EQUIVALENCY ANALYSIS OF SIDESTICK CONTROLLER MODES DURING MANUAL FLIGHT

by

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ABSTRACT

Equivalency analysis is a statistical procedure that can enhance the findings of an analysis of variance in the case when non-significant differences are identified. The demonstration of functional equivalence or the absence of practical differences is useful to designers introducing new technologies to the flight deck. Proving functional equivalence is an effective means to justify the implementation of new technologies that must be “the same or better” than previous technology. This study examines the functional equivalency of three operational modes of a new active control sidestick during normal operations while performing manual piloting tasks. Data from a between-subjects, repeated-measures simulator test was analyzed using analysis of variance and equivalency analysis. Ten pilots participated in the simulator test which was conducted in a fixed-base, business jet simulator. Pilots performed maneuvers such as climbing and descending turns and ILS approaches using three sidestick modes: active, unlinked, and passive. RMS error for airspeed, flight path angle, and bank angle were measured in addition to touchdown points on the runway relative to centerline and runway threshold. Results indicate that the three operational modes are functionally equivalent when performing climbing and descending turns. Active and unlinked modes were found to be functionally equivalent when flying an ILS approach, but the passive mode, by a small margin, was not found to be functionally equivalent.

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CHAPTER 1: INTRODUCTION

Flight control systems have evolved continuously since the first day of powered flight. What was once a simpler implementation of mechanical controls designed for slower, low flying aircraft, are now highly complex and integrated fly-by-wire designs, built for aircraft flying near and beyond the sound barrier. This advanced technology allows for a simpler pilot control interface such as a sidestick controller, rather than the complex, mechanical control yoke assemblies of the past. Since the initial development of sidesticks, research has been conducted involving sidestick controllers which can be broken down into three phases. Early on, the majority of sidestick research focused on force and displacement characteristics of sidesticks. Once these relationships were better understood, research topics shifted to study control implementation concepts. Finally, performance related testing has dominated sidestick research in recent years as sidestick controllers have become more common in the aviation industry.

Sidestick controllers have been common in commercial flight decks for several decades. Active sidestick controllers, which provide feedback to the flight crew through the feel characteristics based on aircraft parameter input to the fly-by-wire flight control system, have only been implemented in military aircraft until recently. The commercial aviation industry is seeing its first active sidestick controller on a Gulfstream aircraft, a transonic business jet with a minimum flight crew of two pilots (Warwick, 2015). The move to active technology could be a noticeable change for pilots. This has provided an opportunity to examine the differences, if any, in flight crew performance between an active sidestick controller and a passive sidestick controller. This study specifically examines the differences in multiple performance measures for normal in-flight maneuvers and landings using a sidestick controller in three modes of operation. This study does not examine the differences that may exist during abnormal events that stress the flight crew’s cognitive bandwidth. Significant differences in achieved performance between the three modes of operation is not expected during normal operations which will be demonstrated using equivalency analysis.

CHAPTER 2: LITERATURE REVIEW

The evolution to fly-by-wire did not arrive without encountering its challenges and much has been learned over the last decades. Sidestick controllers have been heavily researched as it has been desired to understand how their design can influence pilot's control of aircraft and produce superior handling qualities. This review strives to compile the knowledge gained so that flight control systems of the future can make further advancements.

Conventional Flight Control Systems

Traditionally, commercial transport aircraft were mechanically linked to the pilot's control inceptor via cables and pulleys. This provided a direct control of the control surface positions and allowed for full authority of the flight controls at all times (Hegg, 1995). As aircraft size and airspeed increased over time, the need for new methods for assisting the pilot in applying control forces was evident. Reaching aerodynamic regimes near and above Mach 1 led the introduction of powered control actuation. From this artificial feel systems evolved. With the addition of stability augmentation systems, these methods allowed for satisfactory flight control over the complete range of flight conditions. With the introduction of fly-by-wire, the design of the control stick has been considerably simplified. The complexity of the feel system has been transferred to complexity in the flight control system computers.

With fully powered controls, artificial feel became essential to manual flight. Possibilities included varying control force with dynamic pressure (q feel), speed (V feel) or control deflection (spring feel). These systems could also be augmented by bobweights and springs which were already used on conventional aircraft. Lighter roll control forces were necessary for fighters in

WWII. As speeds increased, hinge moments on controls increased resulting in larger control forces. Springs and bobweights were used to balance these forces, but this solution was limited. As aircraft speeds exceeded 500 mph prior to jet aircraft being developed, hydraulic power boosted controls were necessary. For example. pilots felt some of the aerodynamic hinge moment directly at the inceptor in the P38J Lightning, and the control forces stiffened in proportion the dynamic pressure in the conventional manner (Gibson, 1997).

Fly-by-Wire Flight Control Systems

Fly-by-wire technology offers advantages and disadvantages compared to conventional mechanical flight control systems. As mentioned earlier, fly-by-wire systems have the capability to provide improved handling qualities over the entire flight envelope, but the benefits of such a system are much more. This section will discuss the benefits of weight and cost savings, cockpit arrangement, improved aircraft maneuverability, and handling qualities. Additionally, fly-by-wire flight control systems introduce new challenges in design which will also be discussed.

Conventional flight control systems use heavy mechanical links from the pilot controls to the flight control surfaces. This includes cables, pulleys, and for powered systems, feel systems, backdrive actuators, and stick shakers. By implementing fly-by-wire technology, a tremendous weight savings can be achieved, in some cases, an estimated 600 pounds by Bleeg (1988). This is done by reducing the complex mechanical system of pilot controls to one line replaceable unit (LRU). The simplification of the physical control system architecture results in reduced maintenance actions and less cost over the lifetime of the aircraft relative to conventional control systems (Hegg, 1995).

When simplifying the pilot's interface with the flight control system by reducing a complex system to a single LRU, designers are able to improve the efficiency and effectiveness the pilot's work space in the cockpit. Conventional control column design requires a trade-off between the design of the control column and the pilot's view of the instruments as well as out the window view. The transition to fly-by-wire has allowed designers to implement sidesticks which eliminate these issues. Further, there is the added benefit of easier ingress and egress for the pilots. With sidestick controllers, there is no longer a large control column they have to step over or around when getting in and out of their seat (Hegg, 1995).

An additional benefit of fly-by-wire technology is improved aircraft performance. Traditionally, pilot controls were mechanically linked to the control surfaces, so pilots essentially commanded surface position. Now, with fly-by-wire flight control systems, pilots don't necessarily have to command control surface position, but can command aircraft response. Aircraft control laws can be developed to receive inputs from the pilot as well as other sensors on the aircraft, and output commands to produce a desired response. This ability makes it possible to fly aircraft with statically unstable airframes, which designers can leverage to achieve superior performance characteristics typically found in fighter aircraft. Human pilot response and reaction times may not be fast enough to control unstable aircraft, but fly-by-wire technology can compensate for this (Knoll, 1993).

Lastly, fly-by-wire allows for improved handling qualities over the entire flight envelope. Conventional flight control systems must overcome backlash and friction of mechanical linkages. Additionally, control forces typically increase with airspeed due to higher aerodynamic loads. Fly-by-wire flight control systems provide ideal control forces throughout the flight envelope. This can be implemented using passive or active sidestick controllers, which will be the focus of this discussion.

Passive sidestick controller designs provide limited tactile feedback to the pilot. Implementing passive sidesticks decouples the pilot from the flight process, co-pilot inputs, flight boundary exceedance, and autopilot inputs. These capabilities are not required for safe flight, but the limitations of passive sidesticks do not enhance pilots' situation awareness in high workload situations. However, passive sidestick controllers offer advantages over active sidesticks such as less weight, lower cost, and are generally simpler implementations. Passive sidesticks forego artificial feel systems and implement fixed force and deflection characteristics by using spring and damper systems. This is a proven design and was first implemented for civilian transport on the Airbus A320 (Hanke & Herbst, 1999).

Active sidestick controllers address many of the issues faced when implementing passive sidesticks but are inherently more complex. Active sidesticks replace the spring damper systems found in passive sidesticks with servo motors for each axis of control which allows for the feel characteristics to be tailored throughout the entire flight envelope. Additionally, this capability permits active sidestick coupling to the co-pilot stick and autopilot inputs. This feature emulates conventional controls that are mechanically linked, and allow two pilots to engage in a force fight. This helps to prevent inadvertent dual inputs by providing tactile feedback from electronic coupling rather than visual or aural feedback which can more easily be missed or ignored in critical situations. According to Hanke and Herbst (1999) the tactile sense is fast and does not consume as much cognitive bandwidth. Regarding autopilot coupling, tactile feedback is a clear indication of autopilot inputs to the flight control system. A visual indication of changing flight path can be mistaken as autopilot inputs if the flight crew is unsure or unaware of the autopilot status. Autopilot coupling eliminates the possibility of this error (Hegg, 1992).

There are obvious advantages of sidestick controllers in cockpit design such as weight savings and improved cockpit layout. Conversely, the sought-after improvements in aircraft performance and handling qualities are less easily obtained and require in depth development to be realized. The following section provides an overview of research conducted to explore these technical challenges.

Review of Experimental Results

Since the inception of the fly-by-wire flight control system, the implementation of a sidestick controller has become feasible. Research has been conducted in many diverse fields including: design of control force and deflection characteristics, design of controls in a vibration environment, flying qualities, control laws, active and passive technologies, and adaptive control interfaces. The following sections contain a chronological review and discussion of experimental results accumulated since 1975.

Flight Investigation of Fighter Side-Stick Force-Deflection Characteristics (1975)

In 1974, Calspan Corporation conducted flight test evaluations at Edwards Air Force Base under the sponsorship of the Air Force Flight Dynamics Laboratory. The primary objective of this investigation was to evaluate sidestick force-deflection characteristics and determine if motion of the sidestick was necessary for good flying qualities. To do this, two pilots participated in this study, and data were collected via comment cards and Cooper-Harper ratings. Table 1 describes the configurations that were flown using a variable feel sidestick, capable of operating both as a rigid sidestick, and providing motion via varying spring gradients on each pitch and roll axes independently. Four force-response gains were evaluated: very high, high, medium, and light; and three sidestick motions were investigated: fixed stick, small motion, and large motion.

Table 1. Test Case Configuration Matrix.

Sidestick Force-Response Gain	**Sidestick Motion**		
	Fixed	Small	Large
Light	x	x	x
Medium	x	x	x
Heavy	x	x	
Very Heavy	x		

Multiple piloting tasks were performed during flight evaluations of each sidestick configuration shown in Table 1, including up-and-away tasks and landing tasks. Up-and-away tasks included ability to trim, formation flying, offensive and defensive tracking and evasion, and acrobatic maneuvers. Landing tasks included Instrument Landing System (ILS) approaches and touch and go’s.

