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A multi-factorial model for performance under vibration

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Abstract

Whole-body vibration affects drivers and passengers in vehicles. These people could be performing a variety of tasks that could be directly related to the control of the vehicle, or could be something unrelated to the vehicle. There is potential for the exposure to WBV whilst performing a task to adversely affect task performance. This paper uses two case studies to illustrate a model of performance and workload whilst exposed to vibration. It is shown that performance whilst completing a discrete task (Purdue pegboard) is easily affected by vibration, but a continuous task (steering wheel) is unaffected. However, in both cases, the self-reported workload increases with vibration. A model is presented that shows that where there is adaptive capacity of the operator, they are able to compensate for the vibration with greater control but at the cost of workload. However, beyond a coping threshold the performance will degrade.

1. Introduction

Drivers, workers and operators of off-road machinery are required to perform many types of tasks whilst exposed to whole-body vibration. For a driver, their whole task could simply be to safety and quickly transport people and/or a carried load from one location to another. The task would most likely involve the use of a steering wheel and pedals to control the speed and direction of the vehicle. An excavator operator has several components to their work. For part of their work time they could be driving from one location to another (sometimes called 'tracking'); at times when they are excavating they are exposed to a different characteristic of vibration and using different controls. Other workers are exposed to vibration but are not in control of it. For example, someone could be operating equipment in the back of a military vehicle whilst a different driver drives the vehicle. In each of these three examples, the task and the interface that the worker has to use are different, but in each case there will be some type of vibration disturbance and some required level of workload / performance.

If an individual is required to perform a task in a moving environment they are exposed to forces that will affect their direct motor control, and could also affect their cognition. The extent of the effects on control and cognition depend on the task and the motion to which they are exposed. As a rule-of-thumb, most well-established primary control mechanisms are robust to the environment to which they are usually exposed. For example, a classic steering wheel and accelerator, brake and clutch are very for controlling a car. Mansfield (2012) suggests that this is a form of 'natural selection' whereby any poorly functioning designs would have naturally died out whilst superior methods evolved in the early periods of vehicle innovation. However, new forms of controls, such as for navigation systems or other newer innovations, are more likely to be prone to being adversely affected by vibration exposure than primary controls. Despite there being an element of robustness to control it is possible that the workload associated with a task could be affected by exposure to whole-body vibration.

This paper uses two case studies demonstrating the effects of vibration on performance and workload and uses the results of these to develop a workload and performance model.

2. Methods

Two studies were carried out. Study 1 comprised a discrete manual control task using a purdue pegboard. Study 2 comprised a driving task with continuous manual control. Both tasks were performed whilst subjects were standing.

16 participants were used in case study 1. These comprised 6 males and 10 females (age: 19-30, stature: 1600-1830mm; mass: 63-90kg). 21 participants were used in case study 2. These comprised 10 males and 11 females (age: 20-31, stature: 1540-1835mm; mass: 53-93kg). Participants received detailed information regarding the purpose of the studies, experimental protocols and possible risks associated with participation.

The experimental conditions consisted of single-axis vibration, in both horizontal directions: fore-and-aft (x-axis) and lateral (y-axis), as well as dual-axis horizontal vibration (xy-axes). Vibration was generated using a 6 degree-of-freedom multi-axis vibration simulator (MAViS) at the Environmental Ergonomics Research Centre, Loughborough University. Participants were required to stand on the simulator platform and for safety reasons; a harness was worn at all times while standing on the simulator. During the discrete control study, a guard rail was mounted on three sides of the platform at a height of 1000mm to provide additional safety for the participants. For the continuous control study, the guard rail was removed, however additional support was provided by the steering wheel rig that was fitted to the platform.

For both studies, the vibration stimuli were band-limited up to a frequency of 4Hz. This frequency band was selected as the majority of vibration exposure from field measurements occurred in this range. In addition, previous studies reported the greatest influence of horizontal whole-body vibration on workload and task performance occurred between 2 – 4Hz and 1 – 3Hz (Lewis and Griffin, 1978 and Westberg, 2000, respectively). Vibration magnitudes are described in Table 1.

