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Quest Q-348 Sea Trial: Human Postural Stability Studies

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Abstract - Postural stability modelling and analysis that attempts to quantify the effect of high-severity ocean environments on human performance offers the potential for providing practical insight into activities ranging from operational planning through ship design. Due to the magnitude and range of motions experienced, it is difficult to validate these models without actual rough weather sea trial data. This paper summarizes the procedures and results of postural stability and human factors research which took place on the Q-348 Quest sea trial over the course of eight days in November 2012. Thirteen participants took part in an experiment carried out by Carleton University and DRDC Atlantic researchers. Measurements were made using two full-body motion capture systems, foot pressure insoles, a six-axis load cell, and a head-mounted vision/inertial measurement system. Participants were also provided with a cognitive task to complete while maintaining balance. These tools provided quantitative measurements for the inputs and outputs of the human postural control system as it maintained balance in a typical ocean environment.

Keywords**:** Quest, human postural stability, sea trial.

1. Introduction

One of the applications of modelling human postural stability is to quantify the effects of moving environments on human performance. For instance, shipboard motion environments can hinder a person's ability to perform specific tasks which in turn can result in increased costs of commercial vessels and less effective warships (Graham, 1992). Opportunities may exist to introduce postural stability analysis earlier in ship design cycles thereby leading to more relevant ship design and operations. Research in this subject area is current and ongoing, as researchers have not agreed on what model complexity is needed to accurately predict incidents of loss of postural stability. One of the deficiencies in this area is the lack of experimental shipboard data that focus on human performance in various sea conditions while performing various shipboard activities.

In order to address the need for relevant experimental data, a number of postural stability experiments were carried out on board Canadian Forces Auxiliary Vessel (CFAV) Quest during the Q-348 sea trial from November 20th through November 28th, 2012. Thirteen participants took part in postural stability and cognitive efficiency experiments carried out by researchers from Carleton University and Defence Research and Development Canada (DRDC) Atlantic. Participants took part in 90-minute experimental sessions in which they were asked to maintain balance while performing a cognitive task, and at various orientations with respect to the ship centreline. The data measurement procedures in this experiment were unique in that they attempted to measure all of the sensor inputs that a person might use to maintain balance. This experiment was also unique in its use of a cognitive task to investigate the overall impact of motion induced interruptions on task performance from a memory for goals theory point of view. This paper presents the context of the current research and the data measurement technologies and procedures that were used to measure human performance in the Q-348 sea trial.

2. Background

The ship design community quantifies a loss of stability of a person on board a ship at sea using the rate of motion induced interruption (MII). This rate is a measure used to represent the number of loss-of-balance events that occur during an arbitrary deck operation (Graham, 1992). It is typically measured as the number of MII events per minute. A loss of positional stability is typically defined as the time when a subject in a moving environment has to stop their current task and grab on to something or focus on stability in order to maintain their balance (Crossland, 2007).

Since the 1990s, various human balance models have been created to predict the occurrence of MIIs. Records of experimental MIIs are used in combination with biomechanical models of the human body to construct models that predict the frequency of MIIs for a standing person during particular ship movements or sea states. Using these results, one can generate criteria as to when it is safe or dangerous to perform particular shipboard tasks (Wertheim, 1998).

Similar experiments to the ones presented by this report were carried out aboard Quest trial Q-303 in 2007. Those experiments were different in that their execution was the primary objective of the sea trial (rather than a secondary objective), and incorporated a variety of tasks and measurement strategies contributed to by a multi-national group of researchers from Australia, Britain, Canada, and the Netherlands. The Canadian contributions were provided by Memorial University of Newfoundland, the University of New Brunswick, and DRDC Atlantic (Colwell, 2008). That sea trial is the first known attempt at quantifying MIIs in an at-sea shipboard environment for which the transient ship motion and times of occurrence of MIIs were recorded. During the Q-303 sea trial, 12 subjects were asked to perform a series of manual materials handling (MMH) tasks. The subjects were videotaped such that MIIs, as defined by an adjustment in their stance, could be identified through post-experiment analysis of the video records (Duncan, 2010). Overall, the current experiment is similar to the Q-303 sea trial, but with more precise and extensive use of data measurement systems.

