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Article

Research Using Virtual Reality: Mobile Machinery Safety in the 21st Century

James P. Dickey [1,*], Tammy R. Eger [2], Ryan J. Frayne [1], Giselle P. Delgado [1] and Xiaoxu Ji [1]

1 Joint Biomechanics Laboratory, School of Kinesiology, Western University, Thames Hall 3159A, 1151 Richmond Street, London, Ontario N6A 3K7, Canada; E-Mails: rfrayne2@uwo.ca (R.J.F.); giselle88@gmail.com (G.P.D.); xji23@uwo.ca (X.J.)

2 School of Human Kinetics, Laurentian University, Sudbury, Ontario P3E 2C6, Canada; E-Mail: teger@laurentian.ca

* Author to whom correspondence should be addressed; E-Mail: jdickey@uwo.ca; Tel.: +1-519-661-2111; Fax: +1-519-661-2008.

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Abstract: Whole-body vibration is a significant health risk for between 4% and 7% of the work force in North America. In addition, many factors compound the health risks of heavy machinery operators. For example, twisted trunk and neck postures stiffen the spine and increase the transmission of vibration to the head. Similarly, workers adopt awkward postures in order to gain appropriate lines of sight for machine operations. Although the relative contribution of these various issues can be evaluated in field studies and models, we propose that virtual reality is a powerful medium for investigating issues related to health and safety in mining machine operators. We have collected field data of posture and vibration, as well as visual environment, for a forklift operating in a warehouse. This paper describes the process and outcome of this field data collection, and provides a discussion on the next steps to develop and test the virtual reality model to enable laboratory testing. Our ongoing studies will evaluate the interplay between posture and vibration under conditions replicating routine heavy machinery operations, such as underground mining.

Keywords: mining; whole-body vibration; posture; line of sight; machine operators; mobile machines; low back injury; neck injury; biomechanics

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1. Introduction

Epidemiologic studies have shown that heavy machinery operators are more likely to have low back problems than workers who are not exposed to whole body vibration [1,2]; this association has been further substantiated in a recent meta analysis which identified that operators exposed to driving heavy equipment vehicles are at more than twice the risk of developing lower back pain compared to individuals that are not exposed to driving heavy equipment vehicles [3]. Due to the high prevalence of heavy machinery in mechanized societies, between 4% and 7% of the work force in North America and Europe is exposed to potentially harmful levels of whole-body vibration [4,5]. These risks are evident in epidemiological studies that report an increased risk of low back pain, and degenerative changes to the spinal column [6,7]. Certain industries, notably mining, construction, steel making and forestry, involve high levels of vibration [8–18], including complex 6 degree of freedom (df) vibration [17,19].

In terms of a benchmark for evaluating vibration exposure, the ISO 2631-1 standards [20] define the frequency weighted acceleration values corresponding to the lower and upper limits of the health guidance caution zone (HGCZ) for 8 h of exposure as 0.45 and 0.90 m/s^2, respectively. The workplace vibration levels in underground hard-rock mining often exceed the ISO 2631-1 HGCZ [15,21–24]. One recent study showed that the HGCZ was exceeded in all 8 small load-haul dump vehicles (LHDs; <3 m^3 bucket haulage capacity) and in one of the nine large LHDs (>3 m^3 bucket haulage capacity) [22]. Haulage truck operators in surface mining operations also regularly exceed the ISO 2631-1 HGCZ [15,23], and one study that evaluated 20 different mining vehicle operations found that five were within the HGCZ and seven exceeded the HGCZ [10]. Similarly, between 14% and 25% of heavy earth moving machinery operators at metalliferrous mines in India were exposed to whole-body vibration levels that exceeded the prescribed limit [25].

Although these data are important for characterizing the severity of the exposures to whole-body vibration in mining, they have some significant limitations. For example, they cannot independently evaluate the effects of vibration in specific directions, nor can they easily evaluate the influence of interventions aimed to reduce vibration exposure since the input vibration is not directly controlled. Similarly, field research has shown that WBV is affected by a number of variables including vehicle operating speed, vehicle maintenance, vehicle size, vehicle suspension, seat suspension, and road maintenance [18,22,26–28], but it is difficult to evaluate the relative contribution of these factors, and their interactions. Some field studies have attempted to ensure similar vibration across subjects by using the same route, same vehicle and similar velocity [29] while other studies have used repeated tests along a test circuit [22,30,31]; however, these efforts are unlikely to have exactly the same vibration exposure in all of the trials due to the extreme sensitivity of the vibration exposure to factors such as vehicle velocity. In addition, the costs of collecting field data such as whole-body vibration and electromyography are large [32], and the fundamental nature of the mining industry can make it difficult to perform field research [33]. In contrast, controlled studies can be performed in laboratory environments to uncouple the relative contribution of these interrelated factors.

