AIAA-2003-5678

# THE EFFECTS OF ENHANCED HEXAPOD MOTION ON AIRLINE PILOT RECURRENT TRAINING AND EVALUATION

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## Abstract

A quasi-transfer experiment tested the effect of simulator motion on recurrent evaluation and training of airline pilots. Two groups of twenty B747-400 pilots were randomly assigned to a flight simulator with or without platform motion. In three phases, they flew four maneuvers designed to reveal differences due to motion. In the first phase, termed Evaluation, the two groups flew the maneuvers as they would in a check ride. In the second phase, termed Training, the two groups flew the maneuvers repetitively and were given feedback on their performance. In the third phase, termed Quasi-Transfer, both groups flew the tasks again, but both in the simulator with motion (quasi-transfer instead of real transfer to the airplane). This was to determine whether or not their previous training with or without motion made any difference. Statistically significant effects of both motion and the phase of experiment were found for all four maneuvers. Platform motion was shown to make a difference in Evaluation, but was not found to be of benefit in Training. Results of this study and the previous hexapod motion research should assist the FAA in determining future research directions in the effort to develop motion requirements for today's airline evaluation and training needs.

## Introduction

The Federal Aviation Administration (FAA) has proposed flight-simulator Qualification Performance Standards that would replace the criteria contained in the Advisory Circulars that have guided simulator qualification for the past two decades. However, as these qualification criteria transition from advisory to regulatory status, it becomes increasingly important that, to the extent possible, they are based on sound scientific data. FAA decision making on future changes to those standards, if any, would benefit from data that relate training and evaluation effectiveness of the simulator to the simulator performance.

One area that warrants further investigation is platform motion. To date, the existing qualification standards for simulator platform motion remain controversial due to the lack of supporting data. For example, there is a paucity of data supporting the hypothesis that motion effects observed in the simulator subsequently transfer to the airplane. Such effects have been shown in a simplified context using quasi-transfer to a simulator with motion as a stand-in for the airplane, but not in the framework of airline operations. Also, most studies addressing this issue in the past used non-diagnostic maneuvers or participants, introduced bias, or lacked the required number of participants to prevent

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individual differences from masking an effect of motion.[1,2]

To address the FAA need for data, an initial study in the framework of the Volpe Center's Flight Simulator Fidelity Requirements Program[3] investigated the role of motion in a typical FAA qualified Level C turboprop simulator on recurrent airline pilot qualification. No operationally relevant effects of simulator motion on pilot control-input behavior or pilot-vehicle performance during Evaluation, Training, and Quasi-Transfer to the simulator with motion were found. The presence or absence of motion also had no effect on pilots' opinions of the simulator. The same study also found, however, that the lateral acceleration motion cueing provided by the simulator was substantially attenuated.[4] A preliminary look at eight other FAA-qualified simulators indicated that attenuated lateral acceleration may be typical for the type of simulator regularly used in initial and recurrent airline training and evaluation.

This paper presents the follow-up study to this work, another quasi-transfer study performed in collaboration with the National Aeronautics and Space Administration (NASA). This study tested whether improved motion cueing would affect recurrent evaluation and training of pilots. For this purpose, the platform motion software of the NASA/FAA B747-400 simulator was modified to enhance its translational motion fidelity for the maneuvers tested. Pertinent results of this study are presented below.

## Method

### Design

Participants serving as Pilots Flying (PF), were divided into two groups: Motion and No-Motion. In Phase I and Phase II, i.e., Evaluation and Training, the Motion group was evaluated and trained in the simulator with motion. The No-Motion group was evaluated and trained in the simulator with the motion system turned off. Both groups were then quasi-transferred to the simulator with motion as a stand-in for the airplane to examine whether any effect of motion during Training would persists in the airplane (Phase III, Quasi-Transfer).

This design resulted in two Independent Variables (IVs), the Group variable with two levels (Motion group and No-Motion group) and the Phase variable with three levels (Training, Evaluation, and Quasi-Transfer testing). Participants belonged to either the Motion or the No-Motion group, but all participants were subjected to the three phases. The Dependent Variables (DVs) were derived from over 100 variables, from which the directional, lateral, and longitudinal pilot-vehicle performance and pilot control-input behaviors appropriate for each maneuver were calculated. PFs and Pilots Not Flying (PNFs) also provided their opinions in detailed questionnaires.

Precautions were taken to assure that no effects were overlooked or emerged as a result of nuisance variables unrelated to the IVs. First, quasi-transfer to the simulator with motion, instead of real transfer to the airplane, kept constant any extraneous variables other than motion that could affect PF performance and behavior (e.g., weather and traffic). Quasi-transfer to the simulator also removed any restrictions on the maneuver choice due to safety reasons. Also, PFs were randomly assigned to the Motion or No-Motion group, provided that they were equally distributed across groups with respect to seat, PNF, and experience (number of landings in the past 12 months). To prevent bias, the purpose of the experiment was concealed from the PFs. Finally, simulator-calibration checks were performed before each experiment run to ensure the consistency of all functions.

### Participants

Forty current Boeing 747-400 Captains and First Officers participated as PFs. Each flew from their authorized seat. Each PF participated in either the Motion or the No-Motion group, resulting in 20 PFs per group.

Two retired airline captains served as the PNFs and performed non-flying tasks as instructed by the PF. The motion status during the experiment was concealed from both the PFs and PNFs. A retired air traffic controller provided instructions and operated the simulator.

