A Methodology to Determine the Psychomotor Performance of Helicopter Pilots During Flight Maneuvers

Terry W. McMahon; David G. Newman

INTRODUCTION: Helicopter flying is a complex psychomotor task requiring continuous control inputs to maintain stable flight and conduct maneuvers. Flight safety is impaired when this psychomotor performance is compromised. A comprehensive understanding of the psychomotor performance of helicopter pilots, under various operational and physiological conditions, remains to be developed. The purpose of this study was to develop a flight simulator-based technique for capturing psychomotor performance data of helicopter pilots.

METHODS: Three helicopter pilots conducted six low-level flight sequences in a helicopter simulator. Accelerometers applied to each flight control recorded the frequency and magnitude of movements.

RESULTS: The mean (± SEM) number of control inputs per flight was 2450 (± 136). The mean (± SEM) number of control inputs per second was 1.96 (± 0.15). The mean (± SEM) force applied was 0.44 G (± 0.05 G). No significant differences were found between pilots in terms of flight completion times or number of movements per second. The number of control inputs made by the hands was significantly greater than the number of foot movements. The left hand control input forces were significantly greater than all other input forces.

DISCUSSION: This study shows that the use of accelerometers in flight simulators is an effective technique for capturing accurate, reliable data on the psychomotor performance of helicopter pilots. This technique can be applied in future studies to a wider range of operational and physiological conditions and mission types in order to develop a greater awareness and understanding of the psychomotor performance demands on helicopter pilots.

KEYWORDS: rotary wing, control, flying, psychomotor, pilot, performance.

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The helicopter is an inherently unstable aerial platform, with unique aerodynamic characteristics. As a result, flying a helicopter is a complex psychomotor task.[2,7,13] A helicopter pilot must make continuous control inputs to maintain stable flight and to conduct various maneuvers. The pilot must regularly and frequently adjust all of the available flight controls, especially since they are all interlinked. Various automated systems have been developed to reduce pilot workload, such as stability augmentation systems and automatic flight control systems. However, not all helicopters have these systems and autopilot systems may not be suitable for low-level operations.

Low-level helicopter flying increases the complexity of the psychomotor task even more, since the objective is to avoid ground contact. Each control input requires a level of cognitive information processing, a decision as to what type and degree of control input is required, and a judgement as to the outcome of the input (appropriate or not). This high level of psychomotor performance can be impacted upon adversely by many factors, such as environmental conditions, fatigue, workload, and time on task, with a potential risk to flight safety.[4,6,9]

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From a psychomotor performance point of view, much has been written about various aspects, including skill acquisition, selection and training, aptitude testing, and so on. The aeromedical literature contains only limited information relating to the in-flight psychomotor performance of helicopter pilots, either during routine flight[2,7,12] or emergency situations.[8,11] A comprehensive understanding of the psychomotor performance of helicopter pilots, particularly in terms of how they control the aircraft under a wide range of operational and physiological conditions, remains to be developed.

In light of this, the purpose of this study was to develop a flight simulator-based experimental technique for capturing psychomotor performance data of helicopter pilots. Such a technique could then be applied across a range of flight conditions and operations to help develop a greater understanding of the psychomotor performance demands on helicopter pilots.

METHODS

Subjects

Three male helicopter pilots participated in the study. No female helicopter pilots were recruited to this study, reflecting the low numbers of female pilots in the global helicopter industry. The pilots in this study had a broad range of aeronautical experience, with an average of 4433 h (range 600-8600) of helicopter flight time (including helicopter simulator time). One of the subjects was an experienced ex-military helicopter test pilot. All subjects refrained from eating for 2 h prior to the test and from drinking caffeinated beverages for 4 h prior to the test for standardization purposes. The research was approved by Swinburne University's Human Research Ethics Committee (Protocol Number 2012/058). Each subject provided free and informed written consent before participation.

Equipment

Flight sequences were carried out in Swinburne University's Research Helicopter Flight Simulator (Fly-It Inc.®, Carlsbad, CA). The simulator was configured to represent a Bell 206 JetRanger single-engine helicopter. All helicopter systems were set to normal and no automatic flight control systems were used during the flight sequence. Flight data sheets for each required maneuver were provided to the pilot before the flight. Prior to commencement of the flight sequences each pilot underwent a 20-min free flight simulator familiarization exercise. Sequences were timed using a digital stop watch.