Whole-body vibration is also associated with muscular fatigue [34,35], which appears to be related to increased risk of injury [36]. In addition to whole-body vibration, worker posture is also strongly related to the risk of injury [37–39]. For example, there is a high rate of neck and shoulder symptoms in office workers [40], dentists [41] and sewing machine operators [42] that appears to be related to the high static postural loads. Twisted spine postures are associated with increased muscle activation and concomitant spinal loads [43,44], and have also been associated with increased fatigue [45]. Although subway operators and on-board switchboard operators would be exposed to similar levels of vibration, the subway operators more often report neck problems [46]; this difference has been attributed to the greater postural demands of subway operators, including trunk and neck bending and rotation. Accordingly, in terms of risk of injury, there seems to be a strong interaction between worker posture and whole-body vibration [47]. This is a particular concern in the mining industry as specific vehicles, such as load-haul-dump vehicles, have a high level of vibration exposure [48] and high proportions of concurrent trunk and neck twisting (Figure 1) [49]. Furthermore, these operators sustain awkward postures for prolonged periods, which is not recommended [50]. Some research has shown that vehicle operators adopt specific postures in order to gain the necessary line-of-sight to safely operate their vehicle [51].

Figure 1. Sample images from a video camera mounted within the cabin of a load-haul-dump vehicle in a hard-rock mining operation in Northern Ontario, Canada showing the neck and trunk postures during routine operations. The strips of reflective tape on the shoulders, trunk and helmet, help to identify landmarks and the awkward postures that the vehicle operators assume while operating the load-haul-dump vehicle. Each of the three rows of this figure show different operators, each adopting awkward or twisted postures. A portion of this figure was previous published [49], and we have received a license to reprint it.

Given the important individual health effects of both whole-body vibration and worker posture, and likely meaningful interactions between these factors, laboratory studies are necessary to enable assessment of these specific parameters [52,53]. Many laboratory studies have used Stewart/Gough motion platforms to control multi-axis vibration exposures [54–59]. As well, there has been a trend to incorporate virtual reality (VR) environments to evaluate the visual field and work environment for research [60,61] and training [62–64]. However, these initiatives have emphasized the fidelity of the visual environment, not the vibration environment; for example, many initiatives have used fixed-base simulators and therefore have no whole-body vibration [65–67]. If motion platforms have been incorporated, their implementation has focused on the haptic elements of the vibration environment (to increase the amount of presence) [68–70] rather than the fidelity of the whole-body vibration exposure. Virtual reality-based modeling studies have been particularly useful for evaluating line-of-sight for different vehicle configurations [71,72], for predicting line-of-sight for specific worker populations, such as child farm tractor operators [73], or for evaluating handling performance [60] and hazard responses [74] which would be dangerous to investigate in the real world.

The purpose of this paper is to describe a linked field- and laboratory-based approach for performing investigations of vehicle operations that can be applied to evaluate factors related to safety in mining in the 21st century. This approach extends our previous efforts investigating multi-axis whole-body vibration [75] by incorporating a VR environment that will simulate both the visual and vibration environments and thereby enable controlled investigations of issues such as posture, whole-body vibration and line-of-sight.

2. Methods and Results

The following sections describe our preliminary research evaluating lift trucks; these initial studies illustrate the implementation of a complementary field- and laboratory-based testing system for evaluating the risks of injury with mobile machinery. Based on our success with this initial application (lift trucks in a warehouse environment), we can and will be expanding our applications to evaluate mining environments.

2.1. Field Studies

The data collection phase took place at a local distribution and storage facility. The desired measurements were obtained during normal forklift operations of a 55-year-old male (1.88 m, 107 kg) with 20 years of forklift driving experience. We quantified the whole-body vibration exposure (seatpan and chassis measures) and the operator posture during routine machine operations. The instrumentation used consisted of three video cameras (one Sony model HDR-XR550V, Tokyo, Japan, and two JVC model GZ-MG555U, Kanagawa, Japan; 30 Hz), two inertial measurement units (IMUs; MAG3; MEMsense, Rapid City, SD, USA including ±5 G triaxial linear accelerometers and ±1200°/s triaxial angular rate sensors; 1000 Hz), and an eye-gaze tracking system (ASL H6 Eyetracking system, Applied Science Laboratories, Bedford, MA, USA; 30 Hz). All instrumentation was attached to the lift truck such that that it did not interfere with normal machine operations. The video cameras were attached with clamps (Manfrotto Super Clamps, Cassola VI, Italy) to an extruded aluminum cross that was secured to the fall-on protection above the cabin of the forklift [76]. This mounting system enabled us to collect multiple views of the operator within the cab of the forklift; camera vibration did not seem to influence our image quality. These video cameras were located far enough away from the cabin such that the field of view encompassed the various postures of the operator without interfering with normal driving tasks nor obscuring the operator's line of sight.