### Maneuvers

Test maneuvers were selected based on the criteria described as emphasizing a possible need for motion cueing.[5,6] These included 1) skill- (instead of procedure-) based to prevent cognitive factors from masking an effect of motion; 2) closed-loop to accentuate feedback from motion; 3) external disturbances to highlight an early alerting function of motion; 4) asymmetric high-gain to magnify any motion effects and to reduce the stability margins of the pilot-vehicle control loop; 5) high workload to increase the need for multiple cues.

Four maneuvers were selected, consisting of two engine failures with continued takeoff and two hand-flown engine-out landing maneuvers with weather-related disturbances, as follows:

1. Takeoff with an engine failure at $V_1$ (termed "$V_1$ cut"), 600 ft runway visible range (RVR), 10-knots tailwind.
2. Takeoff with an engine failure after $V_2$ (termed "$V_2$ cut") at 40 feet above ground level, 600 ft RVR, 10-knots tailwind.

3. Precision Instrument Approach with an engine-out, 500 ft cloud ceiling and 5200 ft RVR, shifting 10-to-12-knots quartering head-to-tailwinds.
4. Sidestep Landing with an engine-out from left to right parallel runway (1200 ft apart), 5 miles visibility, 1100 ft cloud ceiling, constant 10-knots crosswind and a vertical upgust with 25 ft/s peak at about 2 nm from the runway threshold.

All failures involved an outboard engine to maximize the impact due to loss of engine thrust. The failure represented an engine flame-out with failure profile showing exponential loss of 90% of initial thrust in about two seconds. The auto throttle was set to be inoperative throughout the experiment to further increase pilot workload. Both landing maneuvers were hand-flown without a flight director. The Precision Instrument Approach, as well as the final part of the Sidestep Landing, were guided by the Instrument Landing System [ILS, localizer (LOC) and glide slope (GS)].

## Procedures

Briefings to the PFs were given upon arrival. All briefings were given orally and in writing. The PFs were informed that they would be flying challenging maneuvers to test different simulator configurations and specifically told to fly the flight director and/or guidance systems as precisely as possible. They were told that they would be given a chance to practice the maneuvers with graphical feedback on their flight path precision and were shown generic feedback displays depicting the performance criteria. Also, they were informed that they would fly in the vicinity of a specific airport and were given airport, weather, and airplane information. During the course of the experiment, PFs and PNFs would complete extensive questionnaires on how they perceived the simulator and their workload.

The phases and sequence of the experiment are given below.

**Phase I. Evaluation**
(Motion group with, No-Motion group without motion)
1. Evaluate Scenario 1: $V_2$ cut (Engine 1) followed by Precision Instrument Approach.
2. Evaluate Scenario 2: $V_1$ cut (Engine 4) followed by Sidestep Landing.
3. Complete Questionnaire 1.
4. Briefing on Feedback Displays using display printouts created from flight data collected during Scenario 2.

**Phase II. Training**
(Motion group with, No-Motion group without motion)
1. Each maneuver was flown three times with the opposite engine failed from the Evaluation phase. For the landing maneuvers, the simulator came off freeze with an engine failed. The maneuver sequence was different for each pilot and counterbalanced across groups. Pilots knew which maneuver would be trained and received performance feedback after each individual maneuver on the navigational display screen.
2. Complete Questionnaire 2.

**Phase III. Quasi-Transfer Testing**
(All with motion)
1. Quasi-Transfer to motion Scenario 1, Test 1
2. Quasi-Transfer to motion Scenario 2, Test 1
3. Complete Questionnaire 3.
4. Quasi-Transfer to motion Scenario 1, Test 2
5. Quasi-Transfer to motion Scenario 2, Test 2
6. Complete Final Questionnaire. [††]

The feedback during Training showed the flight profile of the maneuver just performed in comparison with the ideal profile and the boundaries of acceptable performance suggested in the Practical Test Standards (PTS).[7] For the take-offs, performance feedback was given for heading, speed, bank angle, and altitude. For heading and speed, the ranges of desired performance were ±5 degrees or knots from take-off heading or desired speed ($V_2$ + 10 knots for the $V_2$ cut, and $V_2$ for the $V_1$ cut). For bank angle, ±5 degrees were given as a reference (the PTS recommend a bank of approximately 5 degrees toward the operating engine, as appropriate for the airplane flown). For altitude, profile feedback was given up to 1000 ft, with no PTS available. For approach and landing performance, feedback was given on glide path, localizer, and approach speed performance. The criteria for glide-path and localizer compliance were shown as ±1 dot. This is more lenient than the PTS criterion of ±0.5 dot, to compensate for the added difficulty of mandatory removal of the flight director. The speed criterion was set to ±5 knots from the speed selected.

## Simulator

The experiment used the NASA-FAA B747-400 simulator.[8] Its high-brightness and high-resolution visual system provided a wide field-of-view, panoramic, out-the-window image with cross-cockpit viewing. The sound system provided direction and sound-quality cues covering the entire operating range of the engines, including the simulated failure. A digital hydraulic control-loading system provided high-fidelity control-feel cues.

The simulator met the FAA Level D Quarterly Test Guide requirements. The six hexapod actuators were capable of providing a 54-inch stroke. The measured transport delays for visual and motion cues of the simulator were well within the Level D 150 ms

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[††] The Final Questionnaire for the PF was open ended and will not be presented here.

requirement. Frequency-response testing indicated that the motion system had sufficient bandwidth (9 Hz at $90^o$ phase lag for heave acceleration).

The motion-washout filters were adjusted to improve lateral side-force and heave motion cues, which were considered critical for the test maneuvers. These enhancements, which consisted of increasing the cue magnitude and decreasing the phase error in the lateral side-force and heave motion cues by trading off rotational motion, were in compliance with previous motion fidelity research.[9–12] Figures 1 and 2 show the before-and-after motion-cueing fidelity levels according to Sinacori and Schroeder achieved for the translational and rotational degrees of freedom, respectively.

