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ABSTRACT

Vehicle motions can adversely affect the ability of a driver or occupant to quickly and accurately push control buttons located in many advanced vehicle control, navigation and communications systems. A pilot study was conducted using the U.S. Army Tank Automotive and Armaments Command (TACOM) Ride Motion Simulator (RMS) to assess the effects of vertical ride motion on the kinematics of reaching. The RMS was programmed to produce 0.5 g and 0.8 g peak-to-peak sinusoidal inputs at the seat-sitter interface over a range of frequencies. Two participants performed seated reaching tasks to locations typical of in-vehicle controls under static conditions and with single-frequency inputs between 0 and 10 Hz. The participants also held terminal reach postures during 0.5 to 32 Hz sine sweeps. Reach kinematics were recorded using a 10-camera VICON motion capture system. The effects of vertical ride motion on movement time, accuracy, and subjective responses were assessed. Performance decrements associated with vertical ride motion were found to depend strongly on reach direction and frequency.

INTRODUCTION

Controls that require pushbutton activation are increasingly common in land vehicles, particularly those intended for military applications. Previous studies of reach kinematics and performance have focused on either static environments or aircraft environments with motion frequency distributions that differ substantially from land vehicles (Harris et al. 1966, McLeod 1988, etc.). Research on vibration transmissibility to the head and extremities of seated operators has shown that posture substantially affects transmissibility (Messenger et al. 1989). These findings suggest that reaching motions might be disrupted by vehicle ride motions. If operator performance in push-button tasks is degraded relative to static conditions, then design guidelines and simulation tools that are based on data gathered in static environments should be reassessed.

This pilot study investigated the extent to which sinusoidal vertical inputs with amplitudes typical of rough-road vehicle operation altered reach kinematics and degraded push-button performance. The study examined the effects of reach direction, posture, and ride-motion frequency. Motion paths of the arm, movement time, fingertip accuracy and excursion, and subjective responses were all used to evaluate the performance degradation compared with a static environment.

METHODS

PARTICIPANTS

Two participants volunteered for this study, one man and one woman. They were both TACOM employees who did not receive additional compensation.

Table 1. Summary of Participant Information

Subject	Gender	Age	Height	Weight
S1	Male	25 yrs	172.2 cm	77.3 kg
S2	Female	34 yrs	167.6 cm	59.1 kg

RIDE MOTION SIMULATOR (RMS)

The RMS is a six-degree of freedom human-rated motion platform owned and operated by the U.S. Army Tank Armaments and Automotive Command's (TACOM). The RMS is capable of simulating broad-spectrum ride motions through a hexapod hydraulic system. The following specifications are taken from the RMS technical specifications:

- Payload = 1,600 lbs
- Platform Diameter = 46 in
- Axes Linear Displacement +- 20 in
- Axes Linear Velocity +- 50 in/s
- Axes Linear Acceleration +- 2 g's

The RMS cab was instrumented with a High Mobility Multi-purpose Wheeled Vehicle (HMMWV or Hummer) instrument panel, shown in Figure 1.

Figure 1. RMS with HMMWV instrument panel.

A trained RMS operator verified the operational status and safety of the system prior to testing by sequencing through all of the combinations of input frequencies and amplitudes of the experiment. Three tri-axial accelerometers on the RMS cab were professionally calibrated the week prior to testing. Safety limits were engaged and emergency-stop buttons were available to the experimenter, the participant, and the spotter, who monitored the physical response of the subject during the test sessions.

Past studies of vibration have largely determined that frequencies between 4 and 6 Hz, also known as a principal resonant frequency, most significantly affect the performance of manual tasks. Furthermore, the principal resonant frequency depends largely on the participant's posture (Messenger et al. 1989). Additional research has shown that there is a direct relationship between vibration amplitude and performance degradation (Lewis et al. 1978). For these and other reasons, the RMS input parameters during the experiment were chosen to include the sinusoidal vertical frequencies of 0, 2, 4, 5, 6, 8, and 10 Hz, and peak-to-peak amplitudes of 0.5 g and 0.8 g.