One IMU was magnetically attached to the floor at the base of the seat, and the other IMU was embedded in a semi-solid rubber mold, as defined in ISO 10326-1 [77], and positioned on the seat pan, similar to previous studies [17]. Two 8-channel data loggers were used for data recording (DataLOG No.P3x8USB, Biometrics, VA, USA) with a sample rate of 1000 Hz. We synchronized the dataloggers and video cameras using a custom-designed system that simultaneously activated a small light within the field of view of the video cameras and the eye-gaze camera, as well as an electrical pulse that was sampled by the dataloggers. Sync pulses were collected at the start and end of data collection periods to align all of the data from these various sources. The continuous record of routine lift truck operations was divided into a series of individual tasks such as driving forward/backward, with/without a load, and on the warehouse floor or onto and in the transportation truck; interruptions in routine that were caused by the researchers were identified and excluded from analyses. Previous work has shown that 15 or 20 s vibration exposures are adequate for quantifying discomfort in vertical, planar and 6 df vibration exposures [78], so we attempted to identify segments of subtasks with 20 s durations.

The four synchronized video records (three views of the operator and the view from the eye-gaze monitor) were assembled into a composite video using commercial software (DartFish TeamPro, Fribourg, Switzerland; Figure 2). These video data were downsampled to 6 Hz (Prism Video File Converter version 1.88; Boston, MA, USA) and analyzed to extract posture categories for the trunk and the neck including flexion/extension, lateral bend, and rotation using specialized software (3D Match software version 5.03, Callaghan, University of Waterloo, Ontario, Canada, 2006) [49,61]. The head and neck postures were evaluated on a frame-by-frame process by selecting the appropriate posture category bin from the available options. The thresholds for defining the postures as low, medium and high potential risk of injury were based on the neutral, moderate and awkward categories previously defined for theneck [79] and the trunk [80]. These sources have identified that both the duration and degree of the non-neutral postures are associated with musculoskeletal disorders. This video-based analysis approach has been used by other researchers to quantify worker postures [61,81].

The chassis acceleration data are essential for assessing the input vibration, but are not directly related to the health effects as they are modulated by the dynamics of the industrial seat. Accordingly, for this study, we will emphasize the seatpan accelerations. The seatpan acceleration data were analyzed in accordance with the ISO 2631-1 standards [20]. In more detail, frequency-weighted accelerations (a_{wx}; a_{wy}; a_{wz}) were calculated using the appropriate weighting factors as described in ISO 2631-1 (x-axis = W_d; y-axis = W_d; z-axis = W_k) using the National Instruments Sound and Vibration Measurement Suite. Scaling factors associated with the determination of health for seated exposure were also applied (x-axis, $k = 1.4$; y-axis, $k = 1.4$; z-axis, $k = 1.0$). These data were effectively downsampled to 30 Hz to match with the video data by calculating the r.m.s. for non-overlapping windows of 0.033 s duration. The resulting data were categorized as low, medium or high vibration based on the ISO 2631-1 magnitudes for the 8-hour health guidance caution zone [20]; r.m.s. frequency weighted acceleration values less than 0.45 were defined as low, between 0.45 and 0.90 as medium, and greater than 0.90 m/s^2 were defined as high; other researchers have used similar approaches for categorizing vibration exposures [48,82,83].

Figure 2. Sample images from the composite video showing the time-matched video data from the eye gaze camera and the views of the operator. The top left view shows the image from the eye gaze camera. The red cursor in the bottom-right of this image identifies the operator's point of regard at this particular instant; the top right view shows the image from the rear video camera at the back—in this case it shows a similar perspective as the eye gaze camera; the bottom left view shows the image from the video camera at the side of the cabin; the bottom right view is from the video camera at the front of the forklift.