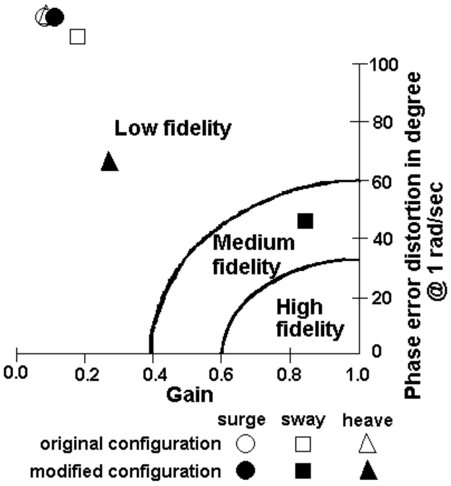


Figure 1. Translational High-Pass Specific Force Cues Before and After Tuning

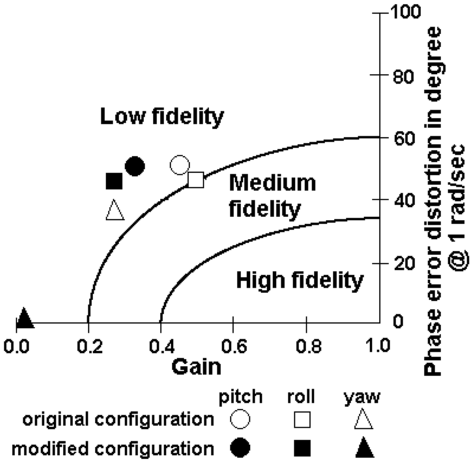


Figure 2. Angular Rate Cues Before and After Tuning

Figure 1 shows that the washout-filter adjustments improved the heave and especially the lateral side-force cues (from low fidelity to medium fidelity).

Figure 2 shows that this improvement was primarily achieved by trading off yaw motion. This trade-off was based on Ref. 11, finding that pilots perceive strong yaw-motion cues from the combination of translational lateral motion and yawing in the visual scene. Thus, actuator usage consumed by yaw platform motion was put to more effective use in the lateral axis. Magnitudes of roll- and pitch-motion cues were also reduced slightly. These trade-offs were evaluated by test pilots who were familiar with motion-cueing fidelity and did not find noticeable differences.

## Results

### Pilot-Vehicle Performance and Control Behavior

*Analyses.* The details of the analyses to determine whether a difference in the results is a mere coincidence or may be attributed to an effect of Group or Phase are given in Ref. 13. In summary, maneuvers were broken into segments, and then Multivariate Analyses Of Variance (MANOVAs) were performed on each flight segment separately. All the analyses included DVs to assess performance and behavior in all axes, which were calculated from the following data: heading (HDG) deviation, bank angle, pitch angle, roll rate, yaw rate, airspeed deviation, wheel response, pedal response, and column response. In some cases, additional DVs were used as necessary, e.g. reaction time based on pedal response in takeoff maneuvers, and LOC and GS deviations in landing maneuvers. In the MANOVAs, highly correlated DVs were reduced to one representative DV. Significant main effects and interactions were followed up with further tests as appropriate.

For the purpose of this paper, only the probability that a difference between two results is a chance occurrence will be given. Any difference with a probability to have occurred by chance of lower than 5 percent ($p<.05$) is considered a significant effect. Probabilities of lower than 10 percent are considered a trend ($p<.10$). In Phase III, the data for Tests 1 and 2 were collapsed, because no significant differences were found between them. This paper focuses on the results from the most critical flight segment of each maneuver. Results for the other flight segments are described only briefly.

Only data from successful trials were included in the analyses. A successful trial was defined as one without loss of control or abnormal ground contact (such as a wing or tail scrape). To be considered a success, takeoff maneuvers must also have been flown within four standard deviations (STD) of the mean maximum HDG and bank deviation, while landing maneuvers must have been flown within four STDs of the mean maximum GS or LOC deviations. In calculating the success rate, missed approaches were excluded from the number of total maneuvers. As can be seen in Figure 3, the success rates of the two groups across maneuvers and phases were remarkably similar, with no significant Group differences.

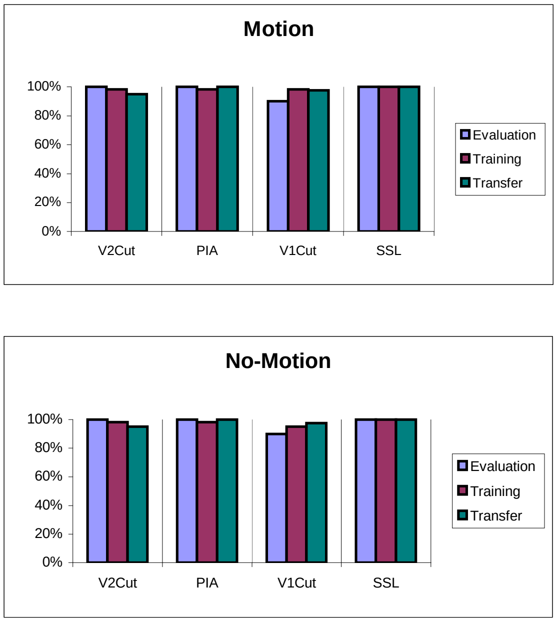


Figure 3. Success Rates by Phase and Maneuver

### Landing Maneuvers

*Precision Instrument Approach.* The Approach-Fix-to-Decision-Height (Fix-to-DH) flight segment was considered the most important for this maneuver, because in this segment the pilots had to track GS and LOC closely with disturbances from shifting cross winds. In this and all other flight segments analyzed for the Precision Instrument Approach, both overall Group and Phase effects were found to be significant ($p<.05$). This means that the pilot performance, behavior, or both were affected by the motion status of the simulator and, during Quasi-Transfer, by whether the Training had occurred with or without motion. It also means that the performance, behavior, or both were affected by whether the measurements were taken during Evaluation, Training, or Quasi-Transfer. There was no interaction between Phase and Group (any differences pointing to an interaction were likely due to chance with a probability higher than 10 percent, $p>.10$). This means that any Group effects for the Precision Instrument Approach Fix-to-DH occurred during all three phases, and that any Phase effects occurred for both groups. Most importantly, this means that any effects found due to the motion condition persisted even when the No-Motion group quasi-transferred to motion.