Two standing postures were selected for both studies, based on the orientation of the feet. The anterio-posterior stance required participants to place their dominant foot in-front of the other, while the lateral stance required the feet to be placed side-by-side (Figure 1).

Table 1. Summary of vibration stimuli used in the discrete and continuous manual control studies.

Task Variable	Condition	Vibration Magnitude (ms^{-2} r.m.s., unweighted)		
		x-axis	**y-axis**	**r.s.s. ∑ axes**
Discrete manual control	1	0.5	---	0.5
	2	1.0	---	1.0
	3	2.0	---	2.0
	4	---	0.5	0.5
	5	---	1.0	1.0
	6	---	2.0	2.0
	7	0.5	0.5	0.71
	8	1.0	1.0	1.41
	9	2.0	2.0	2.83
	Control	---	---	---
Continuous manual control	1	0.75	---	0.75
	2	1.5	---	1.5
	3	---	0.75	0.75
	4	---	1.5	1.5
	5	0.75	0.75	1.06
	6	1.5	1.5	2.12
	Control	---	---	---

Figure 1. Postures used in the two studies (fore-and-aft stance).

Discrete manual control performance was assessed manually using a timing device (Casio® stop-watch, Casio Computer Co. Ltd., Tokyo, Japan) to record the time taken to complete a pegboard task. The participants were responsible for starting and stopping the timer at the beginning and end of the task, during each of the vibration conditions. The face of the timer was positioned so the display screen was not in view and therefore the participants were not provided with any feedback concerning the level of performance. Any motion induced interruptions that required the participants to physically brace themselves or adjust their stance in order to maintain stability were logged by the researcher.

Continuous manual control performance was measured automatically using a specific software package dedicated to running the LCT driving simulator. Driving data were recorded at a frequency of 100Hz and using the LCT software the following variables were provided: trial number, time to task completion, x- and y-coordinates of the actual position of the virtual vehicle. The mean deviation (Mdev) between the desired position and the actual position of the virtual vehicle was used to evaluate lane keeping performance.

In both studies, participants were required to provide two subjective measures relating to workload and task difficulty following the completion of each vibration condition. These ratings were used to evaluate the workload experienced by the participants in order to perform the required task. The first rating was a magnitude estimation of workload. The following instructions were provided to the participants (Stevens, 1975):

> *'You will be presented with a series of vibration stimuli in irregular order. You are required to estimate the workload associated with the tasks by assigning numbers to them. The first stimulus will be a static condition with no vibration. Call this stimulus 100, and then*

assign successive numbers in such a way that they reflect your subjective impression. There is no limit to the range of numbers that you may use. You may use whole numbers, decimals or fractions. Try to make each number match the level of workload as you perceive it.'

The second subjective workload measure required the participants to assign a verbal descriptor of task difficulty, based on the following six-point semantic scale:

- Not difficult
- A little difficult
- Fairly difficult
- Difficult
- Very difficult
- Extremely difficult

Each study was conducted during a single laboratory session, lasting approximately 1h, which commenced with the researcher taking anthropometric measures of stature, shoulder width, foot length and body mass. In order to reduce variations in stance posture when changing between testing conditions, the positioning of the feet for each stance were located with reference points marked onto the vibration simulator platform. A safety harness was worn by participants at all times when standing on the simulator platform and the immediate area surrounding the vibration simulator was cordoned off and free of personnel before testing commenced.

Participants were allowed a familiarization period with no vibration exposure to practice performing the required task and become acquainted with providing subjective ratings of workload. The mean deviation (Mdev) was calculated after each familiarization trial was completed. Once the Mdev reached a consistent level and there were no longer any significant 'learning effects' present, the experimental conditions could begin. Following the familiarization trials, a 'reference' condition was performed without vibration exposure. This 'reference' condition was assigned a magnitude estimation rating of '100' and further subjective ratings were made in comparison to this 'reference' condition. The testing conditions included random vibration stimuli and additional control conditions (no vibration), presented to the participants in a counter-balanced order based on a randomised Latin-Square technique in order to minimise 'order-effects'.