In terms of analyzing the combined effect of acceleration and posture, the data were assessed in terms of the proportion of time in different combinations of vibration and posture for each of the tasks. This approach is similar to other researchers [82,83]. We assembled contingency tables to illustrate the relationship between the posture and vibration health risks (Table 1). In the case of these data from a lift truck operator, they show that he spends a greater proportion of the time in awkward postures when driving backwards compared to forwards; furthermore, the vibration exposure is also higher. In particular, the combination of awkward neck posture and high vibration is twice as common while driving backwards than forwards; this combination is three times as common for the trunk postures. In terms of driving loaded *versus* unloaded, these data show increased vibration exposure while unloaded, which is consistent with measures on mining load-haul-dump vehicles [13,22]. One novel finding that can be observed with this form of data presentation is the combination of posture and vibration for specific tasks. For example, the "engaging the forks" task has a high proportion of awkward neck and trunk postures, but they occur with low or medium vibrations (not high).

Table 1. Sample contingency tables showing the relationship between posture and vibration; the percent of time spent in the various combinations is listed. The numbers in the left-hand column describe the neck while the numbers in the right-hand column describe the trunk. The top row describes this relationship for the "engaging the forks" task, the second row describes the driving forward while loaded task, the third row describes driving backwards while loaded task and the bottom row describes the driving forward unloaded task. Apparent trends include a greater proportion of time in awkward postures in the backward driving compared to forwards, and a greater vibration exposure when driving unloaded compared to loaded. Although the trends are similar between the neck and the trunk, the neck typically shows a greater proportion of awkward postures.

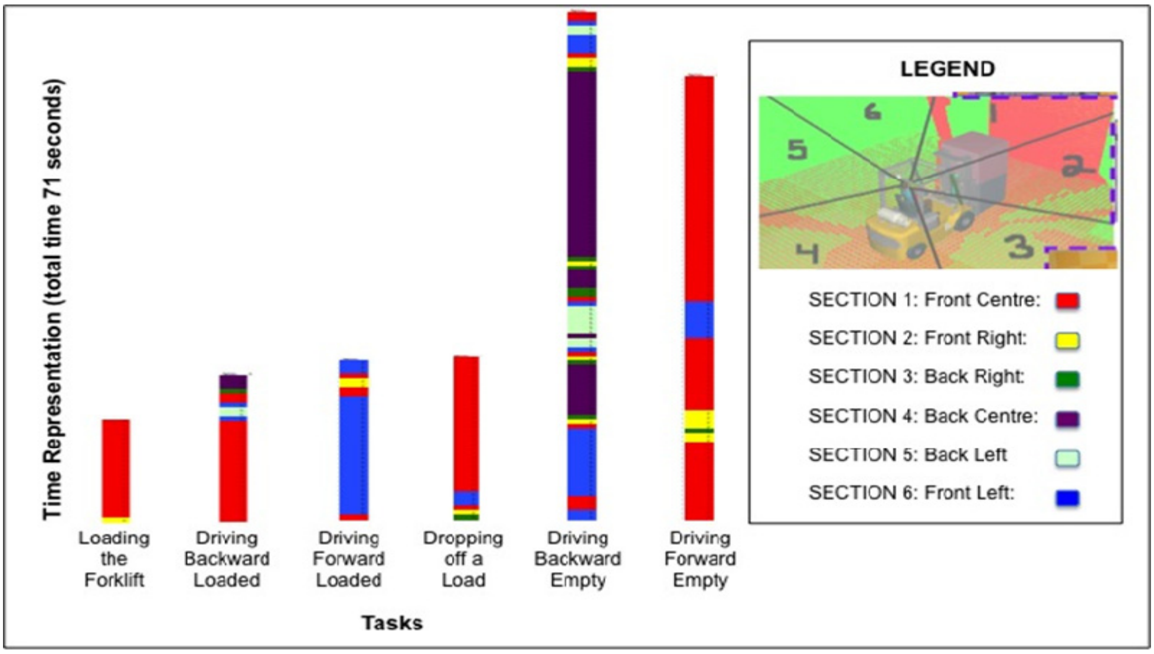
Posture Category	**Neck (%)**			**Trunk (%)**		
Combined risk of postures and vibration while engaging the forks (duration of 277 s)						
Awkward	26%	22%	3%	10%	9%	1%
Moderate	9%	6%	1%	13%	11%	2%
Neutral	18%	13%	2%	30%	21%	3%
	Low	Medium Vibration	High	Low	Medium Vibration	High
Combined risk of postures and vibration while driving forward loaded (duration of 167 s)						
Awkward	36%	26%	8%	21%	16%	5%
Moderate	13%	6%	2%	17%	12%	4%
Neutral	4%	3%	2%	15%	8%	3%
	Low	Medium Vibration	High	Low	Medium Vibration	High
Combined risk of postures and vibration while driving backward loaded (duration of 188 s)						
Awkward	34%	21%	17%	23%	16%	16%
Moderate	11%	5%	1%	10%	4%	2%
Neutral	7%	3%	1%	18%	9%	2%
	Low	Medium Vibration	High	Low	Medium Vibration	High
Combined risk of postures and vibration while driving forward unloaded (duration of 165 s)						
Awkward	11%	8%	7%	5%	5%	3%
Moderate	11%	10%	9%	9%	9%	7%
Neutral	16%	15%	13%	24%	19%	19%
	Low	Medium Vibration	High	Low	Medium Vibration	High