The Group variable significantly affected seven of the 17 DVs examined. Table 1 presents these results collapsed over phases, because the analysis showed that these results were present during all phases, including Quasi-Transfer when both groups flew with motion. The No-Motion group flew more precisely than the Motion group, with lower STDs around the desired HDG and LOC and lower bank STD. The No-Motion group seemed to achieve this performance with wheel-control inputs of lower magnitude, i.e., lower root mean square (RMS) and fewer reversals (number of times the wheel exceeds a ten-degree band around the neutral position). It used higher pedal-response bandwidth (which is the frequency below which the area under the pedal power spectral density curve constitutes half of the total area) than the Motion group.

| Variable | Group Mean | |
|---|---|---|
| | Motion | No-Motion |
| STD HDG (deg) | 3.77 | 2.84 |
| STD bank (deg) | 3.35 | 2.92 |
| STD LOC (dot) | 0.55 | 0.36 |
| Average LOC exceedance (dot) | 0.25 | 0.09 |
| Wheel reversals | 8.93 | 6.68 |
| RMS Wheel (deg) | 2.39 | 2.08 |
| Pedal bandwidth (Hz) | 0.015 | 0.025 |

Table 1. Precision Instrument Approach Fix-to-DH Results for Group, All Differences $p<.05$

Table 2 shows the DVs that were significantly affected by Phase. Both groups improved flight-precision performance (HDG, bank, pitch, and LOC STD) and reduced control inputs (wheel and column reversals, RMS, and bandwidths) progressively with Phase, indicating that both simulator configurations resulted in effective training.

| Variable | Mean | Phase Differences | | |
|---|---|---|---|---|
| | | I-II | II-III | I-III |
| STD HDG (deg) | 3.32 | 1.27* | -0.15 | 1.13* |
| STD bank (deg) | 3.15 | 0.66* | -0.25 | 0.41 |
| STD pitch (deg) | 1.21 | 0.28* | -0.004 | 0.27* |
| STD LOC (dot) | 0.46 | 0.21* | 0.004 | 0.21* |
| Wheel reversals | 7.84 | 2.61 | 0.94 | 3.55* |
| Column reversals | 4.57 | 2.03 | 1.20 | 3.22* |
| RMS wheel (deg) | 2.24 | 0.46* | -0.04 | 0.42* |
| Wheel bandwidth (Hz) | 0.12 | -0.004 | 0.03* | 0.02 |
| RMS column (in) | 0.51 | 0.10* | 0.03 | 0.13* |
| Column bandwidth (Hz) | 0.093 | -0.01 | 0.03* | 0.02 |

* indicates significant difference ($p<.05$)

Table 2. Precision Instrument Approach Fix-to-DH Results for Phase (I=Evaluation, II=Training, III=Quasi-Transfer)

For the Decision-Height-to-Touchdown (DH-to-TD) flight segment, Group and Phase again significantly affected the results, without interacting. As in the previous segment, the Motion group showed higher wheel activity, lower pedal response bandwidth, and a tendency for worse directional control than the No-Motion group (Table 3). In addition, the Motion group controlled airspeed worse than the No-Motion group and had lower column-response bandwidth. As in the previous segment, both groups were successfully trained, showing progressive improvement in flight precision (HDG, bank, pitch, and LOC tracking) and reduction in control activities (wheel and column) with Phase.

| Variable | Group Mean | |
|---|---|---|
| | Motion | No-Motion |
| STD HDG (deg) | 2.95 | 2.38 |
| Average airspeed exceedance (kts) | 5.07 | 3.55 |
| RMS wheel (deg) | 3.81 | 3.20 |
| Column bandwidth (Hz) | 0.08 | 0.11 |
| Pedal bandwidth (Hz) | 0.05 | 0.09 |

Table 3. Precision Instrument Approach DH-to-TD Results for Group, All Differences p<.05

*Sidestep Landing.* The period after the disturbance from the Upward-Gust-to-Touchdown (Gust-to-TD) is considered the most diagnostic flight segment of the Sidestep Landing for the emergence of an effect of motion. In this and all other flight segments of the Sidestep Landing, overall Group and Phase effects were significant. Again, they didn't interact with each other, so all Group effects were present during all phases (i.e., even when both groups had motion), and both groups were equally affected by Phase. Therefore, the results are again presented collapsed across the Phase and Group variables.