Control conditions were conducted in each stance orientation. During each vibration condition, participants were asked to delay performing the task until the vibration simulator had stabilized at the required vibration magnitude. Once the task was completed and the vibration simulator had settled, the participants were asked to provide subjective ratings of workload using the magnitude estimation technique and the semantic scale. The time between each vibration stimuli depended on the responsiveness of the participant to provide these subjective ratings. In order to minimise the effects of fatigue, the number of stimuli were limited to 20 for the discrete control experiment and 14 for the continuous control experiment. The continuous control study had fewer stimuli as each stimulus task took longer than in the discrete control task. The short duration of the vibration exposures meant that time-dependent effects due to fatigue would have minimal influence on performance. For this reason and due to the longer time necessary to complete the driving task for the continuous manual control study; the number of vibration stimuli was reduced.

3. Results

3.1 Discrete manual control performance

During x-axis vibration, the mean time to complete the task (for both stances) increased significantly ($p < 0.05$), with vibration magnitude between the control condition (no vibration) and 2.0ms^{-2} r.m.s. At each magnitude, the highest mean times were found to occur in the anterio-posterior stance however, this effect was not significant (Figure 2).

For y-axis vibration, a significant ($p < 0.05$) increase was found in the mean times to complete the task, with increasing vibration magnitude up to 2.0ms^{-2} r.m.s., for both anterio-posterior and lateral stances. The anterio-posterior stance tended to show higher mean times compared to the lateral stance however, these postural effects were not significant. At the highest vibration magnitude (2.0ms^{-2} r.m.s.) the mean times to complete the task were significantly ($p < 0.05$) shorter during y-axis vibration compared to x-axis vibration exposure, for both stance orientations.

With dual-axis (xy-axes) vibration, mean task completion times increased significantly ($p < 0.05$) with an increase in vibration magnitude for both stances. The effect of stance orientation showed some variation, with shorter mean times found during the anterio-posterior stance rather than the lateral stance at magnitudes 0.7ms^{-2} r.m.s. and 1.4ms^{-2} r.m.s.. At vibration magnitude 2.8ms^{-2} r.m.s. however, the anterio-posterior stance showed significantly ($p < 0.05$) longer mean task completion times than those obtained in the lateral stance.