2.1.1. Operator Point of Regard: Eye-Tracking

Eye-tracking glasses (previously described) were used to determine where the lift truck operator looked when loading the lift truck, driving forward, driving backward and when unloading the lift truck. In order to simplify the analysis the percent time that the operator spent looking to the front centre, front right, back right, back centre, back left, and front left was coded.

The operator's point of regard varied between tasks; this is illustrated in Figure 3. In this example, it took the operator 71 s to complete a loading cycle (picking up a load, driving loaded backward, driving loaded forward, dropping off a load, driving backward empty, and driving forward empty). In this one example, driving backward empty was the only task that the operator spent time looking in every direction. In contrast, driving forward with an empty forklift resulted in the operator looking in the forward direction 84% of the time, and loading the forklift was a shorter duration task, but involved looking in the forward direction 94% of the time. The operator also had more short glances to different sections when driving backward empty (Figure 3).

Figure 3. Representation of the time spent looking to one of six sections (see legend) while loading the forklift, driving loaded, dropping off a load and driving empty for one loading and unloading cycle. The color scheme represents the different sections during the tasks (see legend), and the height of the bars represents the amount of time spent. The total time to complete the load/drive/unload cycle was 71 s.



Since point of regard can vary for the same task we asked the operator to repeat the same loading and unloading cycle three times. The average time spent looking to each zone is shown in Table 2 (Trial 1 took 71 s, Trial 2 took lasted 56 s, and Trial 3 lasted 53 s). Differences between the data presented in Table 2 and Figure 3 illustrate that we observed a considerable amount of variability between loading and unloading cycles; for example, for the cycle presented in Figure 3, the operator spent most of the time looking in section 1 (front centre) while these data show that on average the operator spend more time looking in section 4 (back centre) than any other section. It is clear that the operator's gaze direction depends upon the task, driving direction and load (loaded or empty forklift). For example, when driving forward without a load the operator spent 91% of the time looking front and centre (section 1) but only spent 25% of the time looking to this area when loaded; this is likely related to the load obscuring the forward field of view and accordingly the operator had to adopt an awkward posture and alternative gaze direction (as illustrated in Figure 3). Driving backward was the only task in which the operator looked in every direction. Interestingly, even when driving backward while empty the operator still spent 30% of the time looking front and centre (section 1).

Table 2. Percentage of time looking to each section by task. Each task was repeated three times and the average percentage of time is shown. The section number coding is explained in the legend of Figure 3.

Task	Sections % of time looking to each section					
	1	2	3	4	5	6
Driving Forward-Empty	91.3	2.5	0.4	0.0	0.0	5.8
Driving Forward-Loaded	25.0	17.1	0.0	0.0	0.0	57.9
Driving Backward-Empty	30.2	4.5	6.6	31.3	19.4	8.0
Driving Backward-Loaded	6.6	9.1	12.4	45.6	7.3	19.0
Loading the Forklift	87.6	10.5	1.0	0.0	0.0	1.0
Dropping off a Load	70.6	4.7	1.2	0.0	3.5	20.0

2.2. Laboratory Studies

In this section we describe the approach that we are using to build the virtual reality environment from field data collected (as described in the previous section); this work is in progress. We have completed the virtual environment and fork lift, as illustrated in Figure 5, but have not yet integrated the motion from the 6 degree of freedom platform with this simulation. This stage of development is similar to that reported by others [69]. Our testing approach involves designing laboratory studies that mimic the field trials, in a more controlled laboratory setting. Creation of the virtual field environment requires complex system integration between various hardware systems and several inter-related software packages. The required hardware includes six degree of freedom parallel robotic platform (R-3000 Rotopod; Mikrolar Inc., Hampton, NH, USA), a custom-designed vehicle simulator that includes haptic controls (foot pedals, steering wheel and joystick), a virtual reality head mounted display (VR 1280; Virtual Research System Inc., Aptos, CA, USA) with an integrated eye tracker camera (H6-VR VR Head Mounted Eye Tracking System; Applied Science Laboratories, Bedford, MA, USA) and a six camera kinematic data acquisition system (OptiTrack V100:R2; NaturalPoint Inc., Corvallis, OR, USA). One advantage of this particular robotic platform is that it can undergo large yaw rotations; other approaches have required additional actuators to achieve this range of motion [69].