Two sitpads with triaxial accelerometers were affixed to the seat, one at the level of the T10 vertebrae on the seatback and the other directly below the right ischial tuberosity on the seatpan as shown in Figure 2.

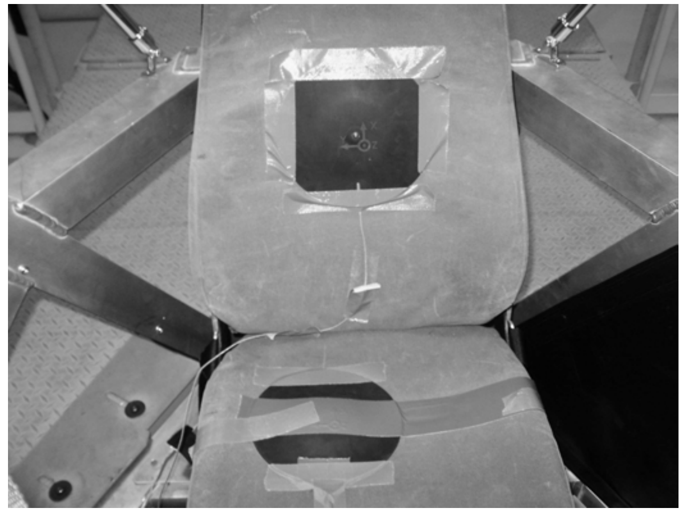

Figure 2. Sitpads affixed to RMS seat.

REACH TARGET LOCATIONS

Six red buttons (diameter = 12.8 mm) were placed at various locations within the participant's right-hand reach envelope; approximate straight-line distances from the seat H-point (centerline) are given in parentheses:

1. Above right shoulder (~1.2 m)
2. Forward of right shoulder (~1.0 m)
3. Forward of elbow, arm at rest (~0.5 m)
4. Elbow height, arm at rest, 45° right (~0.8 m)
5. H-point height, 45° right (~1.0 m)
6. Floor, 45° right (~0.6 m)

Figure 3 shows the EDS PLM Solutions' *Jack* figure in a digital mockup of the RMS cab with the six target locations.

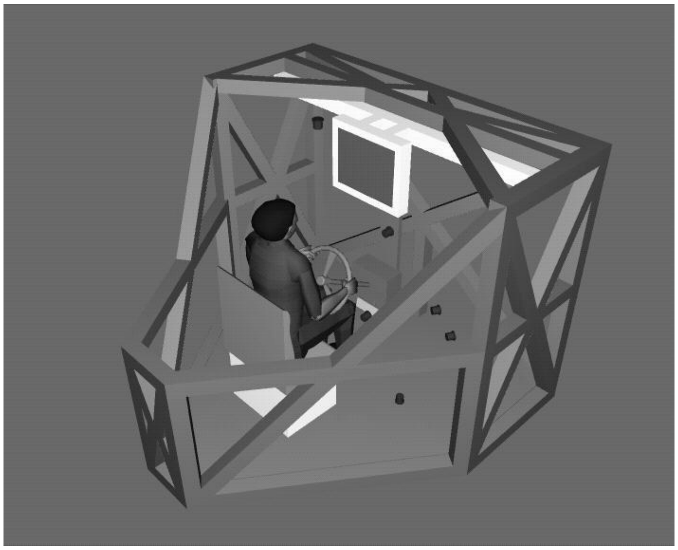

Figure 3. Digital human 3D environment.

MOTION CAPTURE

Movements of the RMS cab and the participants were recorded by a VICON 524 motion capture system, sampling at 60 Hz using ten cameras. Eight standard-sized analog cameras and two lipstick cameras, all with 640 x 480 resolution, were positioned around the rear of the semi-enclosed cab. Of those cameras, six were placed in overhead positions and the remaining four cameras were placed behind the cab, two on each side as shown in Figure 4.