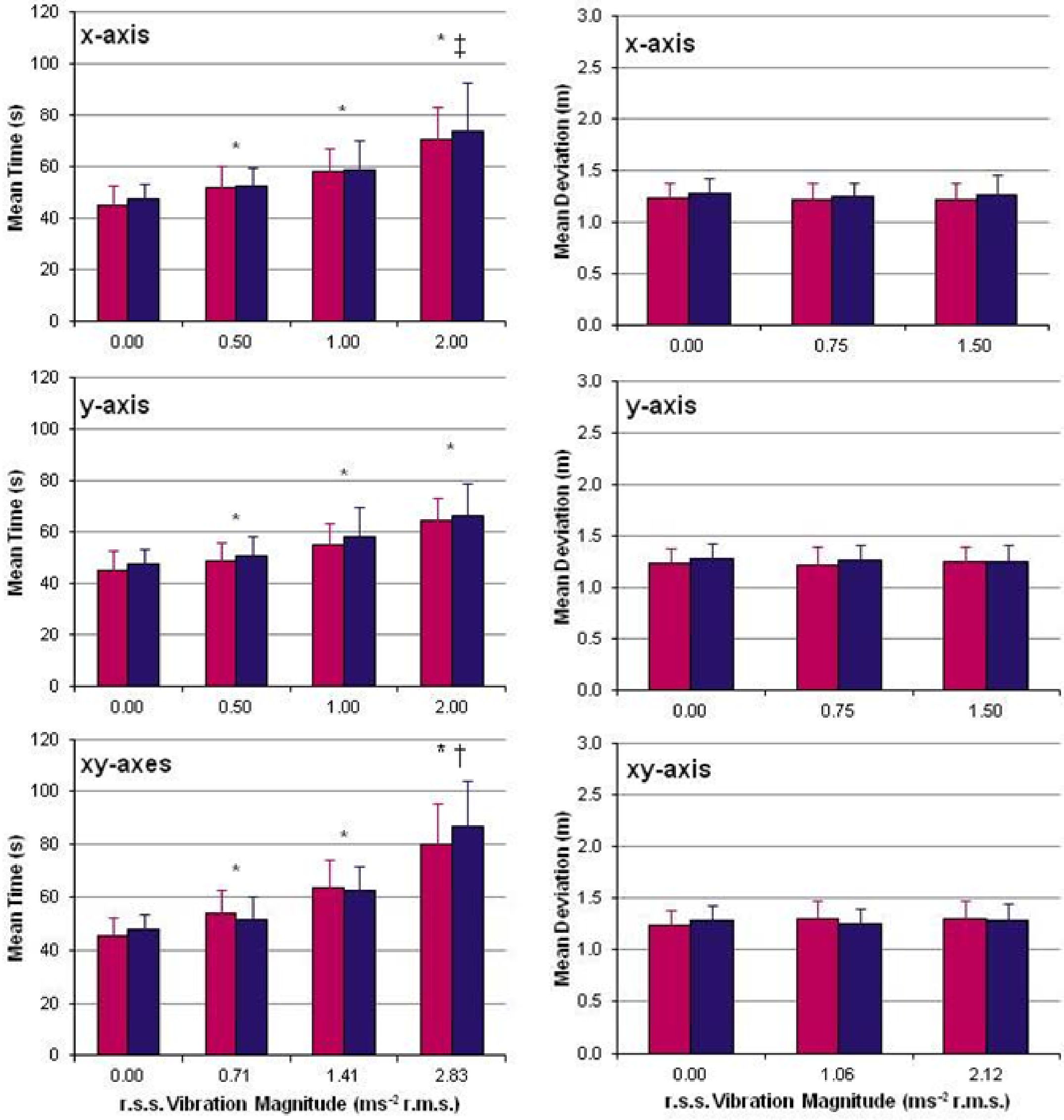
3.2 Continuous manual control performance

For all conditions during the LCT driving simulator task, no significant effects were observed for the mean deviations in lane position (Figure 2). The performance of a continuous control task therefore was unaffected by increasing vibration magnitudes, nor were there any effects between the different directions of motion (x- and y-axis). Stance orientation showed no significant influence on continuous manual control performance. Comparing single and dual-axis exposures, the mean deviations in lane position were slightly higher during dual-axis vibration exposure than during single-axis vibration however, these effects were not significant.