Group effects were observed on three of the 20 individual variables analyzed for the Sidestep Landing Gust-to-TD segment (Table 4). The two groups appear to use different TD strategies regardless of Phase: The Motion group landed softer, but at a farther distance from the runway threshold (yet within the landing box). The No-Motion group again employed higher pedal bandwidths than the Motion group.

| Variable | Group Mean | |
|---|---|---|
| | Motion | No-Motion |
| Pedal bandwidth (Hz) | 0.04 | 0.08 |
| TD distance (ft) | 1660 | 1435 |
| TD des. rate (ft/min) | 285 | 327 |

Table 4. Sidestep Landing Gust-to-TD Results for Group, All Differences p<.05

Both groups significantly improved on nine variables across phases for the Gust-to-TD segment (Table 5), showing again that Training was effective. For pilot-vehicle performance, improvement was only observed in GS tracking (lower deviation STD and deviation exceeding PTS boundaries of ±0.5 dot). In behavior, progressively with Phase, pilots were found to significantly reduce their yaw activity (mean of absolute yaw rate), wheel reversals, wheel and pedal RMS, and wheel, pedal, and column response bandwidths.

| Variable | Mean | Differences | | |
|---|---|---|---|---|
| | | I-II | II-III | I-III |
| Yaw activity (deg/s) | .41 | .07* | -.01 | .06* |
| STD GS (dot) | .56 | .05 | .04 | .09* |
| GS exceedance (dot) | .23 | .10 | .03 | .12* |
| Wheel reversals | 8.07 | 1.84* | .82 | 2.66* |
| RMS wheel (deg) | 2.93 | .46* | -.06 | .40 |
| Wheel bandwidth (Hz) | .15 | .02 | .07* | .09* |
| Column bandwidth (Hz) | .10 | .05* | .04 | .08* |
| RMS pedal (in) | .40 | .12* | -.04 | .07 |
| Pedal bandwidth (Hz) | .06 | -.03 | .04* | .02 |

* indicates significant difference (p<.05)

Table 5. Sidestep Landing Gust-to-TD Results for Phase (I=Evaluation, II=Training, III=Quasi-Transfer)

Except for the difference in the crosswind disturbances, the flight segment from the Approach-Fix-to-Breakout-of-Clouds (Fix-to-BC) at about 1100 ft was similar to the Precision Instrument Approach from Fix-to-DH, yielding similar Group effects (Table 6). The No-Motion group performed again better with regard to directional control (HDG) and LOC tracking, again with lower wheel control activity. However, the significantly lower bank-angle STD and higher pedal bandwidth found for the No-Motion group with the Precision Instrument Approach were not found here, suggesting that these variables were affected by the nature of the wind disturbance. The effects of Phase were also similar to those found for the Precision Instrument Approach. Both groups benefited from Training with better directional performance, lower column activity, and lower wheel response bandwidth, and these benefits quasi-transferred.

| Variable | Group Mean | |
|---|---|---|
| | Motion | No-Motion |
| Max HDG (deg) | 6.53 | 5.66 |
| STD HDG (deg) | 2.58 | 2.04 |
| STD LOC (dot) | 0.23 | 0.17 |
| Average LOC exceedance (dot) | 0.11 | 0.05 |
| Wheel reversals | 2.61 | 1.62 |
| RMS wheel (deg) | 2.24 | 1.79 |

Table 6. Sidestep Landing Fix-to-BC Results for Group, All Differences p<.05

For the flight segment including the side step, which ranged from Breakout-of-Clouds-to-Gust (BC-to-Gust) at about 2 nm from the runway threshold, the only significant difference was the higher wheel activity of the Motion group compared with the No-Motion group with no effect on the pilot-vehicle performance (Table 7). Training, regardless of the motion configuration, was found to have the following significant beneficial effects on Quasi-Transfer: better directional performance (HDG), more accurate GS tracking, lower control activity (column, wheel, pedal) with lower wheel response bandwidth, and less aggressive sidestep (lower sidestep rate and lower sidestep overshoot).

| Variable | Group Mean | |
|---|---|---|
| | Motion | No-Motion |
| Wheel reversals | 2.89 | 2.23 |
| RMS wheel (deg) | 2.74 | 2.32 |

Table 7. Sidestep Landing BC-to-Gust Results for Group, All Differences $p<.05$

*Discussion.* The differences in landing strategy for the Sidestep Landing between the two groups make intuitive sense. The Motion group appears to use the vertical acceleration cues to arrest sink rate, resulting in softer landings but farther from runway-threshold touchdowns than the ones of the No-Motion group. The fact that these performance differences were not replicated for the Precision Instrument Approach might be explained by the lower visibility and the shifting head- and tailwinds distracting the Motion group from taking advantage of the vertical acceleration cues.

The more striking result from the landing maneuvers is the consistent finding of lower control activity with higher flight precision for the No-Motion group, and that this finding persisted even at Quasi-Transfer to the simulator with motion. This shows that even when the No-Motion group is exposed to motion cues, it continues the steady control strategy adopted without motion cues. This was found for all segments of both maneuvers, with the exception of Sidestep Landing Gust-to-TD. The lower control activity refers to the wheel only. Pedal and column inputs were usually the same or, for bandwidths, occasionally lower for the Motion group.

These results are different from some of the previous tracking studies that have found increased control activity when motion was reduced.[11] Other studies, however, are consistent with the results of the present study.[14,15] Whether or not control activity increases or decreases as platform motion varies depends on several factors. If the pilot has been utilizing motion to improve the stabilization of the pilot-vehicle loop, as in Ref. 11, control activity usually increases as the motion cue becomes less usable. This is explained by the theoretical pilot model offered by Hess.[16] On the other hand, if motion is making the pilot aware of high frequency disturbances, then control activity can increase when motion cues become more salient, as the pilot attempts to counter those disturbances. For large vehicles, with relatively low control bandwidths, this increased control activity may not translate to improved pilot-vehicle performance. However, this conclusion appears dependent on task complexity (or, perhaps, task bandwidth).[15]

Take-off Maneuvers

*$V_2$ Cut.* The most important segment analyzed for both takeoff maneuvers is between engine failure and 800 ft above ground. Both maneuvers were affected by Group and Phase. This time, however, the two IVs significantly interacted with each other, meaning that what Group effects were found depended on the Phase and vice versa.