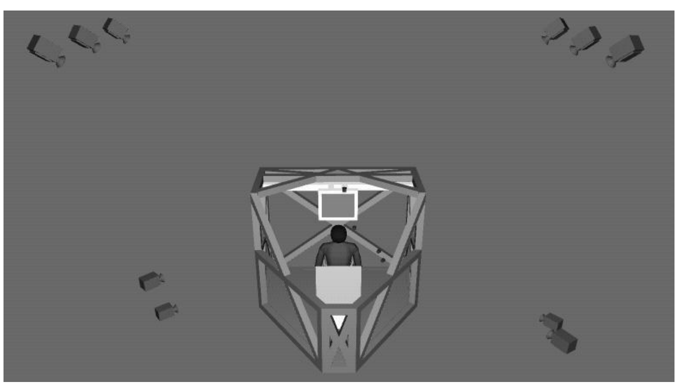

Figure 4. Digital representation of RMS cab with VICON camera setup.

Six reflective 12.8-mm-diameter markers were placed at extreme locations on the RMS cab to record its motion. The participants wore a headband with four affixed markers to collect data on the position and orientation of the head during the reaches. Likewise, wristbands were worn with two markers on each that determined the orientation of the wrists. A total of twenty reflective markers were placed on the participant's body, including the legs, torso, head, and upper extremities as shown in Figure 5.

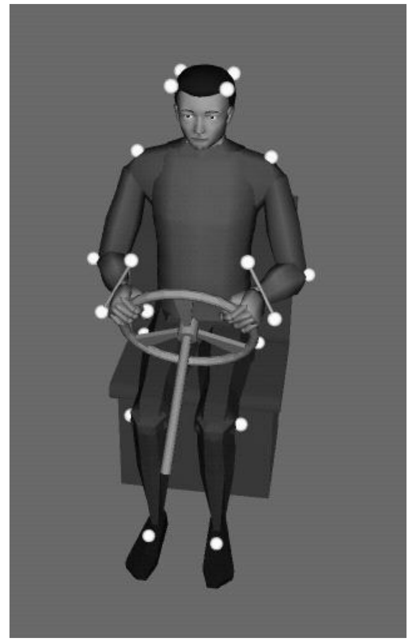

Figure 5. Jack digital human showing reflective marker locations.

EXPERIMENTAL PROCEDURE

The experiment was conducted in four sequential blocks:

1. Reaches with no platform motion, momentary contact at target;
2. Reaches with no platform motion, 2-second hold at target;
3. Sine sweeps with static postures; and
4. Reaches with single-frequency sinusoid inputs.

Reaches in the no-motion condition were performed twice. After performing one set of reaches to each of the six target locations, the participants were given instructions to perform the next set by reaching to the target, holding the outstretched index finger on the target for two seconds, and then returning to the Home position. The objective of these trials was to determine if the requirement to hold the target location altered the reach kinematics.

Within each block of reaches, the order of target locations was randomized. Using a headset, the experimenter communicated a target location for each reach to the participant, who immediately responded by performing a reach to that target. These reaches were performed every ten seconds, which allowed several seconds of rest at the home position between reaches. The reaches were self-paced, with the participants attempting to perform them as quickly as possible.

The third block of trials examined the effects of vertical ride motion on a nominally static posture. Motions were recorded during 72-second "sine sweeps" sequencing smoothly through the frequencies between 0.5 Hz and 32 Hz, with the frequency doubling every twelve seconds. The RMS induced constant amplitude 0.5g peak-to-peak vibration to the platform for these reaches.

The participant reached with a fully extended elbow to the right side, forward, and up, with and without bending the torso (corresponding to near and far reaches). The direction of reach was randomized and breaks were given between reaches to reduce muscle fatigue, particularly in the shoulder.

For the reaches that did not require flexing the torso, the participants were asked to sit erect with an outstretched arm, holding it horizontal during forward and side reaches and directly over the shoulder during upward reaches. The subjects attempted to maintain this posture during the sine sweeps. Participants were instructed to keep the torso and arm comfortably relaxed during the session, rather than to attempt to keep their bodies rigid.