In recent years, research within the Applied Dynamics Laboratory at Carleton University has been focused on the use of articulated dynamic models in prediction of MIIs. Developments include a model that combines an inverted pendulum and a four-bar linkage (Mckee, 2004), a spatial inverted pendulum (Langlois, 2010), and most recently an expansion of the Graham block model which incorporates spatial dynamics, stance position and orientation, and footprint geometry (Morris, 2013). The current research project's primary goal is to develop a four-link inverted pendulum model which is intended to represent the motion and control of ankles, knees, waist, and neck. The objective of the project is to develop a control system for those joints, which behaves similarly to a human, or that represents stability parameters that can be directly related to those of a human in the same motion environment. In order to meet this objective, it is necessary to perform balance experiments with human participants in moving environments that record human body motions and the inputs that human senses use to determine the body's position and orientation.

In order to simplify the modelling process, previous MII research has assumed that ship personnel wait until they are about to lose their balance before taking a step or holding on to something in order to maintain balance. In practice, however, people tend to anticipate interruptions sooner and compensate before absolutely necessary. There is research that has studied this phenomenon (Maki 1997, Santos 2009, Aruin 2010) but very little work has been done within the maritime community. This research project is addressing this by investigating the impact of anticipatory motion and the participant's location relative to the ship centreline. It also intends to incorporate MII recovery time and strategies into the model's control system.

To date, DRDC Atlantic has investigated the impact of motion environments on the operational effectiveness of naval personnel in the Canadian Forces by assessing their perceived ability to accurately and efficiently perform tasks at sea (Colwell, 2000). As part of this research, the performance assessment questionnaire (PAQ) was distributed to personnel on seven ships belonging to the NATO Standing Naval

Forces Atlantic fleet (STANAVFORLANT) (Colwell, 2000). The survey indicated that reduced concentration and increased mental fatigue had a negative impact on task completion time especially when performing cognitive tasks. As such, the current research set out to further investigate the impact of motion on cognitive task performance, especially as it relates to task completion time. To do this, a cognitive data logging task was incorporated into the Q-348 sea trial's experimental protocol. The logging of numerical data was chosen as the cognitive task because it is similar to tasks that are regularly performed by a number of crew members aboard these vessels. In these settings, both the accuracy and timeliness of logged data is vital to the crew's tasks while at sea, and to the debriefing that occurs once the vessel has returned to port.

Another important consideration for this research was the introduction of touch screen tablet technology into motion environments. Given that the use of tablet technology is on the rise in various domains, this was an ideal opportunity to explore the feasibility of touch technology in motion environments. While the introduction of tablets into naval domains seems like a logical next-step, there are a number of human factors considerations that require investigation. For instance, a recent study (Chourasia, 2013) found that participants using a tablet in a standing position had significantly slower time to completion and increased errors when performing a typing task compared to participants who were sitting. These researchers also indicated that button size has an impact on performance in participants who are standing but not for those who are sitting. Given the intricacies of motion environments, there is an even greater need to assess the impact of tablet use on human performance. As a first step in evaluating tablets in motion environments, participants were asked to perform the data logging task using both the traditional method and with an electronic tablet. Time to completion and accuracy will be compared between the conditions to assess if there are significant differences in human performance as a result of tablet use.

In addition to assessing the impact of motion on cognitive performance, this experiment also presents a unique opportunity to isolate MIIs to assess the specific impact they have on accuracy and task completion. To date, the cognitive interruption literature has mainly focused on the impact of cognitive interruptions on tasks. Theoretically, there is reason to believe that memory for goals theory, which stipulates that the cognitive impact of an interruption is correlated with the amount of time it takes an individual to recover from the interruption and continue their interrupted task (Altmann, 2002), would also apply to MIIs. The current experiment allows this concept to be expanded upon by including the impact of motion interruptions and technology use on cognitive performance and efficiency.