The fixed sidestick was considered the baseline configuration in the study, so the best rated force-response gain for each task was reported in the results. Improved ratings due to the introduction of sidestick motion capabilities was also discussed and included in the final results. First, it was shown in formation flying that sidesticks with some motion received better ratings from pilots, but adding more motion did not improve ratings. For the more demanding tracking tasks, pilots provided the best ratings for the fixed stick at the medium force-response level.

Ratings improved with the introduction of motion at the medium and light force-response levels, but more motion degraded results. Overall, for up-and-away evaluations, the best ratings were given for sidesticks with small motion at medium and light force-response levels. Fixed and large motion sticks were considered unsatisfactory. The addition of motion had the effect of smoothing pilots' initial inputs compared to the fixed stick, which contributed to better flying qualities. During landing, pilots preferred a stick with a small amount of motion with light forces. A fixed stick had pilot induced oscillation (PIO) tendencies in pitch during flare and stick motion was always more noticeable in roll than in pitch (Hall, 1975).

Guide for the Design of Control Sticks in Vibration Environments (1975)

The Aerospace Medical Research Laboratory conducted experiments to investigate the effects of vibration on control performance, and how these characteristics are affected by control stick design. Testing was completed using a six degree of freedom shaker table as a means of providing a vibration environment. Z-axis vibrations were tested, focusing on whole body vibration. Seven subjects participated in this study, sitting in a flight crew seat mounted on the shaker table, and performed tracking tasks using the supplied control stick and display. These tracking tasks were tested in both static and vibrating environments. In total, six control stick configurations were tested. Three spring gradients were implemented in both a sidestick controller and center stick controller, and varied between 2 lb/in (light) and 600 lb/in (heavy). Sticks that employed the light and medium spring gradients were referred to as spring sticks, and the heavy spring gradient is referred to as a stiff stick. Control gains were held constant in all configurations at 2.5 volts/in.

Experimental results indicate the spring sticks are the better choice if the vehicle exhibited resonances at frequencies where vibration power was significant. But, there was improved performance in the absence of vibration for stiff sticks. Vibration, however, causes a greater percentage increase in RMS errors with stiff sticks compared to spring sticks. Lastly, there were no statistically significant effects of stick position, indicating there were not significant differences in performance between sidesticks and center sticks (Levison, 1975).

Biomechanical and Performance Response of Man in Six Different Directional Axis Vibration Environments (1977)

Levison performed a follow on study in 1977 to collect more specific data on tracking performance while applying vibration on individual or a combination of translational and rotational axes. This expanded upon the whole body vibration experiments that were conducted earlier, limited to z-axis vibrations. The same setup was used from the previous study, but only two spring gradients were used: medium and stiff sticks. The center stick configuration was eliminated based on previous results, and the sidestick configuration was tested exclusively.

Effects of vibration on tracking error were found to be relatively small, about a maximum of 20% increase compared to the baseline static tracking performance error. Differences between the static and vibration cases were greatest for the stiff stick, consistent with previous findings. This is largely attributed to the greater degree of vibration feedthrough, a common characteristic of stiff control sticks. Vibration inputs causing fore-aft body motion produced greatest shoulder acceleration, greatest stick feedthrough, and greatest increase in tracking error. In conclusion, spring constant has substantial effect on tracking performance and stick feedthrough. This evidence demonstrates the need to evaluate force-deflection characteristics in realistic flight conditions, including turbulence, to achieve satisfactory handling qualities (Levison, 1977).

Flying Qualities Design Requirements for Sidestick Controllers (1979)

During the development of the F-16, fixed sidesticks were used on prototypes and full-scale development aircraft. On the ground, in fixed-base simulators, pilots preferred the fixed stick over a sidestick that had motion capabilities. Both fixed and motion sidesticks were tested in flight, and pilots who previously preferred the fixed stick on ground changed their preference to the motion stick in flight. In fact, it was determined that a fixed stick was only satisfactory for pitch down commands, and the minimum recommended full aft limit for a pitch up command is 2 degrees. This finding exhibits the need for verifying handling qualities and control characteristics in flight, and not just in a fixed-base ground simulator (Black, 1979).

Development of ADOCS Controllers and Control Laws (1985)

A study was conducted by the Boeing Vertol Company with the objective of developing attack helicopter flight control laws that provide satisfactory handling qualities. One of the major elements of this study was the investigation of sidestick controllers, how many axes can they control effectively, and what force-displacement characteristics should be chosen.

Evaluations were conducted in two phases. The first phase utilized the Boeing Vertol flight simulator, a 6 degree of freedom motion base simulator. The second phase evaluations were conducted in the NASA Ames vertical motion simulator, a 6 degree of freedom motion base simulator with 60 feet of vertical travel. Both phases evaluated sidestick controllers that controlled

2, 3, and 4 axes (the fourth axis, collective, is unique to a helicopter and is not relevant to fixed wing aircraft). Seven sidestick controllers were evaluated with varying force-deflection characteristics, including stiff sidesticks as well as displacement sidesticks. All sidestick were a base pivot type, meaning the point of rotation was fixed at the base of the sidestick controller. The two axis controller was implemented using fore-aft control, and left-right control for the two axes. The third axis was implemented by rotating the sidestick about its own vertical axis, like a screwdriver.

Results of the evaluations indicated that pilots preferred sidestick controller with small deflections, resulting in greater precision. Stiff controllers provided poor tactile feedback and were prone to PIO, agreeing with results seen in previous studies. Additionally, pilots preferred 2 axis sidestick controllers over other multi-axis controllers due to cross-coupling pitch and roll inputs in the vertical axis (Landis, 1985).

Fly-by-Wire Sidestick Controller Evaluation (1987)

A study at NASA Ames Research center was conducted to investigate issues with flight deck configurations implementing sidestick controllers and fly-by-wire. The objectives of the study included sidestick characteristics, handling qualities, and sidestick coupling to the autopilot and other sidestick. These objectives were completed by conducting three tests. First, a handling qualities evaluation of sidestick characteristics, second, an evaluation of alternative cross-cockpit sidestick coupling methods, and third, an evaluation of alternative autopilot coupling methods. The advanced concepts flight simulator was used for this study at the Man Vehicle System Research

Facility, NASA Ames. It was configured with dual sidestick controllers that were electro-hydraulically actuated, autopilot, dual throttles, and autothrottle.

Nine pilots participated in the handling qualities evaluations. Precision tracking tasks at high altitude cruise were used to collect data for the various controller configurations. The sidestick spring gradient and the control gains were both varied on three levels. Turbulence was also tested against a static condition. Results indicate the only statistically significant effects were due to turbulence and control gains. Pilots preferred the medium level control gain in both pitch and roll. In agreement with previous studies, the effect of turbulence resulted in increased tracking error. There was less control activity when turbulence was present which indicates that pilots did not track with precision in turbulent conditions.

Thirty-two pilots participated in the evaluation of four sidestick coupling configurations. The coupled configuration used force sensors that were fed to the active feel system to emulate conventional mechanical linking. The uncoupled configuration was a passive implementation that summed the inputs from each controller but saturated the signal at the maximum output of one controller. A visual indication was provided when dual inputs were detected. The uncoupled with disconnect switch configuration was similar to the uncoupled configuration with the addition of switch that would disconnect the other sidestick when pressed. If both switches were pressed simultaneously, the captain's controller (left) would be used. A green light was provided to indicate which controller had authority, and a white light was provided to indicate that authority was lost. The last configuration implemented uncoupled controllers with priority logic. White and green lights were provided to indicate simultaneous inputs, authority loss, and sole controller authority. The evaluation consisted of two test conditions. First, the instructor pilot would attempt to override the evaluator pilot’s maneuver, and second, the pilots would switch roles. Pilots were split into four groups of eight to evaluate just one configuration. A between subject design was used, and data was collected via the modified Cooper-Harper rating scale. Results indicated that pilots preferred the coupled configuration first, and the uncoupled with disconnect switch configuration second. The uncoupled configuration was considered unsatisfactory, and the uncoupled with priority logic configuration was considered unacceptable. These results are compatible with designs implemented today, such as Airbus A320 (and later) and military fighter aircraft (Summers, 1987).

Interaction of Feel System and Flight Control System Dynamics on Lateral Flying Qualities (1988)

Flight tests were conducted using the variable stability United States Air Force NT-33 aircraft to investigate the effects of feel system dynamics and time delay on flying qualities. The NT-33 aircraft had a centerstick installed. Five elements of the test were considered including control system command input (stick force or stick displacement), feel system natural frequency, controls system filter, time delay, and roll mode time constant. Three pilots participated in this study and accumulated fifty-six hours of flight testing. Both up-and-away and power approach were evaluated including gun tracking, head up display tracking, and offset landing. Data was collected via task performance records and Cooper-Harper ratings.

Poor ratings were provided due to roll ratcheting, which was worse up-and-away, but not as severe during power approach. Results indicated a reduction from 4 lb/in to 2.75 lb/in spring gradient improved handling qualities during up-and-away evaluations. This same effect was seen for power approach but was not as dramatic. Similar experiments were done in a fixed-base simulator and results were dramatically different. This illustrates the need to examine handling qualities in an in-flight environment. Airplane motion cues are critical to the accurate evaluation of roll flying qualities (Bailey, 1988).

Active and Passive Side-Stick Controllers in Manual Aircraft Control (1990)

A study was conducted using a research flight simulator at Delft University of Technology to explore the effects of passive and active sidestick on manual aircraft control. The simulator was a three degrees of freedom motion system which provided motion cues when enabled. Three sidestick configurations were used in the experiment, a passive stick and two active sticks, employing attitude and rate feedback. Two aircraft dynamics were implemented in the simulation to see the differences between slow, wide-body dynamics, and the hard to control double-integrator dynamics similar to a fighter aircraft. Participants were asked to perform tracking tasks with and without motion cues. Results indicate both active sticks produced better tracking performance when compared to the passive stick for both wide-body and double-integrator dynamics. Additionally, the presence of motion cues improved tracking performance for all three sticks (Hosman, 1990).

Effects of Mass on Aircraft Sidearm Controller Characteristics (1994)

NASA Dryden flight Research Center conducted test flights to determine what the acceptable mass for a sidestick controller as it varies with spring gradient. A variable feel sidestick controller installed in a modified Learjet Model 25 was used as the test article. The sidestick was powered hydraulically and had the capability of operating with a wide range of natural frequencies and simulated controller masses. Two pilots participated in this study. One was a skilled test pilot with F-16 experience, and the other a private pilot with a brief familiarization in the Learjet. Pilots performed tasks up-and-away, and also performed touch-and-go landings. During testing, both pilots detected the sidestick controller felt like a pendulum when electronically linked to the flight control surfaces, or in active mode, but this effect was removed when the sidestick was uncoupled. This phenomenon had been previously reported but for much lower damping ratios. To remedy this issue, the force gradients were increased, and the pendulum effect was no longer noticeable when the sidestick was coupled. The outcome of this testing confirms the conclusions from previous experiments. Control system characteristics should not be selected using a fixed-base simulator. Aircraft motions have significant influences on control feel and can cause inadvertent inputs (Wagner, 1994).

