Applied Ergonomics 65 (2017) 105–111

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Changes in trunk sway of quay crane operators during work shift: A possible marker for fatigue?

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ARTICLE INFO

Article history:
Received 10 February 2017
Received in revised form
15 April 2017
Accepted 5 June 2017

Keywords:
Sitting posture
Trunk
Postural sway
Quay crane

ABSTRACT

This study investigated changes in task-induced trunk sway of quay crane operators during a four-hour shift performed in a dedicated simulator as an indicator of postural control system effectiveness. Using a pressure sensitive mat placed on the seat pan, center-of-pressure (COP) time series were acquired and processed to calculate sway area, path length and COP displacements and velocities. The results show a well-defined linear trend for sway path and area, with significant increases starting from 65 to 155 min of work respectively. This indicates non-optimized trunk control most likely originated by the combination of physical and cognitive workload and suggests a possible role of long-term monitoring of trunk sway of crane operators as a useful tool in detecting non-optimized movements potentially associated with deteriorating performance.

1. Introduction

Intermodal freight transport is based on containerization, a system that allows standardization of the transported units and mixed sea/land goods transfer and delivery. A critical role in this process is played by quay crane operators assigned to moving containers from and to vessels by means of large cranes. Such operations take place in cabins suspended on a trolley at a height of 30–40 m above ground level.

All handling manoeuvres are performed in view from a control station by exploiting the cabin's glass walls and floor which allow direct visual of both ship and quay. This forces operators to adopt static and non-neutral sitting postures, particularly as regards neck and trunk, which lasts 4–6 h (the typical shift duration). This fact, together with the high level of vibrations present in the cabin, represents a risk factor for musculoskeletal problems (NIOSH, 1997; Bovenzi et al., 2002; Pigini et al., 2006; Huysmans et al., 2006) and may influence the worker's performance (Bhatnager et al., 1985) in terms of operational efficiency (i.e., reduction in the number of containers loaded/unloaded) and safety of the process.

During the work, the repeated forward flexion necessary to check the container position while it is moved over the quay tends to overstress the trunk muscles that provide spine stabilization. It would thus be important to have indicators for early detection of possible critical conditions leading to trunk instability, as they would reflect non-optimal postural control that might trigger the onset of discomfort, fatigue and, in the long run, overuse injuries.

One possible way to investigate trunk control during a seated posture involves the analysis of postural sway through processing of the center-of-pressure (COP) time series. Postural sway, namely the small oscillations that express the synergic action of nervous and muscular systems to keep the body balanced (Era and Heikkinen, 1985), has been investigated for several decades in the case of upright posture, and its features are extremely useful in characterizing the performance of the postural control system. In particular, small amplitude and low speed of sway are signs of effective control in terms of a small amount of effort being needed to maintain the posture (Era et al., 1997).

While sway analysis is usually performed in upright stance conditions, in recent times several researchers have proposed a specific application of this approach to seated posture, thus focusing attention on the sole stability of trunk (Vette et al., 2010; Serra-Añó et al., 2015). Similarly to what has been found for standing, it has been demonstrated that trunk stability is conditioned by sensory and motor impairments caused by brain and spinal cord injuries (Genthon et al., 2007; Perlmutter et al., 2010;

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http://dx.doi.org/10.1016/j.apergo.2017.06.007

Milosevic et al., 2015), neurodegenerative diseases such as Parkinson's Disease (van der Burg et al., 2006) and multiple sclerosis (Lanzetta et al., 2004) as well as musculoskeletal disorders such as low back pain (Radebold et al., 2001).

Interestingly, it has also been observed that trunk sway increases with fatigue, although few studies have investigated this issue. Hendershot et al. (2013) found evidence for an exposure-response relationship between trunk flexion and COP-based measures for the trunk in young adults. Similarly, van Dieën et al. (2012) observed significant increases in trunk sway amplitude in young elite gymnasts after a fatigue protocol for flexor and extensor trunk muscles composed of exercises similar to those performed during their regular training activity.

On the basis of the aforementioned considerations, it appears of interest to verify if, in the case of crane operators, the analysis of task-induced trunk sway can provide information potentially able to indirectly assess discomfort and fatigue. Thus, the aim of the present study is to perform long-term monitoring of trunk movements in a sample of professional quay crane operators under conditions similar to those encountered in their actual working environment. The hypothesis to test is that the prolonged time spent in uncomfortable posture during the task execution induces anomalous non-optimized trunk movements of magnitude related to the task duration.