Four accelerometers were used to acquire movement and control force data (Model ×6-1A USB Accelerometer/Actigraph, Gulf Coast Data Concepts, Waveland, MS). An accelerometer was attached to each flight control in the helicopter flight simulator (rudder pedals, cyclic, and collective levers) and positioned to record data in the appropriate x, y, or z axis of movement. The accelerometers are inexpensive, small, unobtrusive, and easily programmable, and importantly did not interfere with flight control movements. The accelerometers were configured with gain set at ± 2 G, resolution at 12-bit, and the sample rate set at 40 Hz.

Procedure

The starting position for the flight simulation exercise was at the takeoff position on a runway with a 240° orientation. The runway centerline acted as a reference point for the entire sequence. The weather was programmed as International Standard Atmosphere conditions with visibility greater than 10 km (CAVOK conditions). A wind component of 20 kn at 81° was selected in order to increase the level of difficulty and to accentuate likely control inputs, with a quartering tail-wind component.

For the purposes of this study, a low-level flight sequence was selected, as this would increase the likely number and magnitude of control movements. The low-level sequence was designed in accordance with protocols outlined within ADS-33E-PRF Aeronautical Design Standard Performance Specification Handling Qualities Requirements for Military Rotorcraft, United States Army Aviation.[1] There was a 30-s time interval between each flight maneuver for the pilot to stabilize the helicopter in the hover. Each pilot completed two flight simulator exercises with a 15-min rest period between each of them. Total time for the entire exercise was 1 h. During the rest period the pilot exited the simulator. **Table I** shows the sequence of maneuvers and the maximum altitude permitted.

At the commencement of the test sequence, pilots picked the helicopter up into a stable hover. From the hover, the aircraft was maneuvered from the Runway 24 threshold to a target hover point which was oriented approximately 45° relative to the runway heading. The movement parameters were a ground speed of between 6 and 10 kn and an altitude of less than 20 ft.

From a stabilized hover, a hovering 360° pedal turn at an altitude of less than 6 ft was performed to the right and then to the left. This sequence was repeated (for a total of four pedal turns). The helicopter was then flown back to the runway threshold for the slalom maneuvers.

These were a series of smooth coordinated turns at 500-ft intervals (with at least two excursions to each side of the centerline) flown down the runway using the runway centerline as the

Table I. Order of Low-Level Flight Sequences Flown and Maximum Permitted Altitude.

SEQUENCE	FLIGHT MANEUVER	DIRECTION	MAXIMUM ALTITUDE (FT)
1	Hover		6
2	Hover turn	Right	6
3	Hover turn	Left	6
4	Hover turn	Right	6
5	Hover turn	Left	6
6	Slalom		100
7	Slalom		100
8	Acceleration-deceleration		70
9	Side-step		15
10	Slalom		100
11	Slalom		100

reference feature. The turns required a lateral deviation from the centerline of no more than 50 ft. The maneuver was flown below the reference altitude of 100 ft. Upon arriving at the other end of the runway, the aircraft was turned through 180° and the slaloms were then repeated to position the helicopter back at the threshold for Runway 24.

The next sequence was an acceleration and deceleration maneuver initiated from a stabilized hover. The helicopter was rapidly accelerated, using maximum available power and forward pitch, in order to achieve an airspeed of 50 kn as rapidly as possible while simultaneously maintaining an altitude not more than 100 ft above ground level. Upon reaching the target airspeed, rapid deceleration was initiated by aggressively reducing power and pitching the nose up while holding altitude to a level not above 100 ft. The aircraft was then established in a stabilized hover. This acceleration-deceleration maneuver was then repeated.

From the hover position, the helicopter was then turned so that the longitudinal axis of the helicopter was oriented 90° to the reference axis (runway center line). A rapid and aggressive lateral acceleration was then initiated, with the cyclic being deflected aggressively to achieve sideways flight. Altitude was kept constant (not more than 70 ft above ground level), with power adjustments as required (via the collective lever). Stabilized maximum velocity sideways flight was sustained for 5 s and then an aggressive deceleration was initiated to re-establish a stablized hover, which was maintained for 5 s. The maneuver was immediately repeated in the opposite direction.

Statistical Analysis

The accelerometer data were downloaded and tabulated in a PC-based spreadsheet program (Microsoft® Excel for Mac, 2011). The data were subsequently analyzed via a statistical software tool (SPSS Statistics, version 20, IBM Corp, New York, NY). ANOVA was the statistical test of choice and an alpha level of $P < 0.05$ was considered significant.