Haptic Specification of Environmental Events: Implications for the Design of Adaptive, Virtual Interfaces (1996)

An experiment was conducted at the US Air Force Armstrong Laboratory's Synthetic Immersion Research Environment to explore the development of haptic, and adaptive virtual interfaces. An adaptive virtual interface can be described as one being modified continuously as a result of some established inputs. One objective of this experiment was to examine whether augmented haptic feedback is useful to pilots in situations that are known to have increased subjective workload.

This experiment was conducted with two levels of sidesticks. One was a typical displacement sidestick, and the other was a force-reflecting stick capable of providing adaptive active feedback. The force-reflecting stick increased the spring gradient in the direction of lateral displacement from runway centerline. For example, if the aircraft location is right of the runway, stick deflections to the right would become stiffer and stick deflections to the left would decrease. Two levels of turbulence were simulated, present and absent. And lastly, five levels of initial lateral displacements from runway centerline were implemented which resulted in 20 experimental conditions. Eight pilot participants performed one landing for each condition over the course of 4 sessions, and were instructed to land on centerline 500 feet from the threshold and 120 knots. Performance measures included lateral and longitudinal deviation from the target touchdown point.

Results showed no statistically significant effects when turbulence was absent, but when turbulence was presents, better performance was achieved using the force-reflecting stick when observing lateral deviations. No statistically significant effects were found when observing longitudinal deviations, but there is a clear pattern of better performance using the force-reflecting stick (Bart J. Brickman, 1996).

Adaptive Limit and Control Margin Prediction and Limit Avoidance (2002)

Two model simulation studies were conducted to investigate the use of active sidesticks to avoid vehicle flight envelope limits and increase maneuvering performance. The simulation using in these studies was the XV-15 aircraft using the Generic Tilt-Rotor SIMulation model (GTRSIM). A mathematic model representation of a pilot was also used as an outer loop control of the flight path angle. Two simulated pilots were used, one more aggressive than the other (Yavrucuk, 2002a).

Rather than implementing control authority limitations in the control law, this method provides tactile cueing via softstops in the active sidestick controller. Results show this is an effective method of preventing structural limit excursions during flight while still providing full control authority to the pilot (Yavrucuk, 2002b).

Design Considerations

The use of sidestick controllers in fly-by-wire aircraft has been thoroughly tested. The implementation of passive sidesticks in the Airbus A320 and later models demonstrates a proven design. Active sidestick technology has also been shown to be a dependable option, and its merits over passive technology are compelling. Yet, it can only be speculated that cost and complexity are reasons why active sidesticks are not prevalent in the commercial air transportation industry. Over time, technology and understanding of active sidestick controllers has improved and designers will be faced with a decision between active and passive control technology. This section aims to summarize these design considerations.

When designing a sidestick controller, it is vital the force and displacement characteristics produce acceptable handling qualities. Questions of how much force and how much displacement are two key elements. Numerous experiments have been conducted but they do not definitively conclude that a specific force and displacement combination produces acceptable handling qualities for all aircraft. All aircraft are designed with unique purposes in mind, and the pilot population meant to operate those aircraft may not always be the same. It is important to evaluate these characteristics with a representative population. According to Beringer (2006), anthropometric studies have shown that a portion of the current pilot population is incapable of producing the maximum control limit forces that are specified in the Federal Aviation Regulations (Table 2).

Table 2. Maximum Control Force Limits (Beringer, 2006)

Values in pounds force applied to the relevant control	**Pitch**	**Roll**	**Yaw**
(a) For temporary application			
Stick	60	30	…
Wheel (two handed)	75	50	…
Wheel (one handed)	50	25	…
Rudder Pedal	…	…	150
(b) For prolonged application	10	5	20

These limits were developed when mechanically linked conventional controls were prominent and men predominantly flew aircraft. Now, with more female pilots, and fly-by-wire aircraft, these upper limits may be too high. It is important the maximum control forces are chosen based on strength capability of a representative pilot population that is anticipated to operate an aircraft of a new design.

In addition to choosing appropriate control forces, controller displacement is an issue that is closely coupled and complex. Studies have shown pilots prefer controllers that have some amount of motion, but too much or too little can produce controllers that are prone to over-control and PIO. While many studies have concluded the same, it is essential to reiterate the importance of evaluating control gains and handling qualities in flight. During the YF-16A program at General Dynamics, this lesson was learned again. Every pilot who participated in fixed base ground simulator evaluations preferred a fixed stick with no displacement over a displacement stick. After performing the same evaluations in flight, every pilot reversed their preference to the displacement stick due to aircraft motions. This applies to normal aircraft motions as well as influences of turbulence (SCI-026, 2000).

Lastly, a choice must be made between active and passive technology. The decision is a trade-off between simplicity and flexibility. Passive sidesticks are proven and a safe option, but active sidesticks are promising and have compelling reasons to cope with the added complexity. The flexibility an active sidestick offers can provide superior handling qualities according to Hegg (1992). But, the true task is analyzing the overall cockpit design, the instruments, displays, the seat(s), and switches. Fitting them all together for the optimum operational effectiveness is the objective (Gibson, 1997).

CHAPTER 3: METHODOLOGY

The focus of this study was to evaluate the use of equivalency analysis to determine if using a sidestick controller to execute in flight maneuvers and an instrument approach is functionally equivalent between three operational modes. The three operational modes of the sidestick controller that were tested are (1) active, (2) unlinked, and (3) passive. This study required no additional testing as a pre-existing data set was readily available. Flight data recordings from Gulfstream Aerospace simulator testing were processed for data analysis.

Test Article Description

As in many of the experiments discussed in the literature, a fixed-base simulator was used to conduct this experiment to study active sidestick controllers and their equivalency to unlinked or passive sidestick controllers. Specifically, a simulator at Gulfstream Aerospace Corporation called the Integration Test Facility (ITF) was selected. The Gulfstream aircraft is a commercial business jet with active sidestick controllers, first in the civilian market, with a minimum flight crew of two pilots. The ITF uses the same hardware and software as the aircraft and is supplemented by simulations for systems that only function in flight such as air data systems. The out-the-window visual system used in the ITF is a Vital XI system which is Level D qualified, the highest level of flight simulator qualifications by the Federal Aviation Administration. This offers an experience as close to the aircraft in flight and provides as much realism as a fixed-base simulator can provide (Gulfstream, 2015).

System Description

The Gulfstream active sidestick controller is capable of operating in three modes: active, unlinked, and passive. The active mode is achieved by electronically coupling both sticks so they move in unison. This provides each pilot a tactile cue of control inputs made by the other pilot or the autopilot, similar to conventional controls which are mechanically linked. In the event the electronic coupling fails, the sidestick controllers are capable of remaining in the active mode, but become unlinked. This means the force-displacement characteristics are unchanged from the active mode, but the unlinked sidestick controllers will not move in unison with each other or with the autopilot. Lastly, if the sidestick controllers are not capable of operating the active or unlinked modes, the last failure mode is the passive mode. In the passive mode, mechanical springs provide the force-displacement characteristics to the sidestick controller which are slightly lighter than when in the active mode. The passive mode breakout force is also slightly heavier than when in active mode. In the event that both pilots provide inputs to the sidestick controllers in the unlinked mode or passive mode, they receive a visual and aural alert to warn them of the potentially dangerous situation, similar to methods used in other passive sidestick implementations.

Experimental Design

A between-subjects, repeated-measures experimental design was used to test the equivalence of the active control sidestick failure modes during manual piloting tasks. The only independent measure, sidestick controller mode, was tested at three levels: active mode, unlinked mode, and passive mode. As in all repeated-measures experiments “a single sample [of pilots was used], so that the same individuals [were] measured in each of the treatment conditions” (Wallnau, 1996). The advantage of this design is fewer subjects are required to complete testing, but some disadvantages include multiple test sessions for each participant, and counterbalancing is required to prevent learning effects or fatigue (Girden, 1992). Each of the ten pilots who participated in this study performed multiple maneuvers while exposed to the three sidestick controller modes, including climbing and descending turns, and an ILS approach to landing. Criteria for each performance measure which are applicable to all sidestick controller modes are presented in Table 3. These criteria are taken from the Practical Test Standards (Service, 2008) published by the Federal Aviation Administration as a measure of goodness, and therefore were determined *a priori*. The dependent measures corresponding to these criteria consist of RMS error from targeted airspeed, flight path angle, bank angle, as well as lateral and longitudinal error from the desired touchdown point on the runway.

Table 3. Goodness criteria of performance measures

Maneuver	**Performance Measure**	**Criteria**
Climbing and Descending Turn	Airspeed Error	±10 kts
	Flight Path Error	±2.5°
	Roll Error	±5°
ILS Approach	Lateral Touchdown	±15 ft from centerline
	Longitudinal Touchdown	750-1500 ft from threshold

Cognitive workload ratings were also collected as a subjective measure to provide a comparison to the objective performance measures described above. Pilots used the Bedford workload scale to provide their own assessment of their spare cognitive capacity to manage additional tasks. Lower ratings indicate there is little to no impact to cognitive workload and additional tasks can be handled. Higher ratings indicate there is not sufficient spare capacity, additional tasks cannot be handled, and the current task may not be able to be completed. The Bedford Workload scale is shown in Figure 1 (A. H. Roscoe, 1990).