To measure the postural effects associated with reaching in these directions, subjects were also asked to reach their outstretched arms while bending the torso approximately 30° in the forward and side directions. For upwards reaches, subjects were asked to maximally extend the arm without altering the posture below the waist, thus constraining the postural adjustment to the upper body.

In the last capture session (block 4), the participants reached to the six target locations with steady sinusoidal inputs of 0.8 g peak-to-peak. The input frequencies of 2, 4, 5, 6, 8, and 10 Hz were applied in random sequence.

DATA ANALYSIS

Motion data were exported from the VICON workstation and imported into the *Jack* software. A three-dimensional CAD model of the RMS cab was also imported to facilitate visualization of the motion data. Digital figure models were scaled to match the participants' primary body dimensions.

Data from the reflective markers on the RMS cab were used to subtract the motion of the cab from those of the participant so that the movement patterns associated with reaching in static and dynamic environments could be directly compared.

Motion capture of the participants' motions and the movement of the digital human's fingertip were used to analyze the reach duration, movement path, motion tactics, and accuracy of the reaches.

Statistical analyses examined the main and interactive effects of reach direction, posture and ride-motion frequency on movement times and accuracy. Accuracy was evaluated by the "apparent target size" or fingertip excursion size determined by a circle that enclosed the fingertip's position at the target location approximately 95% of the time.

RESULTS

MOMENTARY CONTACT VS. TWO-SECOND HOLD

A comparison of the momentary-contact reaches with the two-second hold reaches at the target locations in the static environment revealed very little discrepancy. The home-to-target time of the fingertip was not statistically different between the blocks. Further Visualization of the motions using the digital human did not reveal noticeable differences.

Significant observations were made during the experiment regarding the effects of frequency on the participants' performance. The participants appeared to have substantial difficulty performing the reaching tasks under frequencies between 4 and 6 Hz, confirming the performance degradation near the principal resonant frequency.

As the frequency moved away from this range, the apparent difficulty of reaching the targets decreased. Performance degradation at 2 Hz appeared minimal, probably due to the participants' ability to compensate for the ride motion effects. At 8 and 10 Hz, the transmissibility of the vibration appeared to be reduced as the participants appeared to be less affected than between 4 and 6 Hz.

There appears to be two phases to the participants' movements, an initial ballistic motion and then a final adjustment nearing the destination. The primary effects of the ride motion were an increase in the duration of the adjustment phase as well as an increase in finger-tip excursions during this phase. During this phase, the operator attempts to compensate for the ride motion by taking additional time to steady the arm as the finger nears the button.

The initial phase of the motion did not appear to significantly change, probably because the primary goal of this phase is for the finger to travel generally towards the target, which requires less accuracy.

FINGERTIP EXCURSIONS AT THE TARGET

For the reaching tasks under input frequencies between 2 and 10 Hz, fingertip excursion sizes were ranked from the largest required to the smallest: 5, 1, 4, 6, 3, and 2. Overall, the far, diagonal reach was worst, and the shoulder-high, frontal reach was the easiest and are presented in Table 2 and illustrated in Figure 6.

Table 2. Average Fingertip Excursions by target and frequency for block 3 (sine sweep in static postures)

	0 Hz	2 Hz	4 Hz	5 Hz	6 Hz	8 Hz	10 Hz	Mean
T1	0.7	3.2	4.8	4.5	4.0	1.9	0.8	**2.8**
T2	0.3	1.2	1.9	1.8	1.5	0.6	0.4	**1.1**
T3	0.4	1.6	2.9	3.2	2.1	0.7	0.7	**1.7**
T4	0.6	2.3	3.3	3.0	3.3	1.1	0.7	**2.0**
T5	0.6	2.6	3.8	3.9	3.6	1.2	0.5	**2.3**
T6	0.4	1.9	2.6	2.5	2.4	0.8	0.4	**1.6**
Mean	**1.0**	**2.3**	**2.8**	**2.8**	**2.5**	**1.5**	**1.0**	