3. Quest Q-348 Sea Trial

CFAV Quest is a civilian-crewed ship used by DRDC Atlantic for research purposes. The ship is a dredger type, built in 1969, and has an overall length of 76 metres and a beam of 10 metres. The ship has been modified for acoustic research by shock-mounting all of its engine components which minimizes vibrations outside of the engine compartments. This makes it ideal for any sensor measurements that involve motion.

There are two main laboratory areas on board Quest. During the Q-348 Quest trial the larger aft lab area was used for a concurrent unrelated research experiment and the smaller mid-ships laboratory was allocated to human motion experiments. Figure 1 shows the location of the lab area within the ship.

The ship left Halifax harbour at approximately 1020 on Tuesday, November 20, 2012, and returned to the dockyard at approximately 0900 on Wednesday, November 28, 2012. The ship spent the majority of its time in the Emerald Basin, an area of water approximately 50 nautical miles off the coast of Nova Scotia, Canada. The primary experiment required the launch of four wave buoys followed by navigating the ship along specific patterns for the remainder of the experiment. The wave buoys were launched as soon as Quest arrived at the Emerald Basin late on November 20 and were retrieved once the weather had settled on November 27. A recording of significant wave height made by one of the buoys is shown in Figure 1. As can be seen in the figure, there were two main periods when the waves were sufficient in amplitude for gathering useful high-sea data.

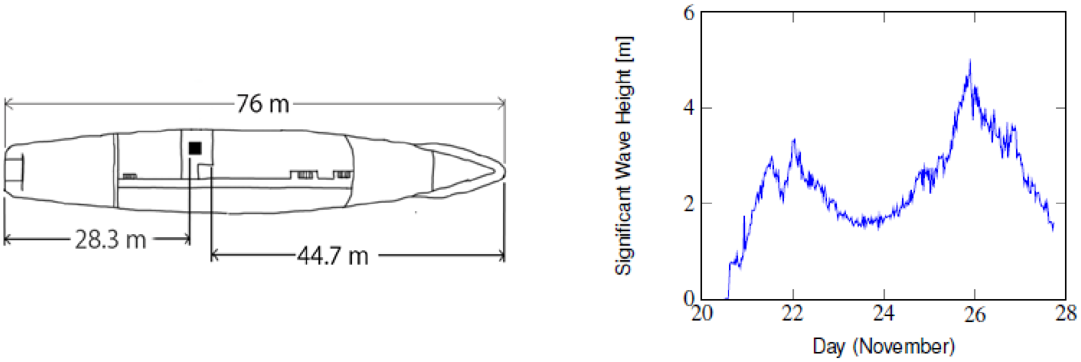

Fig.1. Position of motion capture platform within mid-ships laboratory on board CFAV Quest (left) and significant wave height over the 8-day sea trial (right).

4. Data Acquisition

This section describes in detail the data recording equipment that was used during the sea trial experiments.

4. 1. Experimental Procedures

Due to the goals of this project being secondary to Q-348's primary research goals, participants consisted of volunteers from the crew and scientific staff who were already on board the ship. Of the 35 crew and scientists on board, 13 volunteers were able to take part in the experiments. Of the 13 volunteers, 10 were male and 3 were female. There were no restrictions on who was permitted to participate. The motions experienced by the participants were no different from what they already would have experienced by being on the ship, so there was no increased physical risk to participants by taking part in the study. Each participant was provided with information about the experiment and was required to sign an informed consent form before the experiment. They were also informed that they could withdraw from the experiment at any time.