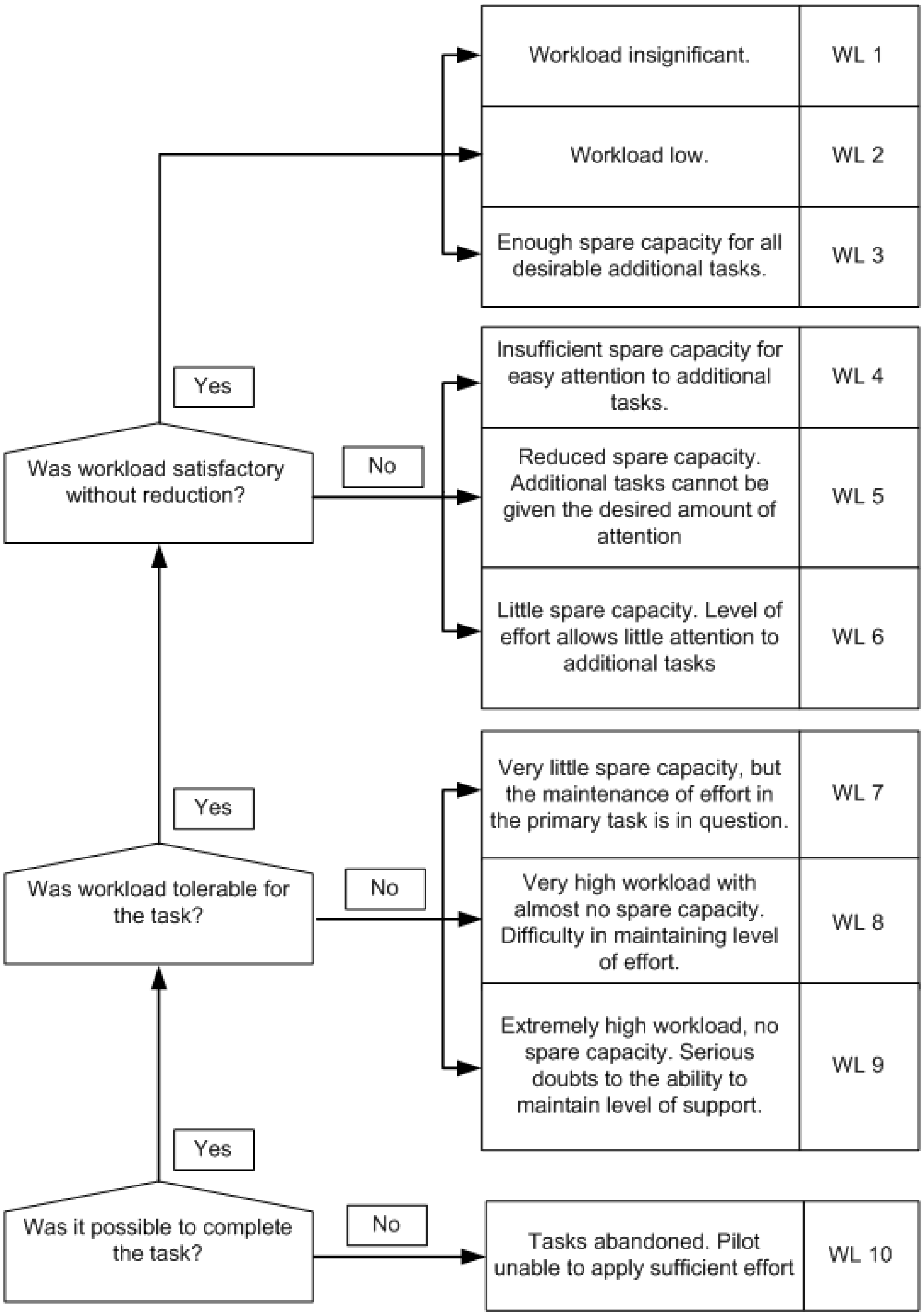

Figure 1. The Bedford Workload scale.

The Bedford Workload scale is a ten point scale which is divided into four sections using the three decision points along the left side of the scale. These collect similar ratings into groups to provide a finer resolution of workload descriptions. For the purposes of this study, the equivalency criteria that will be used will be: the range of workload ratings provided for a task must be contained within the same group of workload ratings for each of the sidestick operational modes. The four groups are 1-3, 4-6, 7-9, and 10. This will ensure that for all sidestick modes, the task can be described as (1) the workload was satisfactory without reduction, (2) the workload was tolerable without reduction, (3) it was possible to complete the task, or (4) the task was abandoned.

Test Conduct

Ten pilots participated in this study over the course of several days. Each pilot flew two manual maneuvers with each of the three sidestick controller modes: a climbing and descending turn, and an ILS approach to landing. The order in which each pilot flew the three sidestick controller modes was counterbalanced to the greatest extent possible to minimize learning effects. All pilots were aware of the sidestick controller mode during each maneuver as the aircraft alerts the flight crew if any sidestick controller has failed down into a non-normal mode.

A pre-flight briefing was conducted for each pilot to review the test procedures and maneuvers they were asked to perform. Table 4 contains detailed descriptions of each maneuver that was briefed to each pilot. Prior to each maneuver, the pilot flying was to confirm the autopilot and autothrottle were disengaged so each maneuver was flown manually. After each maneuver was completed, the pilot flying was to verbally provide a workload. A flight director and head up display (HUD) were provided.

Table 4. Pre-flight briefing descriptions for each maneuver

Maneuver	Briefing Description
Climbing and Descending Turn	Once straight and level flight at 250 knots airspeed is achieved, initiate a 1000 ft climbing turn at a rate of 500 fpm and maintain a 30 degree bank (either left or right). Level off at the top of the climb with wings level. Once straight and level flight is achieved, initiate a 1000 ft descending turn at a rate of -500 fpm and maintain a 30 degree bank (opposite direction). Level off at the bottom of the descent with wings level. Maintain 250 knots airspeed for the duration of the maneuver.
ILS Approach	Fly the ILS approach as published. Follow the localizer and glideslope as precisely as possible. Aim to touch down centered on the runway centerline and -250/+500 ft from the runway aiming point as shown in Figure 2.

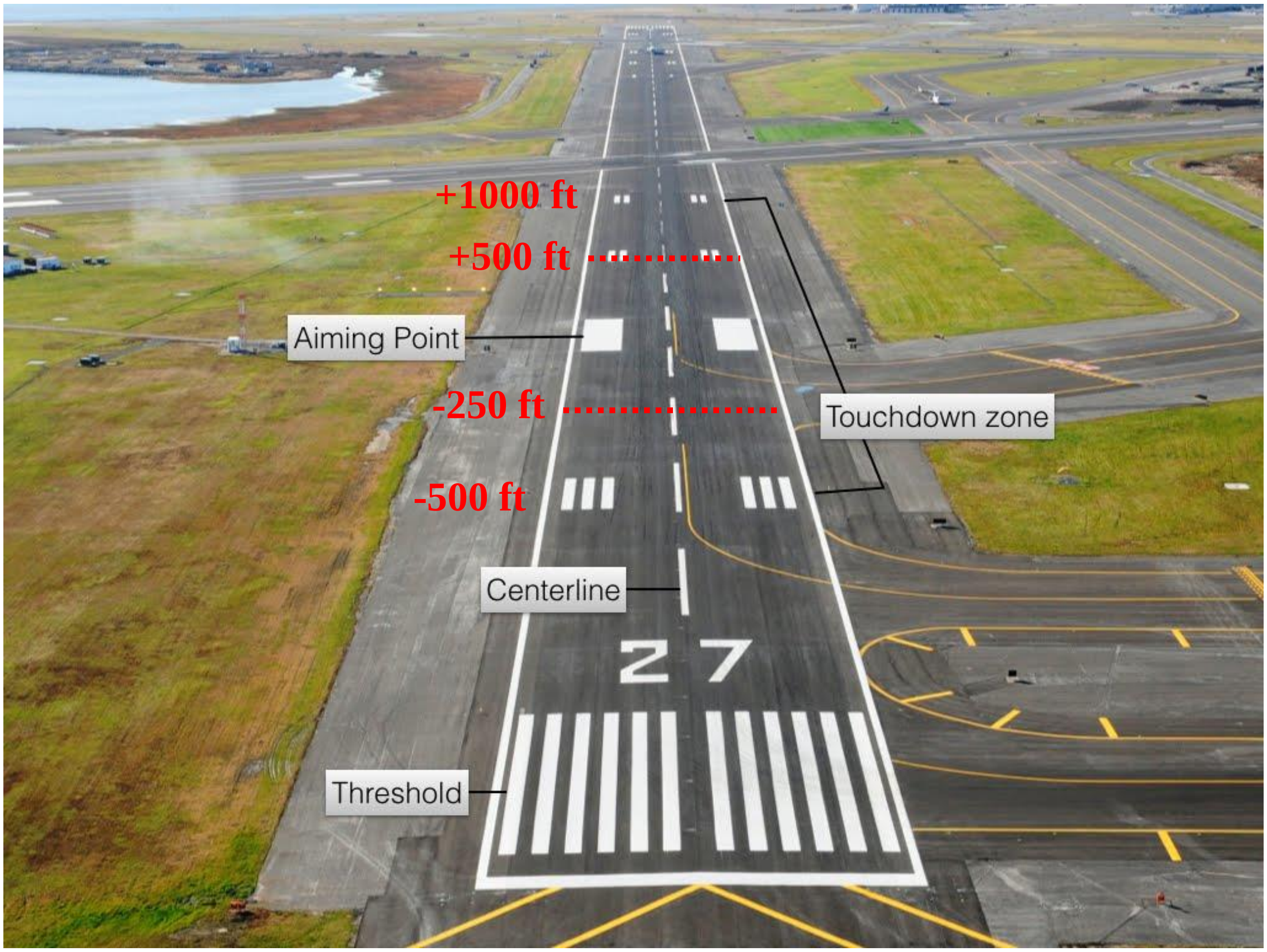

Figure 2. ILS approach aiming point and runway markings.

Data Collection

As mentioned earlier in this chapter, no testing was conducted as part of this study because a pre-existing data set was readily available. During Gulfstream Aerospace simulator testing, flight parameters were recorded for each flight. A detailed list of parameters used in this study is presented in Table 5. These parameters were recorded at a rate of 500 Hz. The sampling rate used for this analysis was scaled down to 20 Hz. In addition to the flight data recordings, workload rating data collected during simulator testing was also analyzed to provide a subjective comparison to the objective performance measures.

Table 5. Flight data parameters used for data analysis.

Parameter	Units
Altitude	Feet
Airspeed	Knots
Airspeed Target	Knots
Pitch Angle	Degrees
Flight Path Angle	Degrees
Flight Path Angle Target	Degrees
Bank Angle	Degrees
Bank Angle Target	Degrees
GPS Latitude	Degrees
GPS Longitude	Degrees
Weight on Wheels	N/A (Boolean)

Analysis Methods

To examine the difference in objective performance measures between the three modes of sidestick controller operation, RMS errors for airspeed, flight path angle, and bank angle were computed as were touchdown point errors (distance from centerline and threshold). Analysis of variance was applied to identify any statistically significant differences between the three modes ($\alpha = 0.05$). Since it is not expected that significant differences exist, an equivalency analysis was performed to support the null hypothesis.