As security reasons prevent data collection in commercial ports during regular vessel loading/unloading operations, the experimental tests were carried out in a dedicated simulator where workers performed their operational tasks with the same control station and for a shift duration equal to those in their real working environment. Results are discussed to highlight the possibility of using this approach to detect anomalies in the postural control system effectiveness associated with a prolonged constrained sitting posture.

2. Methods

2.1. The quay crane simulator

The experiments described in the present study were all carried out on a custom quay crane simulator (the “Chameleon Simulation Team Portainer” Bruzzone et al., 2011) installed in a 40-foot container which served as a mobile shelter. The simulator is equipped with a commercial control station (Brieda DYCS, Brieda Cabins, Italy) used in several ports worldwide. It includes a seat and a console with two joysticks that allow control over quay and spreader movement as well as engagement and disengagement of spreader/container coupling when the container has to be hoisted or put in place. The control station is mounted on a movable platform with six degrees of freedom controlled by a computer that applies vibrations, rotations and translations of suitable amplitudes associated with the task currently performed by the operator, according to patterns previously acquired in actual quay cranes. Four large screens located in the front, sides and under the feet of the operator reproduce the visual field of the quay crane cabin. The screens were placed at the same distance which separates the glass walls of the actual crane cabin from the operator's position to ensure that both visual and postural conditions are faithfully reproduced on the simulator.

The computer also controls all environmental conditions that may influence the operator's performance, including presence of rain or fog, wind direction and intensity, wave motion, position of sky entities (moon, sun, stars) and impose the loading/unloading schedule to/from the container ship. All operator's manoeuvres are logged during the simulated shift and, at its end, a detailed report containing performance indicators (i.e. number of containers loaded/unloaded per hour) and adverse events (i.e.number of collisions) is available.

2.2. Participants

Sixteen male professional quay crane operators (age 37.3 ± 5.1 years, stature 178.5 ± 8.2 cm, body mass 79.2 ± 14.7 kg, working experience 6.2 ± 3.6 years) currently employed at the commercial ports of Gioia Tauro and Livorno (Italy) were recruited for the study. They were informed about the purposes of the study as well as the experimental methodology and signed a written informed consent form.

Although all of them were familiar with the control station used for the experimental tests, as they routinely employ it in their respective workplaces, before the test sessions they were allowed to practice to feel confident with the simulator's response. At the beginning of the data collection session, participants were instructed to transfer as many containers as possible in a safe manner (i.e. avoiding any collision) from ship to shore following a predetermined unloading schedule provided by the computer. The typical work cycle they had to follow included the following phases: the spreader is first moved over the selected container, then locked to the container and hoisted to the maximum clearance height. The crane then travels with its load along the bridge rails to the container-stacking bay, where the container is placed on a truck. Professional operators repeat this sequence at least 20 times per hour (Bruzzone et al., 2009).

2.3. Trunk sway data acquisition and post-processing

Task-induced trunk sway was calculated on the basis of COP time series acquired by means of a pressure-sensitive mat (Tekscan 5330E 471.4 × 471.4 mm active area, 1024 sensing elements arranged in a 32 × 32 matrix, sensor pitch 14.73 mm) located on the seat pan (Fig. 1).

The sensor was connected to a two-port hub (Tekscan Versatek) using RJ-45 cable and then to a PC via USB connection. Prior to the tests, the mat was calibrated according to the manufacturer's instructions. COP trajectories were recorded for 4 consecutive hours, setting the sampling frequency to 10 Hz. The raw data were exported as an ASCII text file using the Tekscan Conformat Research Software v. 7.10, and then processed using dedicated custom software developed under the Matlab® (The MathWorks, Inc, Natick, MA, USA) environment, which allows calculation of the following sway parameters:

- Sway area (SA, 95% confidence ellipse, mm^2),
- Sway path (the overall distance travelled by the COP during the trial, mm)
- COP maximum displacements (the difference between the maximum and minimum values of the selected coordinate recorded during the trial, mm) in the antero-posterior (AP) and medio-lateral (ML) directions
- COP velocity (calculated as the average of the instantaneous values recorded during the trial, mm s^{-1}) in the AP and ML directions.

The sway parameters were calculated for 10-min intervals and thus a curve containing 24 points was obtained for each trial and each parameter. The first interval (from the beginning of the test to $t = 10$ min) was assumed as the baseline reference value.

2.4. Statistical analysis

Changes in trunk sway parameters induced by the work shift