RESULTS

The data captured by the accelerometers were of a consistently high quality and were not corrupted by any electrical interference associated with the operation of the flight simulator. **Table II** shows the total control inputs made by the three pilots during the flight simulator exercises, as well as the time taken and the mean force applied per flight. The mean (± SEM) number of control inputs per flight was 2450 (± 136). The mean (± SEM) number of control inputs per second was 1.96 (± 0.15). The mean (± SEM) force applied was 0.44 G (± 0.05 G). No significant differences were found between the pilots in terms of the number of movements per second. Similarly, there were no significant differences between the time taken to complete each flight by the three pilots, with the average flight time being 20 min 48 s. All of the pilots reported slight subjective fatigue at the completion of the flight test program.

Table II. Number of Control Movements, Time Taken, and Magnitude of Force.

PARAMETER	TEST	PILOT 1	PILOT 2	PILOT 3
No. of Movements	1	2043	2295	2681
	2	2622	2161	2899
Time Taken (minutes:seconds)	1	21:20	22:00	19:27
	2	21:56	21:56	19:26
No. of Movements per second	1	1.6	1.7	2.3
	2	2	1.64	2.5
Magnitude of Force (G)	1	0.35	0.43	0.54
	2	0.35	0.44	0.52

Fig. 1 shows the average number of control inputs made by the pilots according to limb. Right hand (x) and right hand (y) refer to fore-aft and lateral deflections of the cyclic control, respectively. In overall terms, the hands made more movements than the feet. The number of control inputs made by the hands was significantly greater than the number of foot movements ($P < 0.001$). No significant differences were found between the movements of the left and right hands, or between the left and right feet. The data revealed that some control inputs were followed by a small secondary input, particularly associated with large cyclic movements. **Fig. 2** shows the average magnitude of the force exerted by the pilots according to limb. The left hand (collective) control input forces were significantly greater than all other input forces ($P < 0.01$).

DISCUSSION

The results of this study show that the use of programmable accelerometers in a helicopter flight simulator is an effective means by which accurate and reliable data may be collected and analyzed to examine the psychomotor performance of helicopter pilots. Although only a small number of subjects were used in this study, the results revealed that the data generated by this methodology were robust and reliable. Furthermore, the electrical environment of the simulator did not interfere with the data quality and the accelerometers did not compromise the pilot's ability to manipulate the flight controls.

Helicopters have four basic flight controls: the cyclic, the collective, and the two anti-torque pedals (1 per foot). Pilots must continually process large amounts of sensory information, make rapid decisions, and execute motor commands in order to safely operate the aircraft using these controls. Depending on the situation, the cognitive workload and psychomotor demands could be very high for helicopter pilots, potentially leading to impaired flight safety.[6,9,13]

Psychomotor performance can be adversely affected by several factors. Fatigue is a common problem in aviation, especially during long duty periods or demanding flight tasks. Fatigue causes a myriad of performance problems, including difficulties with psychomotor coordination, reduced vigilance and attention, slowed reaction times, and impaired concentration, judgement, and decision-making.[4,5,14] High cognitive workload conditions during demanding flight tasks can also lead to impaired performance, with task shedding, decreased