The vehicle simulator will be mounted to the top of the six degree of freedom robot (Figure 4). This will allow the subject to control the vehicle within the virtual environment using the accelerator and brake pedals as well as the haptic steering wheel. In the forklift simulations the joystick will be used to control tilt and lift of the forks. The operations of these controls can be reconfigured using software switches to represent different styles of vehicles. The geometry of the components can be easily rearranged as it is built from modules of extruded aluminum. Rotations and accelerations that the virtual chassis of the vehicle undergoes during the simulations are relayed to the robotic control system. This will enable the robotic platform to perform motions corresponding to the virtual vehicle. Ultimately this should lead to similar chassis and seatpan accelerations in the field and in the laboratory. During simulations subjects will receive real-time updates of the appropriate visual field through the virtual reality head mounted display. This will be accomplished by tracking the subject's head position and orientation through the OptiTrack camera system using a four marker rigid body attached to the top of the virtual reality head mounted display; as the subjects lean and/or rotate their heads, the visual field is updated accordingly (Figure 5).

Figure 4. The left image shows the vehicle simulator mounted to the six degree of freedom robot; the robotic mechanism is shrouded for human subject safety. The right image shows the various controls that are within the vehicle simulator. The accelerator and brake pedals can be seen in the bottom right of the image. The haptic steering wheel and joystick are located at the top of the image.

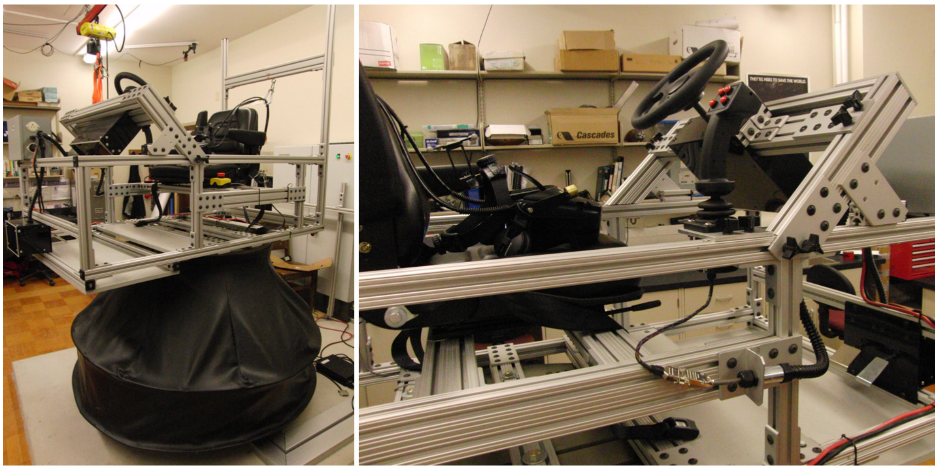


Figure 5. This image shows the subject's head position and the corresponding visual field. The left image shows the subject leaning to their left so they can get an unobstructed view of the ends of the forks. Note the four marker rigid body (cross) that is attached to the top of the head mounted display to measure the subject's head position. The right image is the corresponding field of view showing the lift truck structures within the field of view as well as the tips of the forks. The subject needs to adopt this awkward posture in order to visualize the ends of the forks.

The software responsible for the integration of the virtual reality hardware include Presagis Creator 4.1 (Presagis Inc., Montreal, QU, Canada), Vortex physics-based software (CM labs, Montreal, QU, Canada), Visual C++ 2008 (Microsoft, Redmond, WA, USA) and OptiTrack tracking tools (NaturalPoint Inc., Corvallis, OR, USA). Presagis Creator is used to design and create the virtual environments and vehicles. Vortex is used to modify and animate the environment/vehicles; it designates collision geometries, component masses, centre of mass locations, joints, vehicle suspensions and wheel torques. For example, the creation of our forklift required animating the wheel suspension, torque and tire friction properties. Movements and joint connections of the fork mechanism were also set in Vortex. Vortex applies physics-based properties (*i.e.*, gravity and Newtonian laws) that control how a vehicle interacts with objects in the virtual environment. OptiTrack tracking tools software controls the OptiTrack cameras. This software enables the definition of rigid bodies from marker clusters, and tracks the 3D motion of these rigid bodies in real time. It also outputs the X, Y, Z, Roll, Pitch and Yaw of the VR head mounted display so that the subject's visual field is updated in real time. Lastly, and most importantly, Visual C++ 2008 is the top-level program that integrates all of the hardware and software. All of the simulation data can be recorded for later analysis.