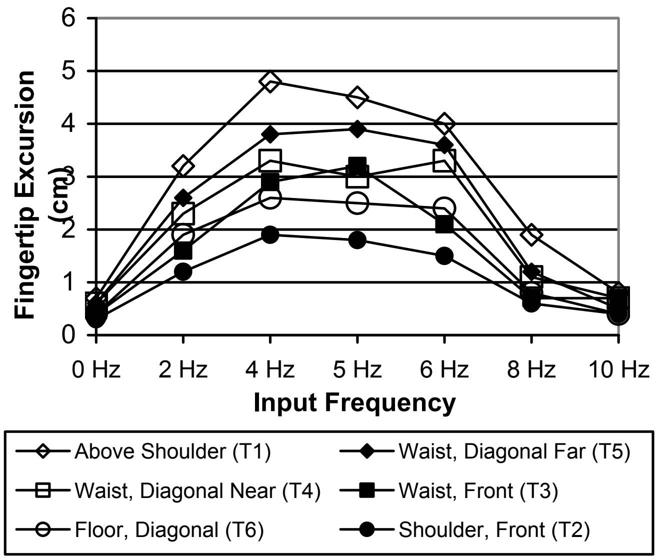

Figure 6. Comparison of Input Frequency and Fingertip Excursion.

In block 3, the extended reaches, where torso flexion was required to reach the desired location, larger fingertip excursions were exhibited during the sine sweeps. In some cases, the subject was only capable of maintaining a fingertip excursion of nearly 5 cm. Conversely, the reaches that did not require torso flexion showed significantly reduced variance.

Fingertip excursion sizes for the holding reaches in block 3 were ranked in order from largest to smallest (direction-distance): Up-Far, Forward-Far, Up-Near, Side-Far, Forward-Near, and Side-Near. The upward and forward reaches had the highest average variation and side reaches showed the smallest average variation.

SUBJECTIVE RATINGS

Subjects gave all of the static reaches (0 Hz) a "Low" difficulty rating. Reaches across the tested frequency range yielded various difficulty ratings. Subjects gave the shoulder-high, forward reach to the close Target 2 the lowest difficulty across the tested frequency range. Conversely, targets 1 and 5 yielded the highest average difficulty, directly upward and an extended diagonal, hip-high reach respectively.

After each reach, the participant was asked to rate the difficulty of the reach as "High", "Medium", or "Low". Scores were coded numerically (Low = 1, Medium = 2, High = 3) and averaged across the participants.

Reaches to Target 3 were more difficult than expected, possibly because of interference from the steering wheel or the partial visual occlusion of the target by the steering wheel. The surface map construction in Figure 7 graphically emphasizes the principal resonant frequency between 4 and 6 Hz while also providing insight into the difficulty of each target location under those frequencies. All reaches at 10 Hz were given "Low" difficulty ratings, the same difficulty as those from the static environment.

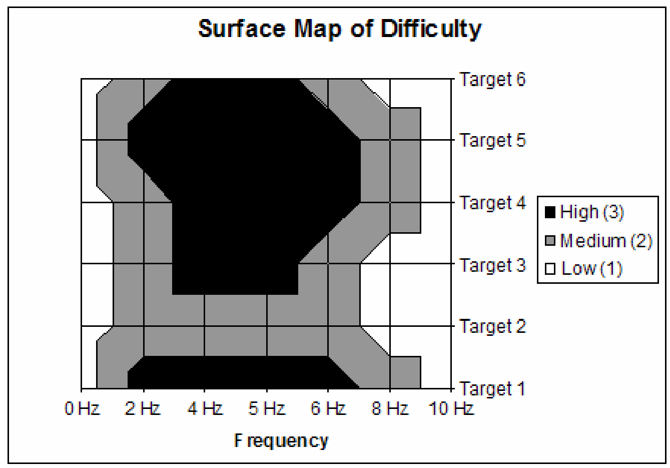

Figure 7. Reach difficulty rating by ride-motion frequency and target location.