3.3 Discrete manual control workload

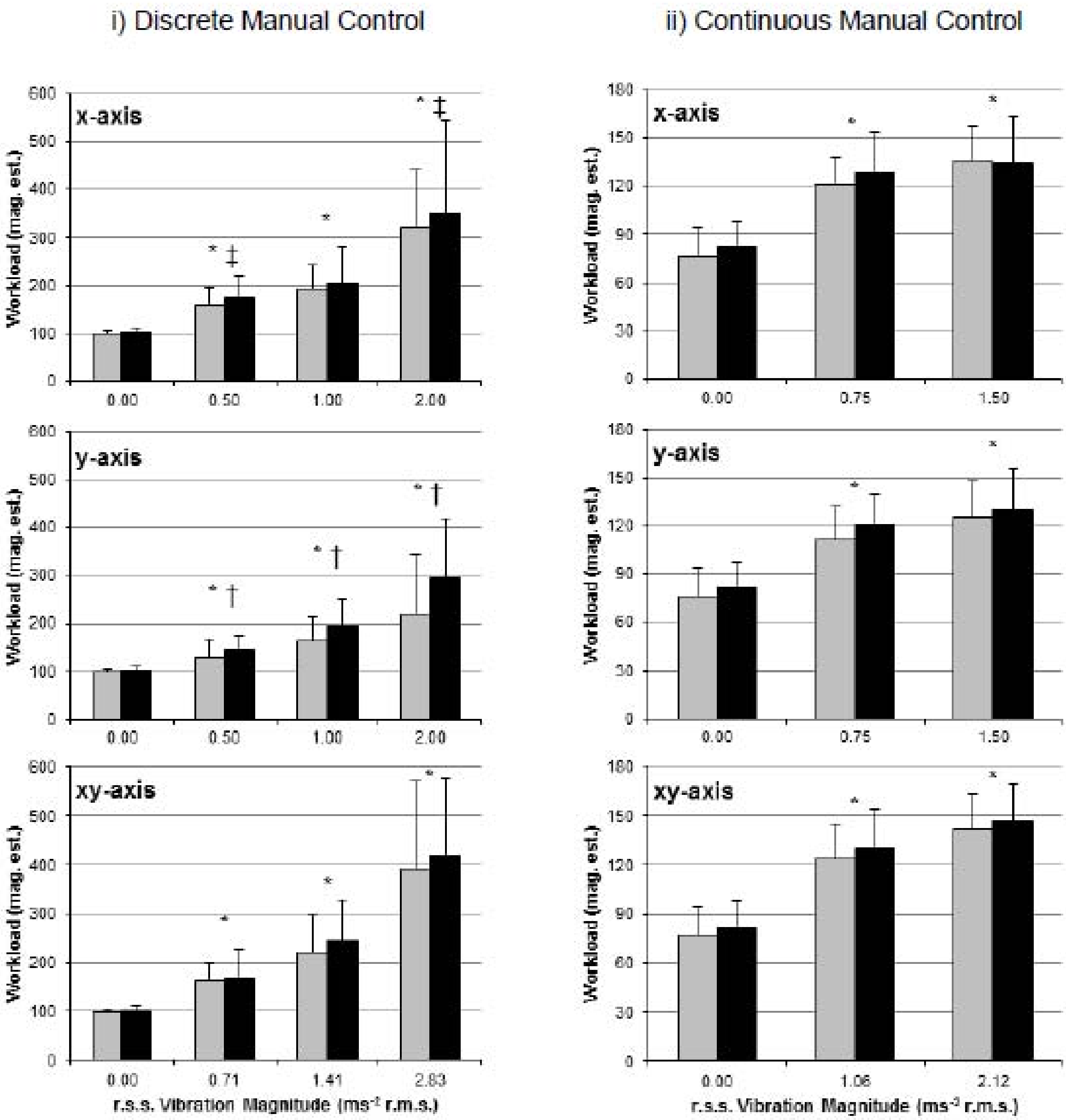
During x-axis vibration exposure, the magnitude estimations of workload increased significantly ($p < 0.05$), with increasing vibration magnitude up to 2.0ms^{-2} r.m.s., for both anterio-posterior and lateral stances (Figure 3). No significant differences were found between the two stances however, workload experienced in the anterio-posterior stance was slightly higher than in the lateral stance.

Exposure to y-axis vibration significantly ($p < 0.05$) increased magnitude estimations of workload with corresponding increases in vibration magnitude. At vibration magnitudes 0.5, 1.0 and 2.0 ms^{-2} r.m.s., workload in the anterio-posterior stance was significantly ($p < 0.05$) higher than in the lateral stance. Additionally, at vibration magnitudes 0.5 and 2.0ms^{-2} r.m.s., magnitude estimations of workload obtained during y-axis vibration were significantly ($p < 0.05$) lower than those obtained during x-axis vibration. The lower magnitude estimations indicate that performing the discrete pegboard task during y-axis vibration resulted in the participants experiencing less workload than during x-axis vibration.



Where: * = significant difference ($p < 0.05$) between vibration magnitudes for both standing postures.
† = significant difference ($p < 0.05$) between anterio-posterior and lateral stances.
‡ = significant difference ($p < 0.05$) between vibration directions (x-axis and y-axis).