Parameters that are related to health and safety will be measured with additional instrumentation. For example, an eye tracker system has been incorporated into the virtual mask and can be used to record the subjects' visual fixation points within the field of view. This information can be used to assess situational awareness [84,85], an important element of workplace safety in and around vehicles. It can also be used to determine experimental lines of sight that can supplement envelopes of sight defined using models [86]. Analog signals can be collected using custom designed LabVIEW programs. For example, Inertial Measurement Units (IMU; Mechworks Inc, West Vancouver, BC, Canada) can be used to collect robotic platform (chassis) and seatpan vibrations. This information can be used to evaluate the effectiveness of the industrial seat at attenuating the vibration [87], and can also be used to evaluate the health effects of whole-body vibration exposure [20]. The kinematics of additional body segments can be tracked with the OptiTrack system for measuring postures and joint motions. For example, other researchers have measured driver safety based on the subject's hand locations on the steering wheel [88]. The levels of muscle activation, and the occurrence of muscular fatigue, can be directly assessed using electromyography [34,35,89]. In addition, the influence of whole-body vibration on parameters such as reaction time [90], task performance [91], distraction [92] and psychological effects [93] can also be measured.

2.3. Verification

We will adopt a two-pronged strategy to verify this linked field- and laboratory-based approach for performing investigations of vehicle operations. One strategy will examine the performance of the physics-based simulation by evaluated similarity of the chassis accelerations in the laboratory tests compared to field data; this is similar to the approach performed by other researchers [60,94]. For this purpose we have created a virtual environment that includes a test track with known vibration characteristics [95]. The virtual track is modeled as described in the ISO-5008:2002(E) standard [95] which defines the two uneven tracks of adjacent slabs of concrete or wood mounted in a base framework at specified heights. There are two tracks: the 35 m rougher track and 100 m smoother track. Since vibration is strongly dependent upon vehicle velocity, the ISO standard suggests that the vehicle should be operated at 4, 5 or 7 km/h for the rougher track and 10, 12 and 14 km/h for the smooth track; however, other researchers suggest that the speeds on the smoother track should be larger (up to 30 km/h) since the slower speeds may not adequately challenge the vehicles suspension features [96]. The vibration exposure can be quantified using the r.m.s. of the frequency-weighted accelerations, as suggested by the ISO standard [95], or by more comprehensive parameters such as the vibration spectra [94]. Although these test tracks were developed for agricultural wheeled tractors and field machinery, they are convenient for our purposes as there is a growing database of chassis and seatpan accelerations for comparison purposes [94,96,97]. By comparing chassis vibration data from the field to our robotic platform (virtual chassis) data we will be able to get an indication of our model's accuracy. This information can be used to guide adjustments to vehicle model such as the suspension stiffness, power train and frictional coefficients to improve the fit between our virtual model and the field testing, similarly to other researchers [94]. The sec strategy that we will adopt to verify our linked field- and laboratory-based approach is a comparison of the operator's postures and their line of sight. Since the operators adopt awkward and twisted postures in order to gain the necessary line of sight to safely operate their vehicles [51], we can assess the similarity between the postures and lines of sight of the operators in the virtual reality laboratory-based testing and the field-based studies.

3. Discussion

We have described an application of robotics and virtual reality technology that may directly influence health and safety in mining—in particular through the issues affecting heavy mobile machinery operators as well as issues in and around these vehicles. We have described how our system can be used to evaluate the independent contributions of whole-body vibration and posture to injury risk by enabling assessment of factors such as muscular activation, muscular fatigue, and seat-to-head vibration transmissibility.

The field study revealed general similarities in the combinations of posture and vibration for the neck and the spine; however, usually the neck had a greater proportion of awkward postures and low vibration compared to the trunk. There were differences in the time spent in posture/vibration combinations for each of the identified tasks. For example, driving backward with a loaded forklift resulted in the highest proportion of awkward neck and trunk postures under high vibration exposure (17% and 16% of the time, respectively), while engaging the forks was associated with the highest percentage of neutral neck and trunk postures under low vibration (18% and 30%, respectively). These examples highlight the impact that line-of-sight has on posture. When the forklift is loaded, the operator cannot see over or around the load, so driving backward is mandated; this necessitates long periods of sustained neck and trunk rotation. This argument is supported by the point-of-regard findings (Figure 3 and Table 2). The operator only looks behind the lift-truck when driving backwards and a greater proportion of time is spent looking to section four (back centre) when loaded (46%) compared to unloaded (31%). Long periods of sustained viewing to section four are also illustrated in Figure 3, and are only possible with sustained rotated neck and trunk postures.