DISCUSSION

The study demonstrated that human motions can be captured accurately and efficiently in a ride-motion environment. Initial concerns regarding the resolution of the cameras were alleviated after examining the motion data. Postures and movements appeared natural and there were no visual deficiencies in the motion capture.

One of the more interesting results was obtained from the subjects attempting to hold their arm upward during the sine sweeps. Near the primary resonance of the torso, the participant's lumbar spine flexes and the torso rotates, inducing a fore-aft motion of the finger during the overhead reach. Each subject commented on the increased difficulty of keeping the arm still during these sessions. Likewise, these reaches exhibited the largest fingertip excursions.

A hypothesis of this effect is that when the seat is rising, the inclination of the seatback creates a forward force on the participant's torso. The vertical movement of the seat combines with the resonant frequency of the torso yielding increased fore-aft motion. The flexibility of the spine is also a likely contributor to this observed motion.

Close reaches forward or to the side have the smallest fingertip excursions and may be preferred locations for critical instruments. However, the primary field-of-view for vehicle operators is directly in front of the torso, thus side reaches may require larger and longer-duration vision deviations from the primary task of driving.

As expected, the far reaches showed increased fingertip excursions compared to the near reaches, due to the variability resulting from a bent posture. This finding provides justification for designers to ensure that critical reaching tasks do not require substantial torso flexion in any direction.

The results showed that vehicle ride motions significantly affect the performance of reaching tasks at any frequency, but the extent to which performance is degraded is dependent on both direction and frequency.

Although this pilot study examined only the effects of vibration frequency, vibration amplitude will also affect the magnitude of the resulting performance degradation. Future studies will include the evaluation of various input amplitudes, including ride vibration spectra typical of both on-road and off-road vehicles, to determine the relationships between vibration amplitudes and performance effects.

It should be further noted that intermittent variations in vibration, such as potholes in roads would be likely result in more severe effects. Future studies will include analysis of randomized input frequencies that more realistically represent vehicle ride motion.

These preliminary findings suggest that design guidelines for push-button controls in land-vehicles should consider ride-motion characteristics and reach direction. In a ride-motion environment, the performance of reaches to buttons of a particular size, in terms of speed or accuracy, is likely to depend on the buttons location in a manner that is different from that observed in static trials. This suggests that design guidelines based on static data should be re-examined for application to moving land vehicles.

Most design solutions must prioritize the importance of speed and accuracy and are almost entirely task-dependent; several general recommendations for improving the performance of a reaching task can be suggested:

1. Increase target size,
2. Decrease distance to target,
3. Place target in most accessible location,
4. Position target in most accessible orientation, and
5. Constrain arm movements to reduce perturbations.

In cases where speed is the priority, increasing target size would likely reduce movement errors. However, larger targets are typically not an acceptable solution in space-constrained environments such as the cockpits of vehicles, and thus target size per se was not evaluated in this experiment.

An arm or wrist rest may be a more acceptable solution in cases where increasing accuracy is necessary, although it may not reduce or could increase movement times. The individual solution for each designer must be based on the particular task's objectives.

Related research has been conducted by the Human Motion Simulation laboratory (HUMOSIM) at the University of Michigan, which has been developing several human motion modules[1] for inclusion into digital human modeling software that predict motions for various reaching tasks in a static environment.

In part, the dynamic data obtained from this pilot study will serve as a "proof-of-concept" for future validation and possible inclusion to HUMOSIM's human motion modules. By determining the ride-motion effects on manual performance tasks, a direct comparison can be made of HUMOSIM's motions in static environments with similar motions performed under ride motions. Gaining understanding of the performance degradation of manual tasks under ride motion may provide significant insight for the design of future vehicles.

Finally, it must be reiterated that this is only a pilot study and that further testing is planned with additional participants to determine the extent to which these findings are consistent across individuals. Additional studies will include broad-spectrum inputs of ride motion to evaluate static terminal posture variability in fingertip excursion associated with the timing and accuracy of movements.

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[1] See HUMOSIM website at http://www.engin.umich.edu/dept/ioe/HUMOSIM.

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