An equivalency analysis is performed by calculating a $100(1 - 2\alpha)\%$ confidence interval "to simultaneously test two one-sided hypotheses" (John M. Reising, 1998) for each performance measure and comparing them against a predetermined performance threshold. Performance thresholds were established *a priori* in Table 3. If each confidence interval for the three modes of sidestick controller operation fall within the bounds of the performance threshold, this supports a conclusion that the sidestick controller is functionally equivalent between the three modes of operation. This finding provides additional support to an analysis of variance where the null hypothesis is not rejected. Normally, this is not a significant finding as it can be attributed to an insufficient sample size or a bias in the results. Applying equivalency analysis in this case can demonstrate that at the same α level, the expected variance in performance capability does not exceed the predetermined performance threshold. Rather than concluding no significant differences were found, this information supports a stronger argument that equivalent performance capability was shown.

CHAPTER 4: FINDINGS

Two analyses were performed to examine climbing and descending turns and ILS approaches separately. For each performance measure, an analysis of variance was conducted to determine if any statistically significant differences in the means existed between the three sidestick operational modes. If no significant differences were identified, equivalence tests were performed to support the null hypothesis, claiming each of the sidestick modes are functionally equivalent. Interval plots and p-value summary tables are provided.

Analysis of Climbing and Descending Turns

Climbing and descending turns are a common tracking task executed during flight testing for handling qualities and control inceptor feel characteristic development. Without the use of automation, it requires the pilot flying to track pitch, roll, and airspeed of the aircraft simultaneously. Feel characteristics such as breakout force and force-displacement gradients impact the pilot’s ability to perform these tasks accurately. To see if there were any significant differences between the three operational modes of the sidestick controller, an analysis of variance was performed for each of the three performance measures as shown in Table 6. The analysis was broken up into two phases to examine any effects seen in a climbing turn versus a descending turn. At an α level of 0.05, no significant differences were found for any of the performance measures in either the climbing turn or descending turn between each of the three sidestick modes. Since no significant differences were found, an equivalency analysis was performed.

Table 6. ANOVA summary for climbing and descending turns. ($\alpha = 0.05$)

Phase	Performance Measure	P-value
Climb	Airspeed RMS Error	0.662
	Flight Path Angle RMS Error	0.727
	Bank Angle RMS Error	0.712
Descent	Airspeed RMS Error	0.998
	Flight Path Angle RMS Error	0.484
	Bank Angle RMS Error	0.767

Performance Measure: Airspeed RMS Error

The first performance measure for climbing and descending turns is airspeed RMS error. Established in Table 3, the lower equivalency limit (LEL) is 0 knots and the upper equivalency limit (UEL) is 10 knots. These limits are depicted in Figure 3 along with 90% confidence intervals for airspeed RMS error for each sidestick controller mode in a climbing and descending turn. A data summary is available in Table 7. The bounds of all intervals lie within the lower and upper equivalency limits suggesting each of the sidestick controller modes is functionally equivalent when controlling airspeed in a climbing or descending turn.

Table 7. Equivalency analysis summary table for airspeed RMS error (knots). (α = 0.05)

Phase	Sidestick Controller Mode	Mean (μ)	90% C.I.
Climb	Active	1.1277	(0.75886, 1.4966)
	Unlinked	1.2890	(0.90997, 1.6681)
	Passive	1.0450	(0.74244, 1.3476)
Descent	Active	1.2330	(0.60992, 1.8562)
	Unlinked	1.2051	(0.82500, 1.5852)
	Passive	1.2175	(0.54745, 1.8876)

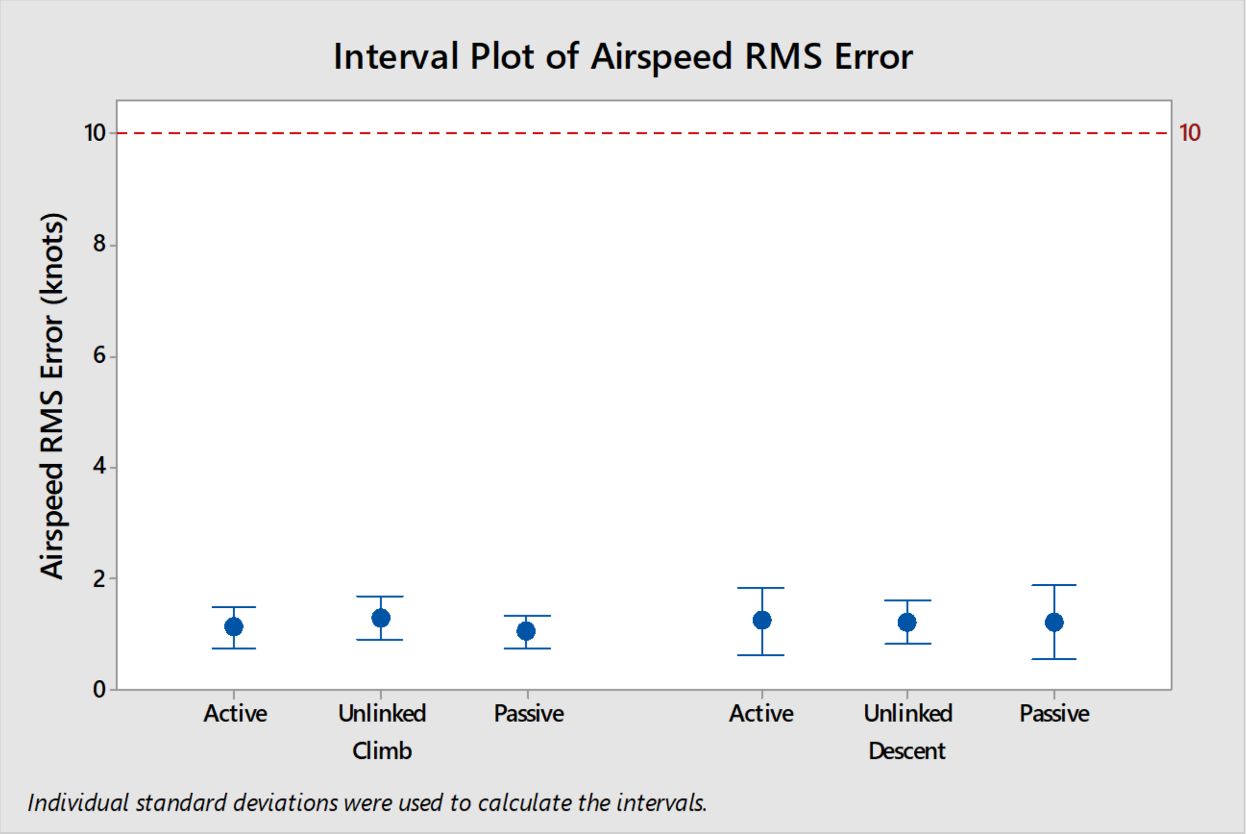

Figure 3. Equivalency analysis plot for airspeed RMS error. (α = 0.05)

The p-values for each equivalency test for airspeed RMS error are summarized in Table 8. The largest p-value of 0.004 is well below the α level of 0.05 which is a strong indication of functional equivalence.

Table 8. Equivalency analysis summary for airspeed RMS error. (α = 0.05)

Phase	**Sidestick Controller Mode**	**P-value (LEL / UEL)**
Climb	Active	0.000 / 0.000
	Unlinked	0.000 / 0.000
	Passive	0.000 / 0.000
Descent	Active	0.003 / 0.000
	Unlinked	0.000 / 0.000
	Passive	0.004 / 0.000

Performance Measure: Flight Path Angle RMS Error

The next performance measure for climbing and descending turns is flight path angle RMS error. The LEL and UEL, established in Table 3, are 0 degrees and 2.5 degrees, respectively. These limits are depicted in Figure 4 along with 90% confidence intervals for flight path angle RMS error for each sidestick controller mode in a climbing and descending turn. A data summary is available in Table 9. The bounds of all intervals lie within the lower and upper equivalency limits suggesting each of the sidestick controller modes is functionally equivalent when controlling flight path angle in a climbing or descending turn.

Table 9. Equivalency analysis summary table for flight path angle RMS error (degrees). (α = 0.05)

Phase	Sidestick Controller Mode	Mean (μ)	90% C.I.
Climb	Active	0.088254	(0.066565, 0.10994)
	Unlinked	0.100420	(0.080776, 0.12006)
	Passive	0.096696	(0.077823, 0.11556)
Descent	Active	0.101790	(0.076339, 0.12724)
	Unlinked	0.116290	(0.070800, 0.16177)
	Passive	0.156550	(0.066138, 0.24697)

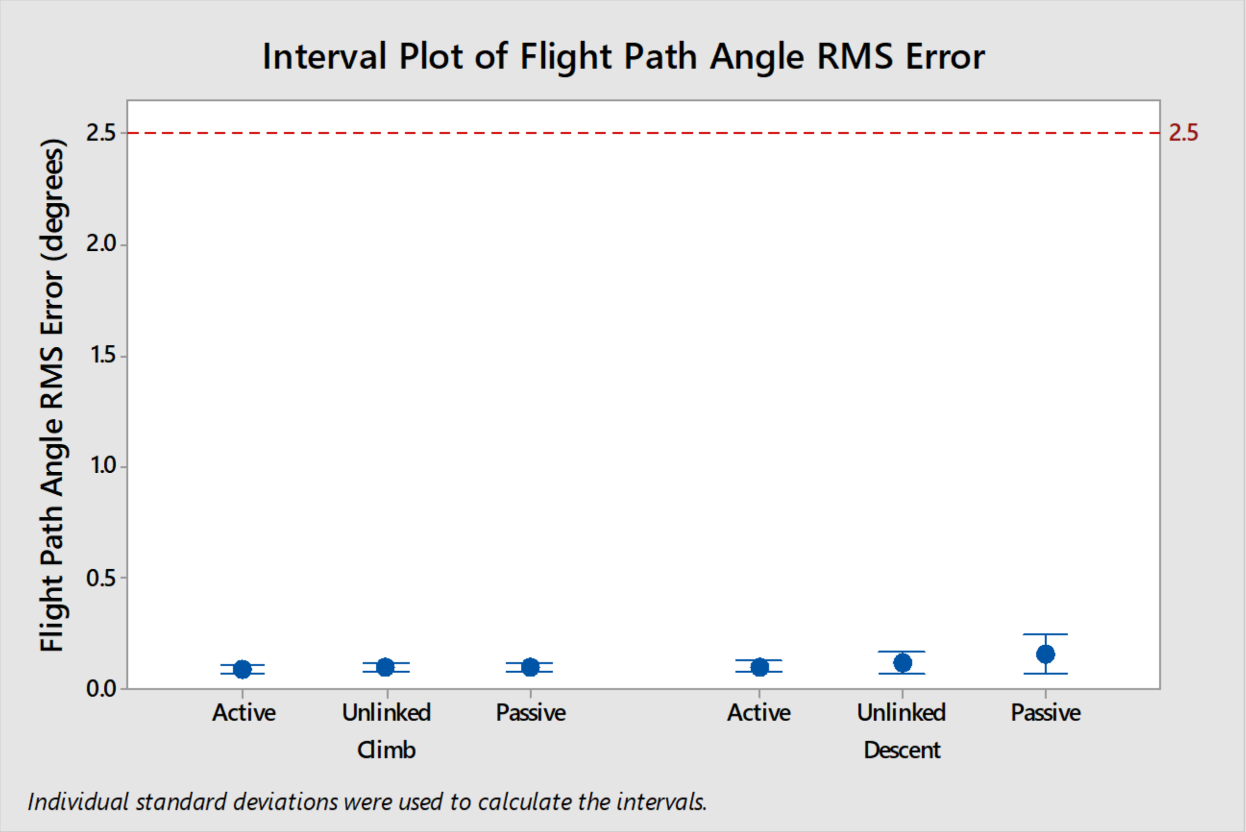

Figure 4. Equivalency analysis plot for flight path angle RMS error. (α = 0.05)

The p-values for each equivalency test for flight path angle RMS error are summarized in Table 10. The largest p-value of 0.006 is well below the α level of 0.05 which is a strong indication of functional equivalency.