Each participant was allocated 90 minutes, in order to allow for a sufficient amount of time for data collection without interfering with their normal schedules. Of that 90 minutes, 20-30 minutes were spent setting up and calibrating the instrumentation, 40 minutes were spent collecting the data, and the remaining time was spent processing the data between trials. Participants took part in 6, 6-minute trials which were divided evenly between three possible orientations: 0°, 45°, and 90° with respect to the ship's longitudinal centreline. Attempts were made to ensure that the ship heading and speed remained constant through a set of the three orientations, but this was often not feasible given the time restraints of the participants and the amount of time spent on each heading.

While maintaining balance, participants were asked to perform a data logging task using a pen and paper attached to a clipboard and then again with an electronic tablet. Each experimental trial was divided into 3 minutes using the clipboard and 3 minutes using the tablet. In both versions, participants were given a list of 3-digit numbers and were required to transcribe a new list using only the odd numbers. It was not possible to finish the task within the allotted time so participants were transcribing for the full 3 minutes.

Since one of the goals of the experiment was to measure each of the possible human sensory inputs used to maintain balance, a variety of data acquisition technologies were used during the experiment.

Two different motion capture systems were used to record body positions and joint angles:

- Natural Point Opti-track full-body motion capture system and Arena software, which uses reflective markers and 8 cameras positioned around the lab to record body positions.
- Microsoft Kinect sensors and iPi Recorder/Studio software packages, which use the Kinect's depth camera to determine the positions and orientations of joints in 3D-space.

In order to obtain somatosensory, or skin pressure data from the bottom of a person's feet, two systems were used to measure foot pressure data:

- Tekscan F-Scan system which consists of two instrumented insoles that are wired to a computer.
- An ATI Industrial six degree-of-freedom load cell which is located underneath a plate that the subject kept one foot on.

Two instruments were attached to the helmet that participants wore during the experiment. The first was an Xsens inertial sensor that measured angles, angular velocities, and linear accelerations similar to the human vestibular system. The second was a GoPro camera that recorded what participants were looking at during the experiment.

There were two additional sensors used during the experiment. A Crossbow AHRS400 inertial sensor was installed on the floor near where the participants were required to stand during the experiments. This sensor recorded the motions that the participants experienced. Also, an additional video camera was used for future verification of collected data and to gain additional insight into the motions of particular participants if required during subsequent data analyses. An image showing one of the researchers fully instrumented is shown in Figure 2. Additional ship data were made available due to the primary sea trial experiment. These included additional inertial sensor data, wave height data, and ship heading data.

4. 2. Opti-track

The Opti-track system was the primary motion tracking system used. NaturalPoint is a recognized industry leader in motion capture technology. Although one must be meticulous during its camera calibration and skeleton calibration procedures, the resulting motion capture data are accurate, at a high frequency, and quickly compiled from the individual camera recordings. The system consists of 8 high-speed cameras arranged around the lab (up to 12 can be used), and 34 or 38 reflective markers affixed using velcro to a skin-tight black suit worn by the motion capture target.

Overall the system was able to obtain the motion capture data that were required: positions and orientations of feet, legs, waist, chest, and head. Unfortunately it was frequently deficient in associating the correct markers with their corresponding body part due to marker occlusion.

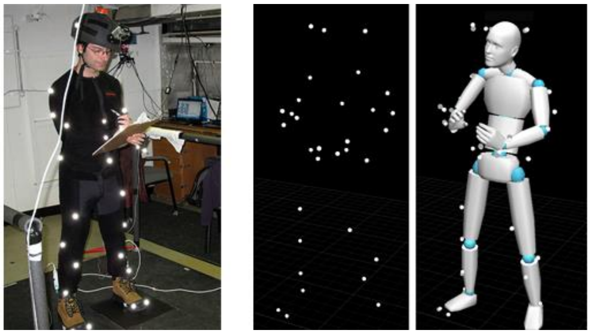

Fig. 2. Fully-instrumented researcher performing clipboard transcription task (left) and motion tracking result in NaturalPoint Arena software (right).

4. 3. Kinect and iPi Studio

The Kinect sensor is a motion tracking device produced by Microsoft which can be used to record an RGB video stream and a depth image stream. A sample of two depth stream images is shown in Figure 3.

