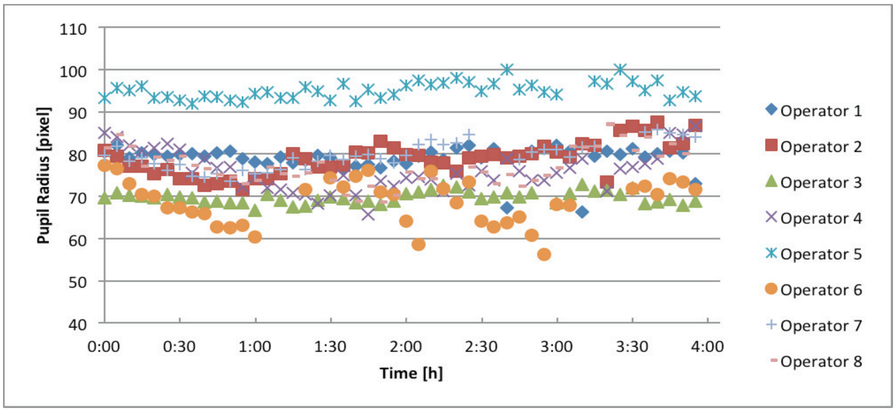


Fig. 3. Average pupil radius per 5 min. for each operator.

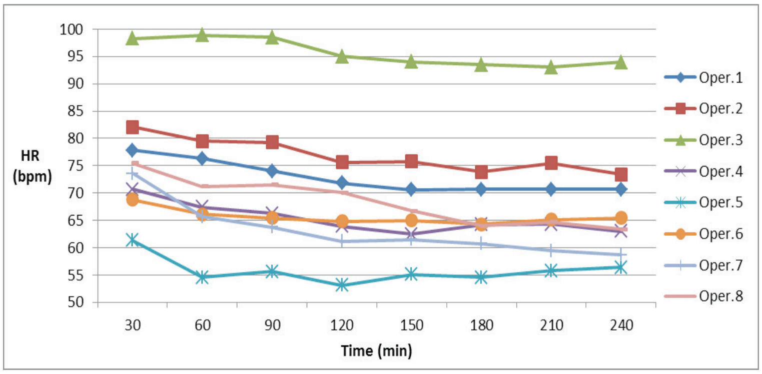


Fig. 4. Average heart rate measured every 30 min.

### *3.3. Behaviour of cardiovascular system*

In our study we focused on heart rate (HR) and heart rate variability (HRV) to evaluate the behaviour of the cardiovascular system for this specific task.

HR, expressed by beat per minute (bpm), showed a significant decrease during the four hours of the test (Fig. 4). HRV was evaluated by standard deviation normal to normal sinus beat (SDNN) throughout the four-hour test and each hour. The comparison of the first (average SDNN 67.76) and last hour HRV values (average SDNN 68.15) of work showed no significant difference. These preliminary results suggest that HRV as a measurement of autonomic function is not indicative of high cardiovascular stress in the experienced workers tested.

### *3.4. EMG*

To evaluate the contraction of both trapezius and spinal erector muscles we calculated mean muscle activation levels for every single muscle during each hour.

In six operators out of eight, we found a reduction of the mean contractibility values that shows good performance and a low level of muscular fatigue in neck-shoulders and lumbar muscles.

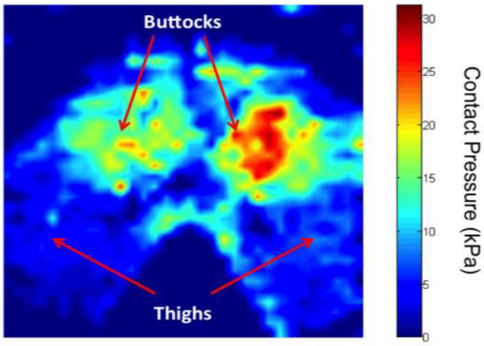


Fig. 5. Example of body-seat contact pressure distribution during the trials (seat pan).

### *3.5. Body-seat contact pressures*

The mean contact pressure calculated on the whole surface of the two mats, shows that the pressure on the backrest decreased from 5.5 to 5.2 kPa, while in the seat pan the pressure increased from 7.4 to 8.2 kPa. The detailed analysis of the 4 sub-regions, shows that at the beginning of the experiment, the contact pressure on the buttocks was 9.1 and 10.6 kPa respectively for the left and right side, while lower values were observed on the thighs (4.4 kPa left, 5.6 kPa right). As the trial progressed, the buttock mean pressure tended to decrease, with a more marked trend on the left side (a 6% reduction was observed after 4 hours). At the same time, the pressure on thighs tended to increase (10 and 20% respectively for right and left side). It is worthy of note that the right limb appears characterized by higher contact pressure, regardless of the part considered, with respect to the left. An example of pressure distribution on the sensitive mat during a trial is reported in figure 5.

## 4. Discussion

We have monitored several physical parameters, such as heart rate, heart rate variability, pupil size, thighs and buttocks pressure and trapezius and spinal erector muscle contraction level.

In this study we present the preliminary results for a small group of eight quay crane operators,

Throughout the four hours of testing heart rate shows a clear and significant decrease in the fourth hour compared with those recorded in the first hour. Change in the activation of the autonomic nervous system, measured as the variation of RR intervals, (SDNN) does not show any significant decrease, comparing the values for the first and last hours. These results indicate that the cardiovascular system has good compliance with the workload and stress in this ergonomically designed seating arrangement.

Only in the first hour of the test was it possible to detect any variation in pupil size due to fatigue, as in the other three hours pupil diameter was mainly altered by the environmental lighting conditions.

As regards the body-seat interface contact pressures, our results appear to suggest that as work progresses, operators modify their posture in such a way as to reduce stress on buttocks (likely to attenuate discomfort) by shifting a larger part of their body weight to the thighs which, not being characterized by the presence of bony tuberosities (as occurs in the ischial region), are less prone to stress concentrations.

## 5. Conclusions

In this work we propose a methodological approach for analysing the performance of quay crane operators, their productivity and biological behaviour, for this specific job task. The proposed methodology, based on a simulation environment, aimed to objectively evaluate the quantity and quality of work performance and to detect early signs of fatigue.

Moreover the simulator layout can be easily modified, making it possible to tests several ergonomic solutions for improving working conditions, such as for example the new dynamic Brieda® seat used in this test.

Technology and work organization affect productivity that still remains the most important factor for assessing the efficiency of a container terminal.

Well-trained operators can safely manage the normal situations taking place in container terminals, and appropriate vocational training contributes to reducing fatigue and to better cope with the workload, which affect the probability of making errors. A simulator is recommended when the use of real equipment and the execution of real operations are too expensive or too dangerous, as in the maritime sector.

The simulator also improves the feedback provided by operators during training and testing new solutions.

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