The effect of Group on three of the 15 variables interacted with Phase (Table 8). The Motion-trained group activated the pedal 0.76 s slower in response to the engine failure than the No-Motion group, but this effect emerged only at Quasi-Transfer, when both groups received motion cues. Also only during Quasi-Transfer, the Motion group had a 0.28 in higher column RMS than the No-Motion group. Finally, the Motion group reversed the pedal 0.45 times more often than the No-Motion group during Evaluation, but this effect disappeared during Training and did not re-emerge.

| Variable | Phase | Group Mean | |
|---|---|---|---|
| | | Motion | No-Motion |
| Pedal reaction time (s) | I | 3.40 | 3.77 |
| | II | 2.49 | 2.30 |
| | III | 3.10 | 2.34 |
| Pedal reversals | I | 1.50 | 1.05 |
| | II | 1.29 | 1.31 |
| | III | 1.49 | 1.61 |
| RMS column (in) | I | 1.17 | 1.23 |
| | II | 0.99 | 1.03 |
| | III | 1.14 | 0.86 |

Table 8. $V_2$ Cut Group and Phase Interactions, Shading Indicates Significant Group Difference

| Variable | Group Mean | |
|---|---|---|
| | Motion | No-Motion |
| Wheel reversals | 3.27 | 2.53 |
| RMS wheel (deg) | 6.97 | 5.44 |
| Pedal bandwidth (Hz) | 0.04 | 0.05 |

Table 9. $V_2$ Cut Group Differences at $p<.05$

Group, regardless of Phase, affected three control related variables (Table 9). The Motion group demonstrated higher wheel activity (RMS, reversals) and lower pedal bandwidth.

Seven variables were affected by Phase regardless of Group (Table 10). HDG STD and average failure-induced HDG deviation improved during Training, but the improvement did not quasi-transfer. This was true also for bank STD and wheel RMS. A pedal RMS decrease during Training quasi-transferred, but some of the improvement was lost. The increased wheel and pedal bandwidths found during Training was exhibited during the Quasi-Transfer for pedal only.

| Variable | Mean | Differences | | |
|---|---|---|---|---|
| | | I-II | II-III | I-III |
| STD HDG (deg) | 3.66 | 0.85* | -0.96* | -0.11 |
| Failure-induced HDG (deg) | 5.47 | 5.40* | -4.03* | 1.37 |
| STD bank (deg) | 5.69 | 1.54* | -1.71* | -0.16 |
| RMS wheel (deg) | 6.20 | 1.22* | -1.15* | 0.07 |
| Wheel bandwidth (Hz) | 0.06 | -0.02 * | 0.01 | -0.01 |
| RMS pedal (in) | 1.07 | 0.19* | -0.11 | 0.08 |
| Pedal bandwidth (Hz) | 0.04 | -0.02* | 0.001 | -0.02* |

* indicates significant difference ($p<.05$)

Table 10. $V_2$ Cut Results for Phase (I=Evaluation, II=Training, III=Quasi-Transfer)

*$V_1$ Cut.* The overall effects of Group and Phase were again significant, and, just as for the $V_2$ cut, interacted significantly with each other. This showed that for some of the DVs, the effects of one IV depended on the level of the other IV.

This was true for five of the 19 DVs, and one (HDG) showed a trend of interaction (Table 11). The Motion group responded 0.4 s and 0.3 s faster to the engine failure than the No-Motion group during Evaluation and Training, respectively. This difference disappeared when all pilots quasi-transferred to motion. The faster pedal reaction time may have allowed the Motion group to apply lower pedal RMS and higher pedal bandwidth than the No-Motion group before quasi-transfer to all motion. Some other effects that appeared during Evaluation only were lower yaw activity, lower pitch STD, and lower HDG STD for the Motion group (although this latter finding is weakened by the fact that for HDG STD, there was only a trend of an interaction between Phase and Group).

| Variable | Phase | Group Mean | |
|---|---|---|---|
| | | Motion | No-Motion |
| Pedal reaction time (s) | I | 1.53 | 1.92 |
| | II | 1.40 | 1.68 |
| | III | 1.46 | 1.42 |
| STD heading (deg) | I | 2.28 | 3.04 |
| | II | 2.41 | 2.59 |
| | III | 2.14 | 1.93 |
| Yaw activity (deg/s) | I | 0.55 | 0.79 |
| | II | 0.60 | 0.66 |
| | III | 0.56 | 0.50 |
| STD pitch (deg) | I | 5.63 | 6.40 |
| | II | 6.43 | 6.44 |
| | III | 6.39 | 6.12 |
| RMS pedal (in) | I | 0.62 | 0.77 |
| | II | 0.60 | 0.70 |
| | III | 0.61 | 0.61 |
| Pedal bandwidth (Hz) | I | 0.11 | 0.08 |
| | II | 0.11 | 0.09 |
| | III | 0.12 | 0.12 |

Table 11. $V_1$ Cut Group and Phase Interactions, Shading Indicates Significant Group Difference

Three variables showed Group differences regardless of Phase (Table 12). The Motion group used the wheel more aggressively (more reversals, higher RMS), but had fewer pedal reversals throughout.

| Variable | Group Mean | |
|---|---|---|
| | Motion | No-Motion |
| Wheel reversals | 5.72 | 4.49 |
| RMS wheel (deg) | 3.99 | 3.41 |
| Pedal reversals | 1.16 | 1.45 |