The different colours represent varying distances from the camera. Various software strategies are available for using these data to determine joint positions and orientations. The commercially-available iPi Studio software that was selected for this experiment is the only software available that can combine the data recorded from two sensors into one 3D skeletal model. The software can be used and works very well with just one Kinect sensor, but in order to deal with issues of joint occlusion it is necessary to use two cameras, one located on each side of the subject being recorded. The resulting configuration can record motion capture data that are reasonably close to what the Opti-track can obtain, but without the need for markers or a lengthy calibration process. A screen shot with depth data from two cameras superimposed is shown in Figure 3.

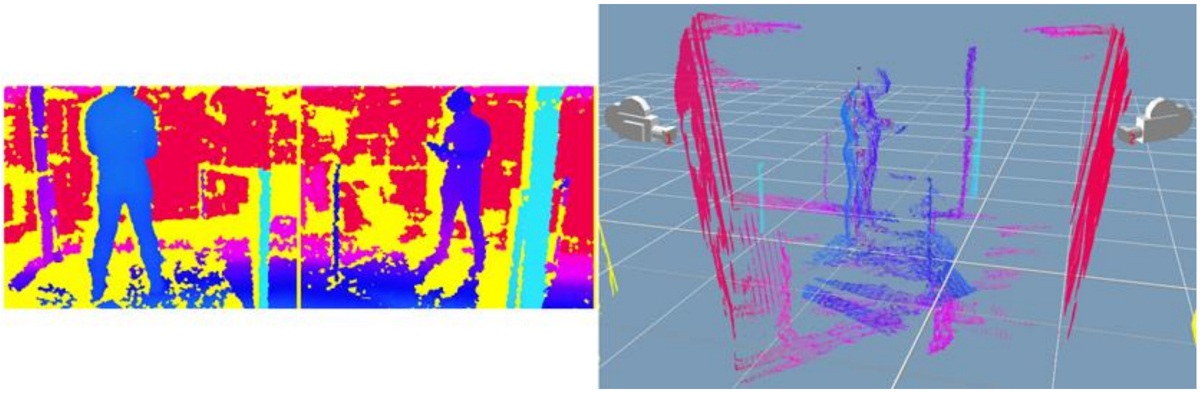

Fig. 3. Kinect depth data from two cameras (left) and the combined depth model in iPi Studio (right).

4. 4. Camera Positioning

The successful acquisition of accurate motion capture data was affected by two major factors of the recording environment. One is that both the cameras and the object being recorded were in a constant state of motion due to the motion of the ship. Both systems were designed to be used in cases where the cameras are stationary and only the recorded subject is moving. In order to prevent camera movement during the experiments, high-quality camera arms and mounts were used to hold the cameras, and the camera arms were tightened regularly. There is no evidence that suggests that camera misalignment developed during the experiment. The second factor is that the recording area was smaller than the recommended recording area for both systems. NaturalPoint recommends that the Opti-track system be used in at least a 4.6 metre square area, or optimally in a 6.1 metre square area. For the Kinect system it was found that the optimal configuration was to have each camera approximately 2.4-2.7 metres away from the subject, oriented so that the cameras are facing each other. Neither of these arrangements was possible in the Quest lab area which was approximately 4.5 metres by 4.0 metres, so both camera systems were used in a smaller than ideal space configuration.