Table 10. Equivalency analysis summary for flight path angle RMS error. (α = 0.05)

Phase	**Sidestick Controller Mode**	**P-value (LEL / UEL)**
Climb	Active	0.000 / 0.000
	Unlinked	0.000 / 0.000
	Passive	0.000 / 0.000
Descent	Active	0.000 / 0.000
	Unlinked	0.001 / 0.000
	Passive	0.006 / 0.000

Performance Measure: Bank Angle RMS Error

The last performance measure for climbing and descending turns is bank angle RMS error. The LEL and UEL, established in Table 3, are 0 degrees and 5 degrees, respectively. These limits are depicted in Figure 5 along with 90% confidence intervals for bank angle RMS error for each sidestick controller mode in a climbing and descending turn. A data summary is available in Table 11. The bounds of all intervals lie within the lower and upper equivalency limits suggesting each of the sidestick controller modes is functionally equivalent when controlling bank angle in a climbing or descending turn.

Table 11. Equivalency analysis summary table for bank angle RMS error (degrees). (α = 0.05)

Phase	**Sidestick Controller Mode**	**Mean (μ)**	**90% C.I.**
Climb	Active	1.10480	(0.86191, 1.3477)
	Unlinked	0.99369	(0.69568, 1.2917)
	Passive	1.16250	(0.90147, 1.4235)
Descent	Active	1.25590	(0.85895, 1.6530)
	Unlinked	1.14420	(0.80420, 1.4842)
	Passive	1.06860	(0.82048, 1.3168)

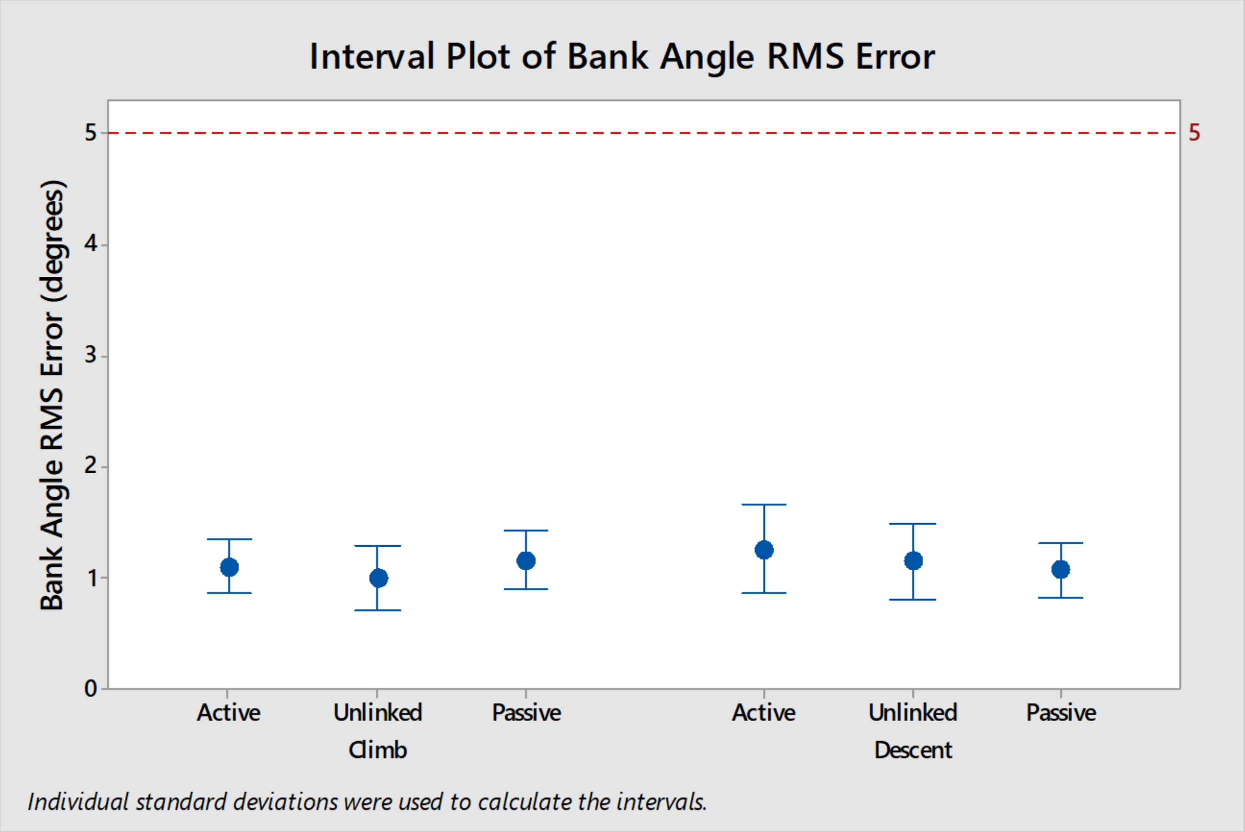

Figure 5. Equivalency analysis plot for bank angle RMS error. (α = 0.05)

The p-values for each equivalency test for bank angle RMS error are summarized in Table 12. The largest p-value of 0.000 is well below the α level of 0.05 which is a strong indication of functional equivalency.

Table 12. Equivalency analysis summary for bank angle RMS error. (α = 0.05)

Phase	**Sidestick Controller Mode**	**P-value (LEL / UEL)**
Climb	Active	0.000 / 0.000
	Unlinked	0.000 / 0.000
	Passive	0.000 / 0.000
Descent	Active	0.000 / 0.000
	Unlinked	0.000 / 0.000
	Passive	0.000 / 0.000

Discussion of Subjective Workload During Climbing and Descending Turns

Performing climbing and descending turns requires coordination between the aircraft pitch and roll attitudes as well as airspeed. It is obvious how the control inceptor, in this case the sidestick controller, controls pitch and roll attitudes which have a direct impact on flight path angle and bank angle. Airspeed is controlled by varying the balance between the thrust and drag of the aircraft. Thrust is controlled by the engine throttles, and drag can be increased or decreased by changing the pitch attitude of the aircraft using the control inceptor. In this manor, the sidestick controller has an indirect impact to the airspeed of the aircraft and can be a good secondary task measure of workload.

An analysis of variance was performed to examine any differences between mean workload ratings during climbing and descending turns. Independent ratings for the climb versus the descent were not available, so this analysis does not include any differences between the climb and descent. The p-value was found to be 0.249 which is well above the α level of 0.05, indicating no significant differences were found. As shown in Figure 6, subjective workload ratings given for climbing and descending turns flown using each of the sidestick modes were not found to be statistically significant. Each of the intervals for workload fall within ratings of 1 to 3, meeting the workload equivalence criteria previously established. Performing climbing and descending turns in each of the sidestick modes was considered a task with satisfactory workload without reduction, and therefore, the workload between these tasks is considered equivalent. A data summary is available in Table 13.

Table 13. Equivalency analysis summary table for workload during climbing and descending turns. ($\alpha = 0.05$)

Sidestick Controller Mode	Mean (μ)	90% C.I.
Active	1.8	(1.2673, 2.3327)
Unlinked	1.4	(1.1007, 1.6993)
Passive	1.9	(1.5509, 2.2291)

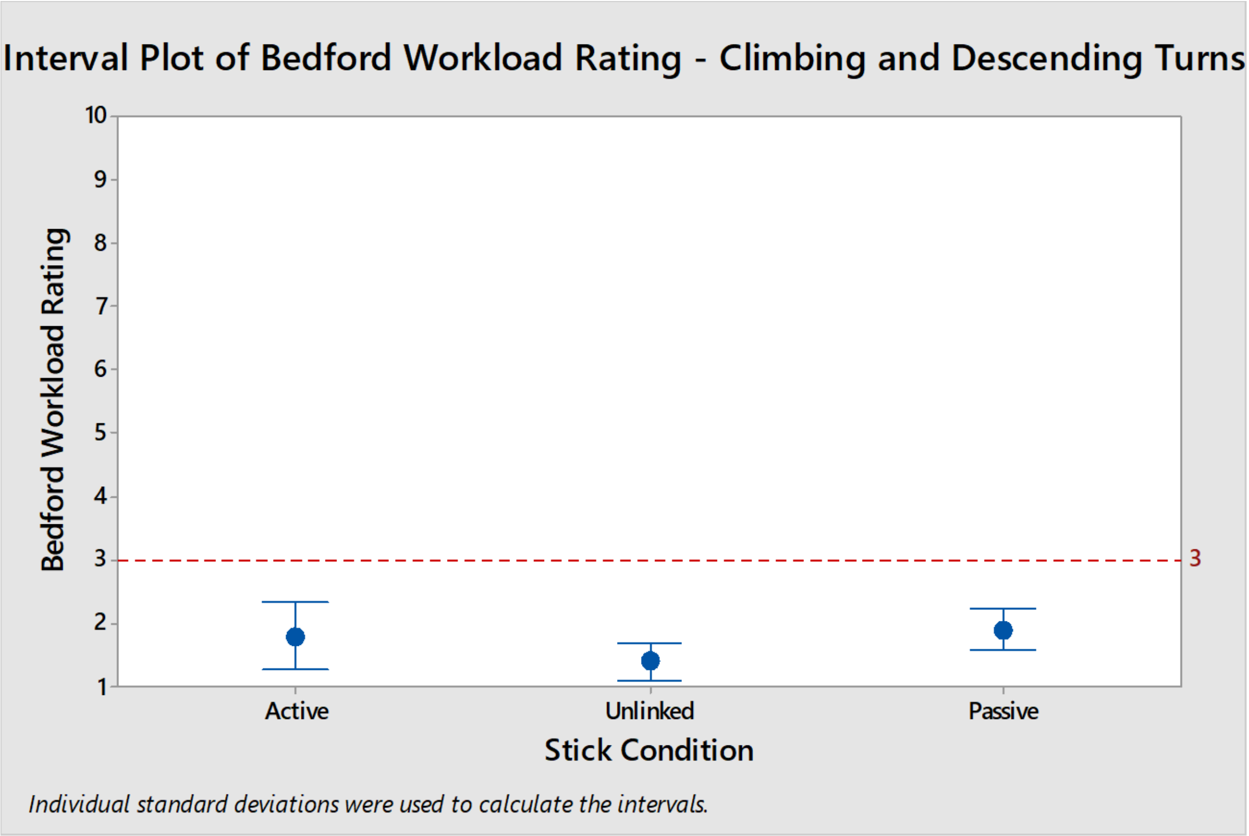

Figure 6. Equivalence analysis plot of workload during climbing and descending turns. (α = 0.05)

The p-values for each equivalency test for workload ratings during climbing and descending turns are summarized in Table 14. The largest p-value of 0.018 is well below the α level of 0.05 which is a strong indication of equivalent perceived workload between each sidestick mode.