Figure 2. Objective performance measures for i) discrete and ii) continuous manual control in an anterio-posterior and a lateral stance, during exposure to horizontal WBV (blue = lateral stance, red = anterio-posterior stance)



Where: * = significant difference (p < 0.05) between vibration magnitudes for both standing postures

† = significant difference (p < 0.05) between anterio-posterior and lateral stances

‡ = significant difference (p < 0.05) between vibration directions (x-axis and y-axis)

Figure 3 Magnitude estimations of workload for i) discrete and ii) continuous manual control in an anterio-posterior and a lateral stance, during exposure to horizontal WBV (black = lateral stance, grey = anterio-posterior stance)

Dual-axis vibration exposure resulted in significant ($p < 0.05$) increases in magnitude estimations of workload with increasing vibration magnitude up to 2.8ms^{-2} r.s.s. There were no significant differences found between the anterio-posterior and lateral stance orientations.

3.4 Continuous manual control workload

During x-axis vibration exposure, the magnitude estimations of workload increased significantly ($p < 0.05$) with an increase in vibration magnitude up to 1.5ms^{-2} r.m.s. in both stance orientations (Figure 3). No significant differences were found between the two stance orientations.

For y-axis vibration, magnitude estimations showed significantly ($p < 0.05$) higher measures of workload with increases in vibration magnitude during both stances. Magnitude estimations of workload showed no significant influence of stance orientation for all vibration magnitudes used in the study. Comparing workload estimations between x-axis and y-axis vibration exposures, slightly less workload was experienced during y-axis motion however, these effects of vibration direction were not significant.

Dual-axis vibration showed significantly ($p <0.05$) higher measures of workload were found with increasing vibration magnitudes up to 2.1ms^{-2} r.s.s., for both stances. No postural effects due to stance orientation were found during exposure to dual-axis vibration.

4. Discussion

The two case studies show that vibration affects the human who is exposed. For the discrete control task, there was an objective performance decrement but for the continual control task there was no change in the performance. This supports the hypothesis that a well-designed control (i.e. a steering wheel) is largely immune to the effect of vibration. However, for the poorly designed task (i.e. the purdue pegboard) the vibration adversely affects the human performance shown by the task taking longer to complete, the more vibration to which the participant was exposed.

Results of workload showed that there was an increase in task difficulty irrespective of how well the subject performed objectively. This means that even if performance is maintained there could be a cost to the human in the system in terms of their workload, and potentially fatigue.

The ability for humans to adapt to additional stressors and maintain performance has been widely acknowledged (Hancock and Warm, 1989 and Hockey, 1997). Through the series of case studies, the influence of vibration exposure on objective measurements of performance have yielded varying results. When performing a discrete manual control task, individuals were unable to maintain performance even at relatively low magnitudes of vibration. No performance degradation was found when performing a continuous control task, individuals were therefore able to adapt and maintain performance even with increasing vibration magnitudes. A consistent trend throughout all these investigations however, was the subjective workload experienced by the individuals when performing these tasks. In all conditions, an increase in vibration magnitude corresponded to increased ratings of workload.

Figure 4 illustrates the relationship between objective performance and subjective workload, using the principles outlined in the ‘extended-U’ hypothesis (Hancock and Warm, 1989) and the compensatory