4. 5. Marker and Body Occlusion

The Opti-track system can track a large number of reflective markers simultaneously in 3D space, which is made more complicated when those markers are attached to a human body because at any point in time a number of markers may not be visible to a sufficient number of cameras in order to be tracked properly, and it is important for markers to not be confused with each other. Opti-track compensates for each of these problems by associating specific marker positional patterns with specific body parts. If the position of one of the markers on a body part cannot be determined, then as long as the others remain visible the software can continue to properly record the motion. This is a very challenging task when camera positioning is limited, and when markers are frequently blocked by structures such as railings, by data logging equipment, or by other body parts. This was frequently an issue with the Opti-track recordings. One of the primary issues with the recordings was with properly tracking a subject's waist. The waist is tracked with four markers, one on each side of the body. The centre front marker was frequently blocked due to the clipboard or tablet associated with the cognitive task the participants were required to perform. This on its own is not an issue, but if for some reason a second waist marker was lost, the Opti-track software would frequently remap the waist to a different set of markers causing the entire human body model to bend into impossible geometries. Another difficulty was with the head tracking. The markers need to be positioned on top of the head, but the cameras could easily lose track of the markers if a subject was very tall. Ideally the cameras should be placed above the recording subject's head, but this was not possible because the vertical space on the capture platform was limited to approximately 2.1 metres. All of these issues with the marker tracking can be corrected in the Arena software in post-processing, but it is a very time consuming process.

Body occlusion was also an issue with the Kinect sensor, although not to the same extent. In the recordings there are occasional cases where a leg cannot be tracked properly, or the camera may incorrectly map a body part due to an object the subject is holding, or the subject may be interacting with another person. Overall these issues did not significantly affect the data recordings, but it does take time to correct for them in iPi Studio.

4. 6. Foot Pressure Measurements

The Tekscan F-Scan system consists of two instrumented insoles which are placed into a subject's shoes. One complication with using this system on board the ship was that the sensors could not be properly calibrated before use because the ship was experiencing constant motion and the calibration processes require a subject to stand on one foot and not change the pressure on the insole. This issue was compensated for with the use of the load cell data. The load cell did not need to be calibrated separately for each participant so the insole measurements could be compared with the load cell data from a calibration procedure at the start of each experimental session and scaled to the proper magnitudes.

5. Future Work

Due to the data collection challenges discussed in the previous sections, much of the time since the sea trial has been spent in post-processing the data so that it is well-formed for inputting into dynamic models. These data will be an invaluable resource for many years, but in the near future it will be utilized in the projects discussed below.

- The differences in camera accuracy between the Opti-track and Kinect camera systems will be quantified for a variety of motion capture scenarios.
- MII rates and durations will be calculated for each of the experimental trials and the results will be compared to past measurements made in equivalent sea states.
- In 2010 a spatial inverted pendulum was developed and verified using MII data from the 2007 Quest sea trial (Langlois, 2010). This model will be updated and compared to the new MII data.
- In recent years, the Carleton University Applied Dynamics Laboratory has been performing similar postural stability motion capture experiments in the laboratory on a 6 degree-of-freedom motion platform. The at-sea and laboratory results will be compared, and additional focus will be on how well ship motions can be reproduced in the laboratory. This work also involves a human dynamics model which, given the Arena motion capture data and the load cell data, can predict internal joint forces and moments.
- As discussed in Section 2, the collected data will be used to tune the control system of a four-link spatial inverted pendulum model with joints intended to represent ankles, knees, waist, and neck of a human. The goal of this control system will be not only to maintain stability, but to reflect aspects of human balance control in motion environments, such as MII onset and recovery times.
- A comparison between the use of pen and paper data logging and tablet use as it relates to performance will be carried out.
- An assessment of the applicability of memory for goals theory to MIIs will be performed and the impact of motion on time to completion and accuracy in a data logging task will also be assessed. The results of these analyses will be used to formulate future research in this area.

6. Conclusions

Human postural stability experiments were successfully carried out by Carleton University and DRDC Atlantic researchers on the Quest Q-348 Sea Trial that took place between November 20 and November 28, 2012. Thirteen participants took part in experiments that recorded body positions, foot pressures, and head motions while performing a cognitive task aboard a moving ship in high seas. This research project was unique in its attempt to record all of the inputs to human senses, its use of advanced motion capture technologies, and its comparison of performance using a clipboard versus a tablet for standard shipboard duties. In the future, these data will be invaluable for studying motion induced interruptions, cognitive workloads in motion environments, and for validating human postural stability models designed to predict how humans perform in various motion environments.

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