Table 14. Equivalence analysis summary for workload rating during climbing and descending turns. ($\alpha = 0.05$)

Sidestick Controller Model	**P-value (LEL / UEL)**
Active	0.011 / 0.001
Unlinked	0.018 / 0.000
Passive	0.000 / 0.000

All three operational modes of the sidestick controller were found to be functionally equivalent when performing climbing and descending turns. No statistically significant differences were found in the subjective workload ratings and were found to be equivalent. This suggests that the pilots' perceived workload was commensurate with the measured performance between of the sidestick modes. During the execution of climbing and descending turns, no force-displacement characteristics of the sidestick controller appear to have impacted the achieved performance of the flight crew, nor have they impacted the perception of the pilots' workload during the maneuver.

Analysis of ILS Approach to Landing

ILS approaches are a common instrument approach type flown by commercial airline pilots and private aviators. They require the pilot to track a lateral and vertical target referred to as the localizer and glideslope, respectively. These two targets lead the aircraft to the runway, specifically toward the aiming point which is located 1000 feet past the threshold of the runway (see Figure 2). This allows some room for error if an aircraft were to touchdown short of the aiming point. Prior to touchdown, a flare maneuver is performed to arrest the sink rate to a comfortable level before contacting the runway with the main landing gear. Pilots are tightly coupled to the tracking task during an ILS approach, therefore, feel characteristics may have an impact on the pilot's ability to fly the approach accurately and touch down near the aiming point with an appropriate sink rate to avoid passenger discomfort. To see if there were any significant differences between the three operational modes of the sidestick controller, an analysis of variance was performed for each of the three performance measures as shown in Table 15. At an α level of 0.05, no significant differences were found for any of the performance measures during an ILS approach between each of the three sidestick modes. Since no significant differences were found, an equivalency analysis was performed.

Table 15. ANOVA summary for ILS approach to landing. ($\alpha = 0.05$)

Performance Measure	**P-Value**
Distance from Threshold	0.843
Distance from Centerline	0.127

Performance Measure: Distance from Threshold

The first performance measure for ILS approaches is distance from threshold. The LEL and UEL, established in Table 3, are 750 feet and 1500 feet, respectively. These limits are depicted in Figure 7 along with 90% confidence intervals for distance from threshold for each sidestick controller mode during an ILS approach. A data summary is available in Table 16. The bounds of one of the intervals, representing the passive mode, do not lie within the lower and upper equivalency limits suggesting the passive mode does not provide functional equivalency, however active and unlinked were found to be functionally equivalent.

Table 16. Equivalency analysis summary table for distance from threshold (feet). (α = 0.05)

Sidestick Controller Mode	Mean (μ)	90% C.I.
Active	991.63	(766.33, 1216.940)
Unlinked	1004.9	(751.52, 1258.330)
Passive	913.22	(743.99, 1082.445)

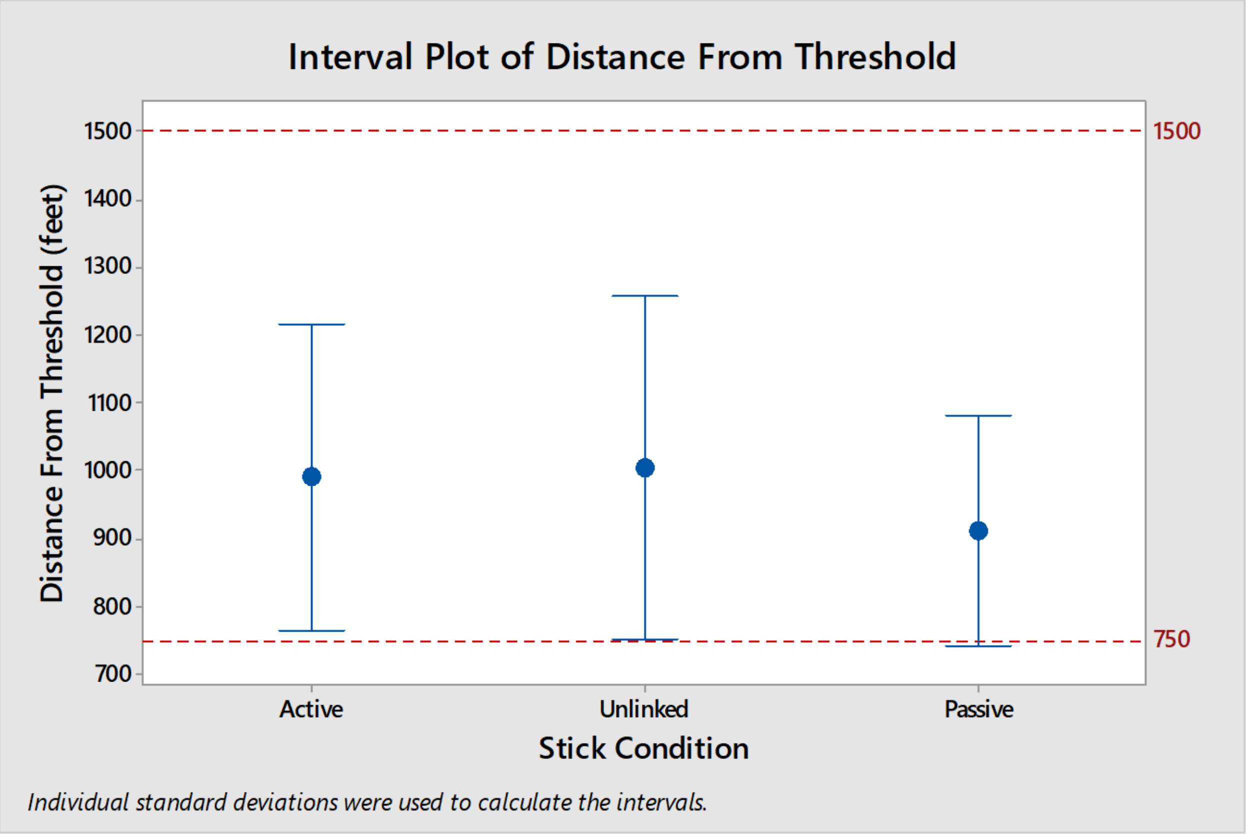

Figure 7. Equivalency analysis plot for distance from threshold. (α = 0.05)

The p-values for each equivalency test for distance from threshold are summarized in Table 17. As mentioned earlier, the interval for passive mode fell outside the bounds of equivalency. At the α level of 0.05, the p-value for passive mode is 0.055 showing marginal equivalency at best.

Table 17. Equivalency analysis summary for distance to threshold. (α = 0.05)

Sidestick Controller Model	P-value (LEL / UEL)
Active	0.040 / 0.001
Unlinked	0.049 / 0.003
Passive	0.055 / 0.000

Performance Measure: Distance from Centerline

The next performance measure for ILS approached is distance from centerline. The LEL and UEL, established in Table 3, are ±15 feet. These limits are depicted in Figure 8 along with 90% confidence intervals for distance from centerline for each sidestick controller mode during an ILS approach. A data summary is available in Table 18 (negative values are left of centerline). The bounds of all intervals lie within the lower and upper equivalency limits suggesting each of the sidestick controller modes is functionally equivalent for touchdown point distance from centerline during an ILS approach.

Table 18. Equivalency analysis summary table for distance from centerline (feet). (α = 0.05)

Sidestick Controller Mode	Mean (μ)	90% C.I.
Active	-7.7633	(-14.616, -0.91085)
Unlinked	-0.34121	(-2.8958, 2.2133)
Passive	-1.4022	(-5.7875, 2.9832)