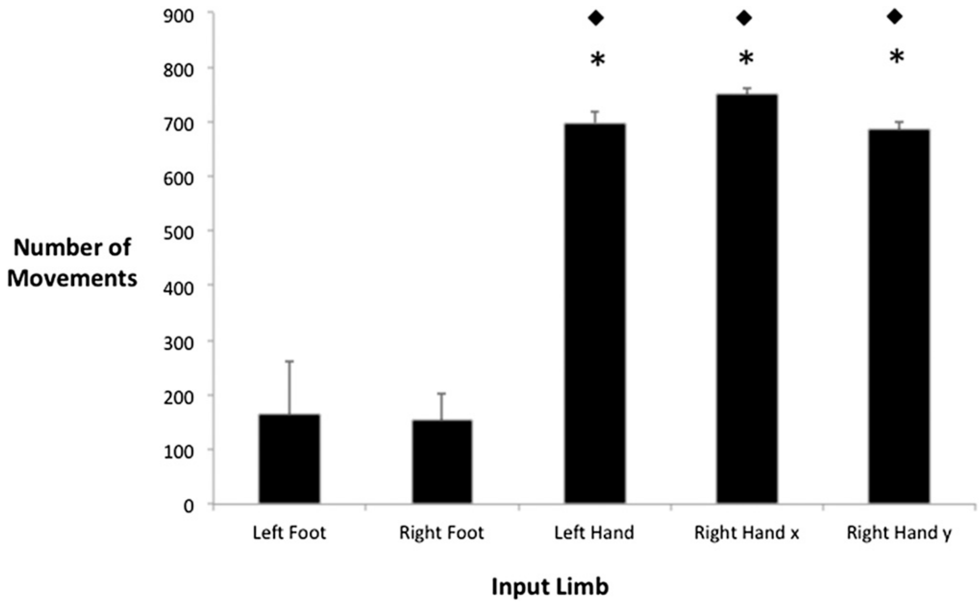

Fig. 1. Number of control input movements. Mean values (± SEM). Black diamonds denote significant difference from the left foot. *Denotes significant difference from the right foot.

control inputs being made during slalom and side-step maneuvers. Low-level flight sequences in close proximity to the ground may explain the high number of cyclic movements and the level of force applied by the collective. Under normal flight conditions (at higher altitudes) the left hand may need to perform additional tasks and use any mission-related auxiliary equipment. The collective can then be positioned with a friction lock for required power, allowing the left hand to perform these other tasks. At low level, the collective control is always active.

Thirdly, the finding that some control inputs were followed by a small secondary input is interesting. This suggests that the primary control input is an initial response of the pilot, based on judgement as to what helicopter performance is required in that situation. Once the helicopter responds to this initial input, a small secondary input may then be made in order to adjust the flight performance of the helicopter, as a fine-tuning exercise.

Finally, the pilots in this study made on average almost two control movements per second. The number and magnitude of control inputs during low-level flight maneuvers may be indicators of the level of cognitive workload in helicopter operations.[2,3] These findings, while not definitive in this study given the small subject numbers, give important directions for future research.

There have been few papers in the scientific literature dealing with helicopter control input movements and forces. Hewson et al.[7,8] conducted several studies using electromyography in both routine and emergency flight conditions. Under routine conditions, muscle activation levels and applied forces were found to be small, and rudder pedal inputs were associated with the largest pilot-applied forces.[7] In emergency flight conditions, the collective and cyclic control inputs were much greater than during routine flight. Landings under hydraulics-off conditions were associated with greater muscle activation levels than during engine-out landings. Interestingly, they also found that control forces were consistently greater than the design standards for cyclic and collective control.[8] This finding has also been shown by other researchers.[12] Other studies have examined the role of aviator experience and gender in terms of control input differences,[10,11] while Billings et al. looked at control inputs (particularly those related to rotor rpm variability) in terms of the impact of fatigue on pilot performance during long duration flights.[2,3]

The large degree of variation in methodologies employed in the few control input studies published makes comparison

situational awareness, and increased error rates, all known problems with high workload.[4,11] Fatigue and workload are often interrelated issues, and their causal relationship to accidents and incidents has been extensively documented.[4,5]

In order to understand the impact of these factors on psychomotor performance and flight safety, it is important to first identify the baseline psychomotor performance of pilots in conditions without the presence of factors such as fatigue. Subsequent comparative studies can then be done specifically to examine the change in psychomotor performance in fatigued pilots, or with high levels of cognitive demand, etc. The methodology outlined in this paper offers a way to achieve this through documenting the control inputs made by the pilot.

The small number of subjects in this study makes interpretation of the data somewhat problematic. Notwithstanding this, the results do show some interesting points worthy of brief discussion. Firstly, there appears to be a high work rate in low-level helicopter flight, requiring continuous flight control input. Hand and foot movements are frequent, but not uniform, with the hands typically generating higher forces and a greater number of movements than the feet. While the force applied to the flight controls during these movements was not particularly high, the pilots were on average making approximately two control inputs per second. The practical significance of this is that every control movement requires some level of cognitive input.