Table 12. $V_1$ Cut Group Differences at $p<.05$

Two roll variables improved across Phase regardless of Group (Table 13). Failure-induced bank increased during Training, but decreased at Quasi-Transfer. Roll activity decreased at Quasi-Transfer.

| Variable | Mean | Differences | | |
|---|---|---|---|---|
| | | I-II | II-III | I-III |
| Failure-induced bank (deg) | 1.20 | -0.44* | 0.54* | 0.10 |
| Roll activity (deg/s) | 1.36 | 0.11 | 0.10 | 0.20* |

* indicates significant difference ($p<.05$)

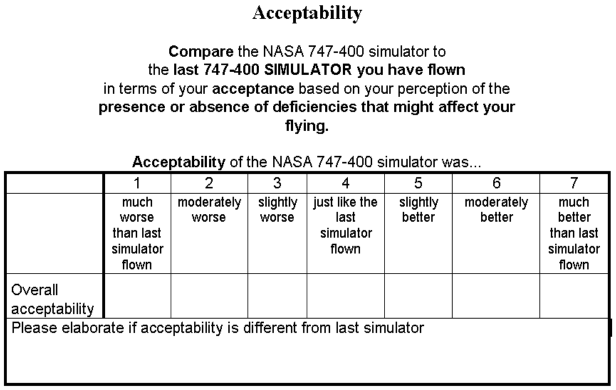
Table 13. $V_1$ Cut Results for Phase (I=Evaluation, II=Training, III=Quasi-Transfer)

*Discussion.* The most important result for the take-off maneuvers was the faster pedal reaction time to the $V_1$ cut of the Motion compared with the No-Motion group during Evaluation and Training. This does point to an early alerting function of the enhanced motion providing sufficient lateral acceleration cues. Despite the fact that PFs were told which engine failure to expect during Training, the No-Motion group had higher reaction times than the Motion group. Once the No-Motion group did quasi-transfer to motion, however, it was immediately able to avail itself of the motion cues, and the pedal reaction time and related differences disappeared. That the pedal reaction time advantage during the $V_1$ cut was not replicated for the $V_2$ cut might be explained by the higher altitude during the $V_2$ cut, which renders a response less time-critical, and the reduced visual reference to the ground, which may have led to consultation of the instruments before responding.

One curious result for the $V_2$ cut is that at Quasi-Transfer, the pedal reaction time of the Motion group is slower than for the No-Motion group. Further statistical examination showed that both groups do quasi-transfer the reaction time improvement achieved during Training, but the Motion group less completely than the No-Motion group. This may be due to fatigue of the Motion group, which in the No-Motion group may be counteracted by the emergence of motion.

Questionnaires

Acknowledging that PFs may not have experienced all maneuvers in the airplane, they were asked to base their comparisons on their expectation of how the airplane would respond in an identical situation. When considering the results, however, keep in mind the difficulty of the test maneuvers and the unusually light weight of the simulated airplane (550,000 lbs, compared to a maximum take-off weight of 870,000 lbs).



**Acceptability**

**Compare** the NASA 747-400 simulator to
the **last 747-400 SIMULATOR you have flown**
in terms of your **acceptance** based on your perception of the
**presence or absence of deficiencies that might affect your flying.**

**Acceptability** of the NASA 747-400 simulator was...

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| | much worse than last simulator flown | moderately worse | slightly worse | just like the last simulator flown | slightly better | moderately better | much better than last simulator flown |
| Overall acceptability | | | | | | | |
| Please elaborate if acceptability is different from last simulator | | | | | | | |

Figure 4. Sample PF Question

The PNFs were asked detailed questions on their observations of the PF. The PNFs were asked to compare the PF with their perception of an "average" PF.

Scales used in the questionnaires ranged from 1 ("much worse than") to 7 ("much better than"), or from 1 (very different) to 4 (the same), as appropriate. Adverbs were adapted to the questions (worse, higher, less, harder, etc.). Many pilots volunteered additional comments in the space provided. A sample PF question is shown in Figure 4.

Pilots Flying

Not all 20 No-Motion pilots mentioned motion. Thirteen commented on the motion during Evaluation, but not all of them mentioned that motion was completely absent. Three realized that motion was reduced during Training. Four never referred to motion throughout the experiment. In contrast to the first 14 No-Motion pilots, where never more than two consecutive pilots had commented on the motion, the final six No-Motion pilots (all from the same airline) all did.

For all phases, pilots found the acceptability of the test simulator to be the same as their company simulator. There were no effects of Group on the acceptability ratings during any of the three phases.

On average, physical comfort in the test simulator was rated as not different from the pilots' company simulator. There was one notable trend of a motion effect ($p<.10$): the No-Motion group apparently did not always like the quasi-transfer to motion, as expressed by lower comfort ratings than the Motion group at Quasi-Transfer.

When pilots were asked, for each maneuver, whether there were any "other cues" that were different from the airplane, they consistently rated them as less than "slightly different" ($p<.05$). The Motion group generally found "other cues" less different from the airplane than the No-Motion group during Evaluation $p<.10$) and during Training ($p<.05$). As would be expected, this effect disappeared at Quasi-Transfer to all motion. There was never any difference across maneuvers.

In all phases, regardless of Group, pilots found their control strategy to be less than "slightly different" from the one they adopt in the airplane ($p<.05$).

Pilots found that the controls were less than "slightly more sensitive" than in the airplane ($p<.05$). Never was there any effect for Group.

While control feel was rated as less than "slightly lighter" than in the airplane, the No-Motion group perceived it as more "lighter" than the Motion group during Training and even at Quasi-Transfer (all $p<.05$).