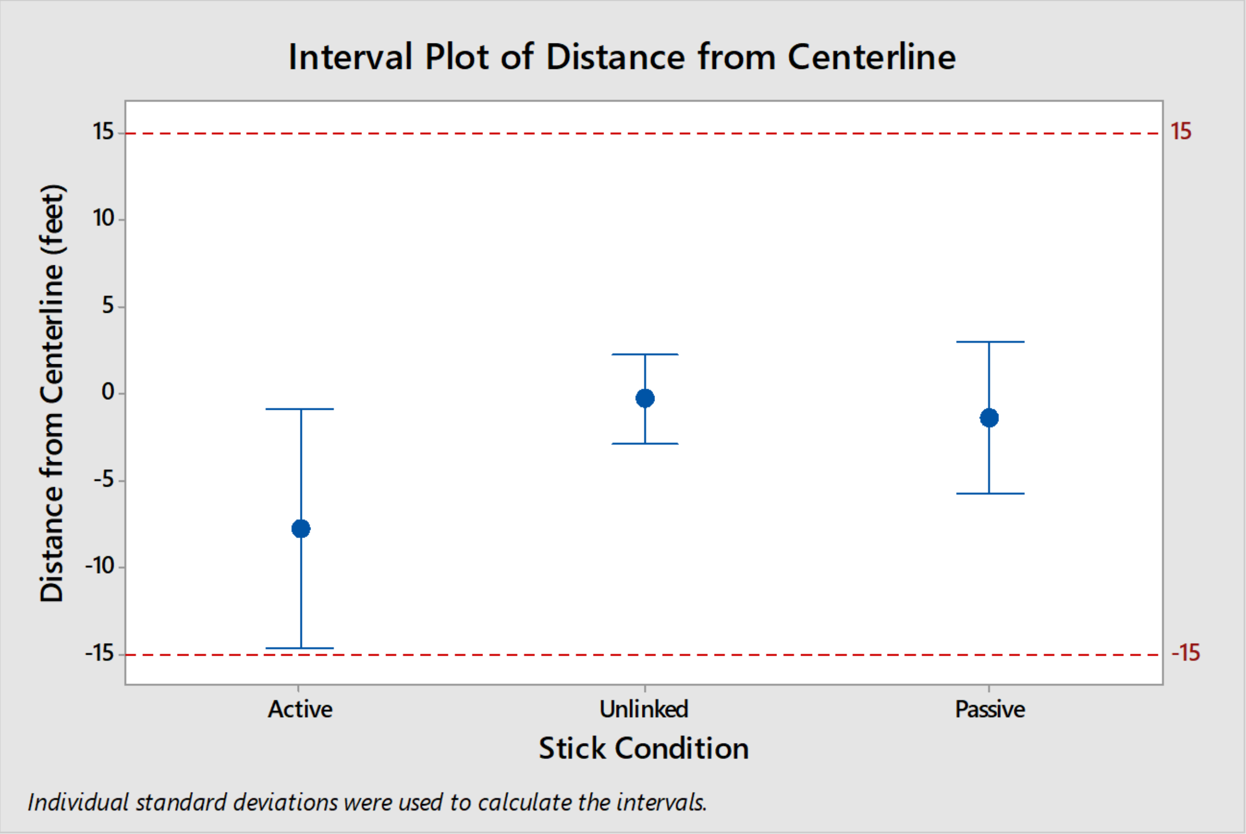

Figure 8. Equivalency analysis plot for distance from centerline. (α = 0.05)

The p-values for each equivalency test for distance from centerline are summarized in Table 19. The largest p-value of 0.042 is below the α level of 0.05 which is an indication of functional equivalency.

Table 19. Equivalency analysis summary for distance from centerline. (α = 0.05)

Sidestick Controller Model	**P-value (LEL / UEL)**
Active	0.042 / 0.000
Unlinked	0.000 / 0.000
Passive	0.000 / 0.000

Discussion of Subjective Workload During ILS Approaches

Performing an ILS approach requires the coordination of the aircraft's trajectory based off of lateral and vertical deviation indications from the localizer and glideslope, respectively. The localizer and glideslope are signals transmitted from ground based equipment near the runway that provide a guide to the runway's aiming point along the runway course. Prior to touchdown, pilots must pull up the nose to perform a flare maneuver which reduces the sink rate of the aircraft. When done properly, it results in a softer touchdown which is more comfortable for passengers.

An analysis of variance was performed to examine any differences between mean workload ratings during ILS approaches. The p-value was found to be 0.038 which is below the α level of 0.05, indicating significant differences were present in the data. As shown in Figure 9, subjective workload ratings given for ILS approaches flown using the passive sidestick mode were statistically significantly higher compared to the active and unlinked modes. Similar to the equivalency findings for the performance measure of touchdown point distance from threshold, the passive sidestick mode was not found to be functionally equivalent to the active or unlinked modes despite the lack of significant differences in the data. This relationship may be caused by the increased breakout forces associated with the passive sidestick mode. During an approach, the pilot is tightly coupled to this tracking task where minor adjustments are frequently made, therefore, higher breakout forces may have contributed to the increase in perceived workload and marginal degradation in achieved touchdown performance. A data summary is available in Table 20.

Table 20. Equivalency analysis summary table for workload during ILS approach. ($\alpha = 0.05$)

Sidestick Controller Mode	**Mean (μ)**	**90% C.I.**
Active	1.5556	(1.2289, 1.8822)
Unlinked	1.5	(1.1945, 1.8055)
Passive	2.1	(1.7709, 2.4291)

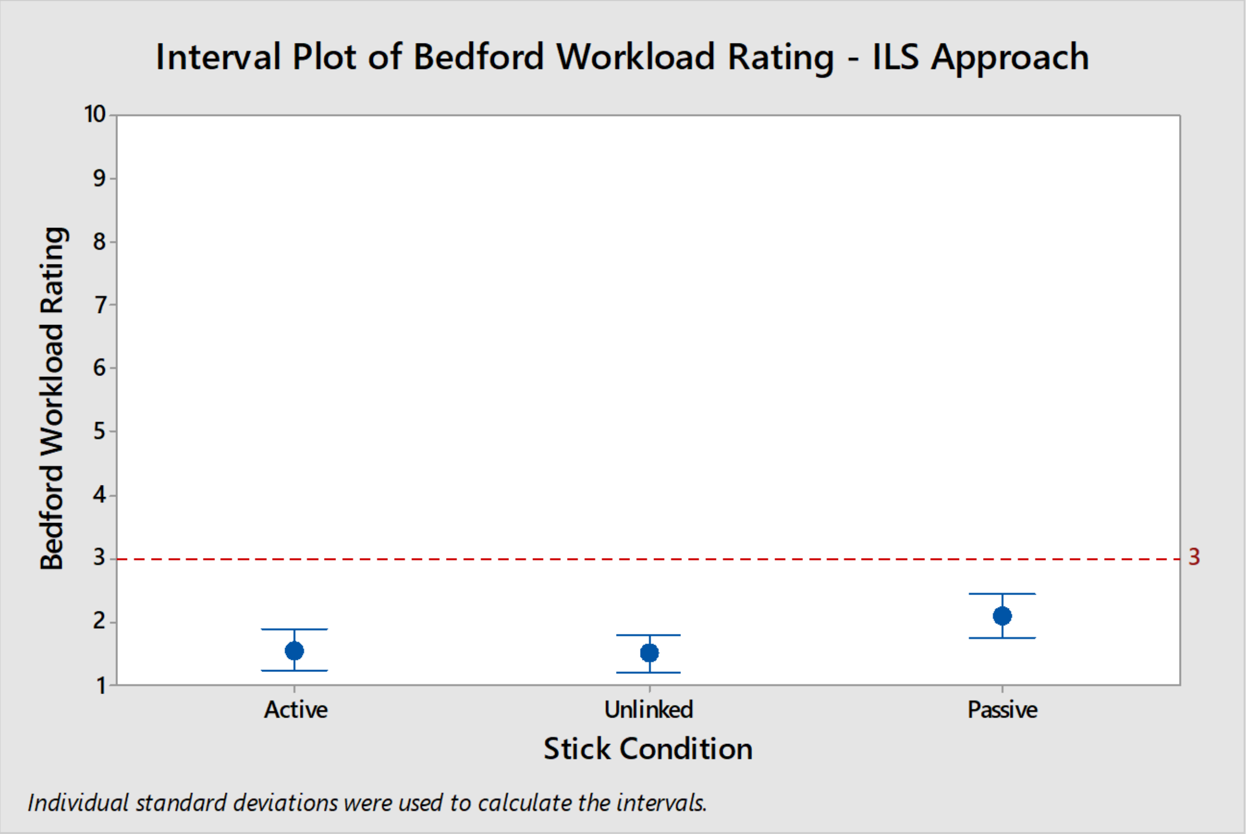

Figure 9. Equivalence analysis plot of workload during ILS approach. (α = 0.05)

Discussion of Equivalency Findings

The results of this study show for all but one performance measure, the active, unlinked, and passive modes of the Gulfstream sidestick controller are functionally equivalent. These include RMS error for airspeed, flight path angle, and bank angle during climbing and descending turns and touchdown point distance from runway centerline during an ILS approach. Marginal equivalency was found for touchdown point distance from runway threshold during and ILS approach. Results indicate that pilots flying ILS approaches in passive mode had a tendency to touchdown short of the aiming point compared to the active and unlinked modes. This could be due to a number of factors.

1. For many of the pilots who participated in the simulator testing that generated this data set, it was one of their first attempts at landing the Gulfstream aircraft in the simulator. While tracking the localizer and glideslope may not be significantly different between aircraft, flare characteristics can be unique for specific aircraft types. Initiating the flare too early or too late will cause the aircraft to touchdown long or short of the aiming point.

2. The GPS simulation in the Gulfstream simulator was not validated against the visual system, therefore, errors could be present in the data, skewing the results.

3. Some amount of parallax in the visual system may have been present, skewing the pilot's perception of their relative position to the runway.

4. The fixed-base simulator does not provide any aircraft acceleration cues to the pilot. As observed in much of the literature, this fact has a significant effect on the pilot's perception of the force-displacement characteristics of the control inceptor in relation to the aircraft response. Performing this analysis on data collected in flight test may produce different results.

5. The increased breakout force in passive mode could cause a delayed aircraft response to pilot inputs during the flare.

CHAPTER 5: CONCLUSION

As the equivalency analyses show, pilots were able to perform climbing and descending turns within the same error tolerance in flight path angle and bank angle while maintaining airspeed regardless of sidestick controller mode. Pilots were also able to fly ILS approaches and touchdown close to runway centerline regardless of sidestick controller mode, however by a narrow margin, they were unable to land near the aiming point within the equivalency limits for all three sidestick controller modes. There was a tendency to land short of the aiming point when flying in the passive sidestick mode which could be due to a number of factors including the increased breakout force and lighter force vs. displacement characteristics of the passive mode. This difference was marginal and would benefit from additional study using a larger sample size.

There are many aspects of this study that could be researched further. As discussed in the literature, fixed base simulators are not solely an effective means to assess the feel characteristics of sidestick controllers. Performing a similar analysis on data obtained via flight test would bolster the conclusions of this study. The real time acceleration cues of flight have a significant impact on the flight crew’s ability to perform manual maneuvers with sidestick controllers. Additionally, potential errors in the simulation of the GPS and visual system would be eliminated in flight. This study leveraged an existing data set which included a demonstration of a limited number of maneuvers that did not test the limits of the pilots’ cognitive workload nor examine the interaction with the second crew member. Future studies would benefit from analyzing scenarios such as upset recovery from unusual attitudes and system malfunctions including autopilot systems and other flight critical systems that interact with active sidestick controllers and require a significant amount of two man crew coordination. There are benefits of active sidestick controller technology that are not realized during the normal operations included in this study. Safety improvements, for example, are more evident during non-normal scenarios when non-verbal communication between pilots via tactile feedback through active sidesticks contributes to crew resource management.

The use of equivalency analysis has been shown to be an effective tool for assessing new aviation technologies, specifically in the flight deck. When design teams introduce new technology to the flight crew, at a minimum, it is held to a standard of “the same or better” than the previous technology. Using analysis of variance does not always result in identifying differences in the means between two or more groups. In these cases, when the null hypothesis is not rejected, equivalency analysis may complement this result to further suggest no practical differences exist and functional equivalency has been demonstrated. This method provides an objective measure of equivalency when no significant differences are found.

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