Secondly, the number of control inputs and the force with which they are applied depends largely on the type of maneuver being performed. As with previous studies, the collective control involved the highest level of applied force.[7,8] Cyclic control is multidirectional and some movements are a resulting vector of the x and y axes. In this study, the cyclic was found to be the most active of all flight controls, with the greatest number of

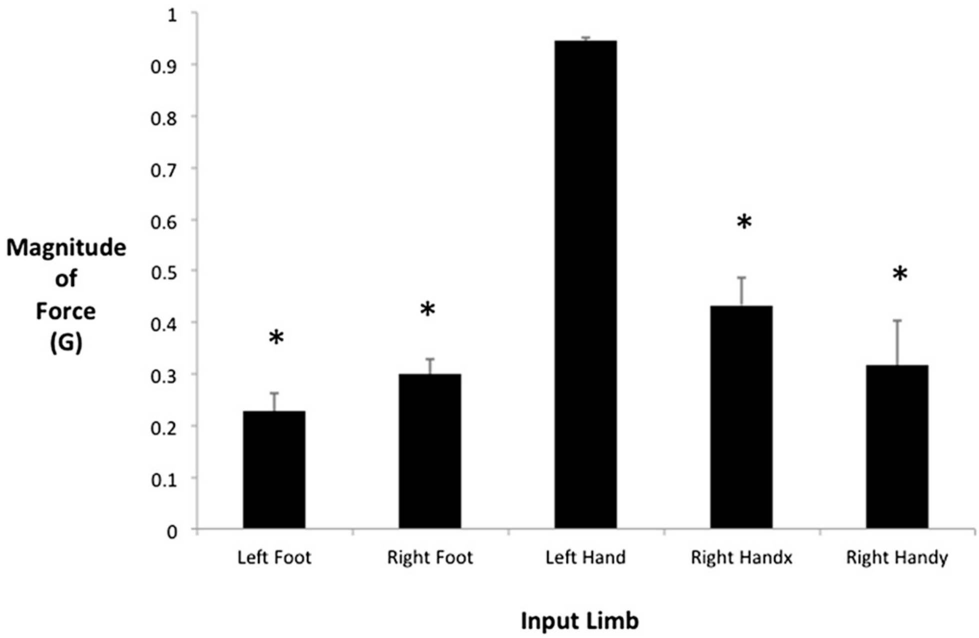

Fig. 2. Magnitude of the force of control inputs. Mean values (± SEM). *Denotes significant difference from the left hand.

between their results somewhat problematic. Experimental aims and flight profiles used were often completely different (routine flight versus emergency situations). However, what is common to all the studies is that they highlight the complexity of helicopter flying with its inherently high demands on cognitive function and psychomotor skills.

This study has some inherent methodological limitations that warrant a brief mention. Only a small number of test subjects were used, largely due to practical difficulties in accessing suitable subjects with appropriate experience or availability. The emphasis of the study was on the investigative technique rather than the subject data. However, the results of the six flight trials showed a high level of consistency, as discussed above, which indicates that the captured data is generally robust.

The use of a flight simulator, rather than an actual helicopter, may be considered a limitation. Flight simulators are not the same as actual aircraft, as not all aerodynamic forces may be represented, some important flight cues may be absent, the pilots are not subjected to the same level of stress as when in an actual helicopter, and there may be issues with negative skill transference between aircraft and simulator. However, the use of a flight simulator allows exactly the same flight conditions to be used for each test sequence, thus ensuring experimental repeatability and data consistency. Actual helicopter flight involves prohibitively high costs and also a higher level of potential risk to subjects.

In order to develop a comprehensive understanding of the psychomotor performance demands of helicopter flight, further studies need to be conducted that take into account the following experimental factors. Larger numbers of subjects need to be used and a wider range of operational conditions (such as bad weather, longer flight times), physiological conditions (such as fatigue, workload, or thermal stress), and various mission types (such as multicrew operations, ship-based operations, oil rig transfers, and even night vision goggle operations) need to be tested. Additionally, it would be useful to compare the psychomotor performance demands of an actual helicopter flight with the simulator equivalent. These studies may provide further insight into in-flight helicopter pilot psychomotor performance.

In conclusion, the aim of this study was to develop a flight simulator-based experimental technique for capturing the psychomotor performance of helicopter pilots. The results of this study show that the technique is effective, easily reproducible, and able to yield robust and reliable data that is free from any electrical interference. Significantly, the accelerometers do not impede the pilot's ability to operate the aircraft.

This flight simulator-based technique can be used in future studies (using a larger number of pilots) to gather psychomotor performance data on helicopter pilots under a wider range of operational, physiological, and environmental conditions, and during different mission types. It would also be helpful to compare the psychomotor performance demands between a flight simulator and an actual helicopter undertaking a similar mission. In this way a greater awareness and understanding of the psychomotor performance demands on helicopter pilots under a wide range of operational conditions can be developed, which might then be helpful in increasing the safety of helicopter operations.

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