Handling qualities were consistently rated as less than "slightly worse" than in the airplane, however as more "worse" by the Motion group during Training. During Evaluation, pilots gave lower ratings to yaw control than to airspeed, bank angle, heading and altitude control. Similarly, yaw control was rated as worse than airspeed control at Quasi-Transfer (all $p>.05$).

Physical and mental workload, although

consistently perceived as less than "slightly higher" than in the airplane ($p<.05$), remained unaffected by Group across phases, with one exception: at Quasi-Transfer, the Motion group perceived the mental workload as higher than the No-Motion group did ($p<.05$). This mainly was due to higher workload ratings by the Motion group compared with the earlier phases.

### Pilots Not Flying

For pilot-vehicle performance during Evaluation and Training, PNFs perceived no differences between the PFs in the experiment and an average PF for either of the two groups. However for both Quasi-Transfer trials, the PNFs rated the No-Motion group, but not the Motion group, as showing a better performance than the average PF (both $p<.05$). The PNFs comparisons of the control strategies of the PFs with the strategy of an average PF were unaffected by Group and Phase.

With regard to workload, during Evaluation, the PNFs rated the No-Motion group as having a "lower" physical workload when compared with the average PF than the Motion group had ($p<.05$). At Training and Quasi-Transfer Test 1, this difference between groups disappeared, only to reemerge during Test 2. Once again the physical workload of the No-Motion group was rated "lower" compared with the workload of an average PF ($p<.05$).

During Training and Quasi-Transfer, PNFs also rated the "ease of gaining proficiency" of the PFs. While they rated the two groups similarly after Training and Quasi-Transfer Test 1, after Quasi-Transfer Test 2 they rated the proficiency gain of the No-Motion group as more effective compared with an average pilot than the one of the Motion group ($p<.05$).

## Discussion

This study examined the effect of enhanced hexapod simulator motion on recurrent evaluation in the simulator and quasi-transfer of recurrent training to the simulator with motion as a stand-in for the airplane.

Motion significantly affected recurrent evaluation in the simulator. For the landing maneuvers, the No-Motion group flew with greater precision but less control-input (especially wheel) effort than the Motion group. The situation was different for the $V_1$ cut, where motion provided an early alert which led to faster pedal reaction time, better heading compliance, reduced pitch variations, and reduced yaw and pedal activity for the Motion group. For the $V_2$ cut, the only difference was that the No-Motion group used fewer pedal reversals. The Sidestep Landing results also showed that for some maneuvers, motion may affect the landing strategy in a predictable manner.

Training was found to occur with both motion configurations, as shown by consistent improvement across repetitions of the maneuver. There were, however, important differences among maneuvers in how the Group effects found during Evaluation and Training quasi-transferred to the simulator with motion.

For the landing maneuvers, all earlier Group effects quasi-transferred, so that even when the No-Motion group quasi-transferred to motion, it still flew more precisely and with less effort than the Motion group. The difference in Sidestep Landing strategy also quasi-transferred. For the $V_1$ cut, however, all earlier advantages of the Motion group were lost once the No-Motion group quasi-transferred to motion, showing that current airline pilots are immediately able avail themselves of the enhanced motion cues provided for this test. For the $V_2$ cut, a new disadvantage for the Motion group emerged at Quasi-Transfer, with the Motion-group pedal response being slower than the one of the No-Motion group. This may be a sign of fatigue, which was counteracted for the No-Motion group by the presentation of new cues. The fatigue explanation is strengthened by the higher mental-workload ratings of the Motion group compared with the No-Motion group at Quasi-Transfer.

Pilot opinions from the questionnaires suggest that the presence of motion may not improve pilots' subjective assessment of the simulator. While the lack of motion cues increased the perception of the No-Motion pilots that "other cues" offered in the test simulator were different from the ones experienced in the B747-400 airplane, this didn't affect their perception of their control strategy or their ratings of simulator control sensitivity. The results from the PNF questionnaires confirmed that there was little difference between the groups, but did support the quasi-transfer benefit from training without motion discussed earlier. The PNFs felt that during Quasi-Transfer, the No-Motion group had lower physical workload, but displayed better pilot-vehicle control performance as well as easier proficiency gain than the Motion group.

## Conclusions

Enhanced hexapod motion, such as the one used in this experiment, may be required for accurate recurrent evaluation of airline pilots. This conclusion is contingent upon whether the industry perceives the effect sizes found as operationally relevant.

For recurrent training, however, no benefit of the motion provided was found. In fact, results from the landing maneuvers showed that training without motion may lower control activity and improve pilot-vehicle performance at quasi-transfer to the simulator with motion compared with training in the simulator with motion. Stimulation with motion cues may induce pilots to overcorrect, while training without motion may help pilots to adopt a more steady control strategy. Because this control strategy leads to successful performance, they maintain this strategy even at quasi-transfer to motion. This conclusion may be dependent on task complexity.

The differential effects of motion on the test maneuvers confirm that the effect of motion depends on the characteristics of the flying task. The importance of the quality of motion is indicated by the emergence of an early alerting effect of motion during the $V_1$ cut with enhanced lateral acceleration cues that was absent in the earlier study.[4]

Results of this study and the previous hexapod motion research should assist the FAA in determining future research directions in the effort to develop improved motion standards. It may also contribute to finding a cost-effective solution to today's airline evaluation and training needs via an appropriate combination of fixed-base and motion-base simulators.

## Acknowledgments

The FAA Human Factors Division, AAR-100, supported this work. We greatly appreciate the insights of our FAA Program Manager Dr. Eleana Edens. We also thank the excellent experiment team at NASA Ames and the participating pilots who volunteered their expertise.

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