These preliminary findings with our combined field- and laboratory-based research approach, as described for lift trucks, are directly applicable to the mining sector. For example, our data are consistent with point of regard data during LHD operation; this research also showed that point of regard varied by task and had an influence on driving postures [51]. The forward line of sight is similarly obscured in lift trucks and LHDs; the forward line-of-sight is restricted when driving a LHD, and is worse when the bucket is loaded. Therefore operators adopt rotated neck postures and look to the left of the bucket to navigate in the forward direction. When driving forward with the bucket loaded, LHD operators rotate their necks greater than 40 degrees for over 92% of the task, and spent 85% of the time looking to the front left of the LHD [51]. When unloaded line-of-sight was slightly better and the operator spent less time with the neck rotated (79%) and more time looking to the front of the LHD.

Virtual reality is a powerful tool for safely investigating different scenarios, with a high degree of control over a variety of parameters. The effects of alternative cab arrangements, different vehicle controls or displays and different seating systems can be readily investigated. This approach provides a robust and flexible platform for many studies related to the health and injury risks of current and future mining operations including crucial issues such as training for machinery operators [62–64], and assessing the rapidly evolving human factors issues related to new technologies such as automated mining equipment [98–101].

Knowing which tasks pose the highest risk of injury from combinations of vibration and awkward postures may lead to interventions that will reduce the risk of injury. For example, they can guide choice of where supplemental equipment should be attached to the vehicle based on the implications for line of sight and the postures that the operators would need to adopt. They could also be used to guide the efficacy of interventions such as secondary viewing systems [102]. However, it is important to evaluate whether theoretical improvements are translated into practice; for example, some research has shown that workers may not adopt their postures to take advantage of ergonomic redesign of cabin design [103]. Similarly, sometimes automated equipment operators responses can differ depending on the context of the situation [104]; this can lead to "automation surprises" [105]. Additional limitations include that we have a limited amount of experience with this current configuration, and have not yet applied it to scenarios that are specific to mining. Our experiments with lift trucks are, however, highly relevant to mining vehicles, and we plan on expanding to evaluate mining vehicles in the near future. One advantage of our approach for laboratory testing using the motion platform and virtual reality system is that factors such as the vehicle and environment can be readily changed and are appropriately incorporated through the appearance, size, mass, stiffness, gearing and other parameters. In addition, our VR system with a head-mounted display offers the advantage of a large field of view; however, the mass of the system adds an inertial burden to the head [106] that may confound the level of neck effort and fatigue. Furthermore, the performance of the motion platform limits the motion envelope and the maximum accelerations that we can simulate; accordingly it is not possible for our equipment to simulate some extreme scenarios such as accelerations greater than gravity, which can result in the operators' heads colliding with the cabin ceiling. Therefore, the VR model purposed in this paper is not able to replicate peak vibration patterns; however, accelerations greater than 1 *g* occur infrequently. Furthermore, the ability to evaluate the interaction between equipment design, line-of-sight, posture, vibration exposure and resulting comfort, injury risk and overall worker productivity in a VR environment cannot be adequately (time, access, money) or systematically accomplished in a field environment [75].

4. Future Directions

Our first step is successfully integrating vibration exposures from the motion platform into the virtual reality system; this work is currently in progress. Next we will be applying our linked field- and laboratory-based approach for investigating the health effects of combined vibration and postural loads to the mining industry. In particular we will expand our previous research on vibration and line-of-sight with load-haul-dump vehicles. We aim to also investigate important issues such as attention and task performance using this powerful approach.

5. Conclusions

This paper describes how leading edge virtual reality technologies, including physics-based models of vehicle dynamics, can be combined with advanced motion platforms to produce powerful systems for evaluating factors related to health and safety of heavy machinery operators in mining. Although all of these technologies are currently available, most current applications are focused on training or remote operations. We describe applications that enable controlled laboratory studies that can simulate occupational workplaces for the purpose of evaluating worker comfort and injury risk and overall worker productivity; this system can evaluate the interplay between whole-body vibration and posture. This approach will enable focused studies to evaluate the effect of intrinsic factors such as driver characteristics, postures and behavioral factors, as well as extrinsic factors such as vehicle type, vehicle mass, suspension, speed, and road conditions.

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