Three-Dimensional Measurement Applied in Design Eye Point of Aircraft Cockpits

Yanyan Wang; Xiaochao Guo; Qingfeng Liu; Huajun Xiao; Yu Bai

INTRODUCTION: Inappropriate design eye point (DEP) will lead to nonstandard sitting postures, including nonneutral head positions and other uncomfortable sitting postures, which are high risk factors for neck pain in fighter pilots exposed to high G forces. Therefore, application of a 3D measurement method to collect data regarding eye position while in the cruising sitting posture in the aircraft cockpit to guide the design eye point has been proposed.

METHODS: A total of 304 male fixed wing aircraft pilots were divided into two groups. Subgroup A (N = 48) were studied to define the cruising posture during flight. Subgroup B (N = 256) were studied with Romer 3D measurement equipment to locate the cruising eye position of the pilots in a simulated cockpit. The 3D data were compared to DEP data in the current standard cockpit.

RESULTS: According to 3D measurement, the vertical distance from the cruising eye point to the neutral seat reference point was 759 mm, which is 36 mm lower than that of the Chinese standard DEP and also lower than the U.S. military standard. The horizontal distance was 131 mm, which is 24 mm shorter than that of the Chinese standard.

CONCLUSIONS: The current DEP data cannot fulfill the needs of fighter pilots and should be amended according to the results of the 3D measurement so that pilots can acquire the optimal cruising posture in flight. This new method has the value of practical application to investigate cockpit ergonomics and the measurement data can guide DEP design.

KEYWORDS: cruising sitting posture, design eye position, 3-dimention digital anthropometry, pilot.

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Structural anthropometry data are widely applied in industrial workplace design. The aircraft cockpit is the workstation for pilots and its layout is based on structural anthropometry data to fulfill the needs of the pilots. The predicted average position of the pilots' bodies in special operations and activities is the design standard. The design eye point (DEP) is a single reference point in space selected by the designer where the midpoint between the pilot's eyes is assumed to be located when the pilot is properly seated at the pilot's station.[11] The pilot should adjust their seat before flight to set the eyes at the DEP for the internal and external view of the cockpit and handling the switches and pedals. Since all cockpit dimensions are related to and referenced by the DEP,[20] careful consideration must be given to it in aircraft design. Many factors can affect the design of the DEP, e.g., the flying task, operational posture, cockpit layout, new instruments, structural anthropometry data, activity range, individual factors, etc.[15] In the modern glass cockpit, pilots can fly the aircraft without looking in a downward angle at lower instrument panels since the head-up display (HUD) can display the key data needed to monitor and control the aircraft. The location of the HUD depends on the DEP[25] and will influence the pilot's flying posture. The side control stick, large seat back angle, and head-mounted display also influence the operational posture and will help to improve the cockpit layout design at the same time.

Inappropriate DEP can lead to an uncomfortable sitting posture, which is one of the causes for neck and back pain among pilots.[30] Coakwell et al.[3] found that various nonneutral head postures were high risk factors for neck pain among fighter jet aviators exposed to high G forces during flight, especially

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during aerial combat maneuvers. Therefore, it is essential to select an optimal DEP through the measurement of the various operational postures of pilots in addition to analysis of the structural anthropometry data.

Theoretically, the pilot's eye position during flight is the optimal location for the DEP, but this is hard to directly measure in actual flight. To improve the accuracy of the selection of the optimal location for the DEP, some concepts were introduced. One of those concepts is the standard sitting eye point. The standard sitting eye point is the sitting eye height[31] in the structural anthropometry of pilots, which is measured at a standard fixed sitting posture. Although it can be directly measured and such a database can become the basis of the main design, it is not the same point as the DEP. Another concept is the cruising eye point.[20] The cruising eye point is normally defined as the eye point of pilots while flying horizontally or cruising. Other researchers also defined it as the eye point of pilots who are relaxed with their hands on the throttle and stick. Theoretically, this point can be used as the DEP, but it is too hard to directly measure using anthropometry tools. Such a database has not yet been developed.

Many methods and techniques have been applied to measure and define human postures in engineering design, including video tracking of the marks attached to the surface of the human body,[26] manual measurement of the skeleton mark locations,[28] and human posture emulation.[22] McCarthy et al.[23] even used a video tracking method to track head movement under G in the Hawk aircraft. As technology has advanced, 3D measurement methods and tools have been applied in recent decades. A kind of articulated coordinate measurement device was developed to measure the three-dimensional locations of the body landmarks in the aircraft cockpit[4] or truck cabin.[27] However, there was not enough to establish a database based on such a small sample, although this kind of measurement technology can provide more precise data on postures rather than by using skin marks.

In this study, we proposed a new in-cockpit method of DEP design based on 3D measurement technology. We applied 3D measurement technology to measure the eye point in the operational sitting posture and acquired 3D data of the pilots' cruising eye points in the simulated cockpit. The pilot's posture was taken into account and the 3D data were compared to current DEP data to guide DEP design during the cockpit design process.