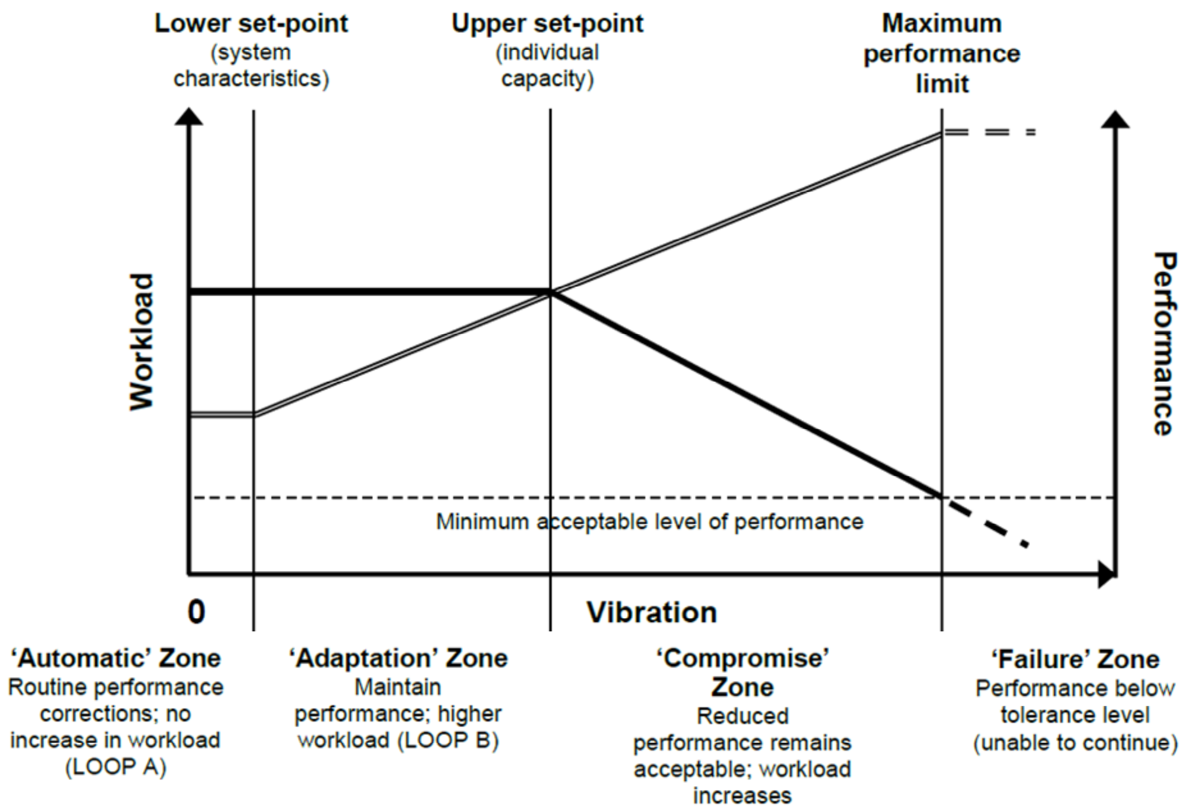


Figure 4. Performance-Workload Model illustrating the relationship between objective task performance and subjective workload during exposure to vibration (bold line = performance; double line = workload)

control model by Hockey (1997). In the performance-workload model shown in Figure 4, the four 'zones' of performance and workload have been developed based on the loops described in the compensatory control model (Hockey, 1997). The 'automatic' zone represents 'loop A' where there is no additional increase in workload and performance remains constant. Performance levels within this zone are limited by the lower set-point based on the characteristics of the system (for example, the physical ability of the individual to perform routine corrections and the capabilities of the device to accommodate for minor adjustments). As the vibration (stress) increases there is an 'adaptation' zone in which performance is unaffected however, there is a corresponding increase in the workload experienced by the individuals ('loop B'). The capacity of the individual to adapt determines the upper set-point and limitation on this 'adaptation' zone.

A continued increase in vibration would result in performance degradation and a further rise in workload ('compromise' zone). In this situation the individual could re-evaluate the performance criteria and objectives – by lowering the acceptable level of performance, the overall tasks may continue to be completed although there will likely be an increase in other performance factors such as accuracy. For example, an individual would still be able to type an email on a mobile device however there would potentially be an increase in the number of misspelt words. The final zone is the 'failure' zone, where performance continues to degrade below a minimum acceptable level and tasks can no longer be completed.

5. Conclusions

Exposure to whole-body vibration can adversely affect the performance of people performing control tasks. Good design of the task can mitigate for the effects of the vibration. Even if performance is protected by good design, the workload for the subject can still increase with increases in vibration magnitude.

6. References

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