METHODS

Subjects

A total of 304 male fixed wing aircraft pilots were studied who were divided into two subgroups. Subgroup A included 48 pilots [mean (SD), age 25.4 ± 5.2 yr, flight hours 1000.4 ± 55.1 h], who were studied to define operational and cruising postures during flight. Subgroup B included 256 pilots [mean (SD), age 26.4 ± 5.1 yr, flight hours 1123.4 ± 58.1 h], who were studied to obtain the three-dimensional data of the cruising eye location in the cockpit.

All subjects were medically cleared fighter pilots and had HUD flight experience. The experimental protocol was approved by the Beihang University Human Ethics Committee. All subjects signed statements of informed consent, which outlined the purpose of the experiment and informed subjects of their rights.

Equipment

A simulated cockpit with an ejection seat and belt was used in the experiment. The locations of the side stick, throttle, and pedal were adjustable, which allowed the pilot to imitate his in-flight posture. The seat height was fixed, as was the neutral seat reference point.

A 3D coordinate measurement machine, the Romer Absolute Arm, a portable measuring arm produced by Hexagon Manufacturing Intelligence (North Kingstown, RI), was used to locate the eye position in the experiment. The single point repeatability was 0.060 mm and the measuring range was 2.5 to 2.8 m.

Procedure

Two different experimental protocols were applied in this study. All 48 pilots in subgroup A underwent the investigation protocol, a questionnaire regarding the design eye position and eye box in the cockpit with HUD, which was completed after a group interview about the most common issues with operational postures and eye positions in flight. All 256 pilots in subgroup B underwent the measurement protocol, which was completed in a simulated cockpit fixed on a horizontal floor.

Before measurement, a Romer arm coordinate measurement machine was fixed near the simulator and a Cartesian coordinate system was established. During the experiment, the location of the simulator and the Romer were fixed. According to the instructions from Romer, a Cartesian coordinate system for a 3D space was established for measurement using PC-dimiss software. The origin point was set at the neutral seat reference point (NSRP). From the perspective of the pilot, the x-axis was oriented from left to right in the horizontal plane, the y-axis was oriented from back to breast in the coronal plane, and the z-axis from foot to head in the sagittal plane. The axes orientation was concordant with the human dimensions measurement in GB 5703-1985 and GJB4856.[21] The NSRP and coordinate system allowed all the data to be expressed in a cockpit design coordinate system,[17] as shown in **Fig. 1**.

Fig. 1 also shows the vertical distance from the DEP to the NSRP (Dv) and the horizontal distance from the DEP to the NSRP (Dh), which were important for determining the DEP. In MIL-STD-1333B,[7] Dv was calculated when the seat back angle (SBA) was 13° using

$$\mathrm{Dv} = \text{sitting eye height}\left(\mathrm{P}_{50}\right) \times \cos(\mathrm{SBA}). \qquad \text{Eq. 1}$$

In consideration of the sitting eye height (P_{50}) of U.S. Air Force flying personnel being 809 mm (1967), we calculated the vertical distance from the DEP to the NSRP as Dv = 809 × cos13° = 788 mm.

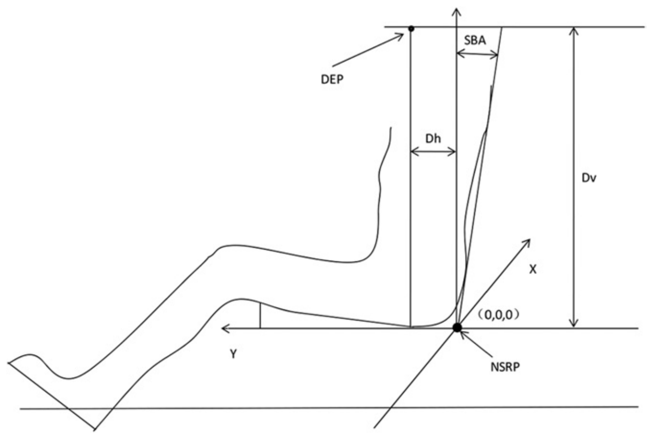

Fig.1. Schematic of Cartesian coordinate system and DEP.

In GJB35B-2008, Dv is also calculated in the same way. The sitting eye height (P_{50}) of PLAAF flying personnel was 816 mm (1999). So, we obtained the vertical distance from the DEP to the NSRP as Dv = 816 × cos13° = 795 mm.

In MIL-STD-1333B, Dh varies from 196–127 mm as the seat back angle increases from 10–15°. For fixed wing aircraft, the back angle should not be less than 13°; that is, the shortest distance should be 155 mm. In GJB35B-2008, Dh is 155 mm with a seat back angle of 17°.

In this study, Dv equals the z-coordinate value of the mean and Dh equals the y-value of the mean. The results were compared to those in MIL-STD-1333B and GJB35B-2008. The 95% confidence interval (CI) of the distance was calculated by:

$$Lower\,endpoint = \overline{X} - 1.96 \times S/\sqrt{n}, \qquad \text{Eq. 2}$$

and

$$Upper\,endpoint = \overline{X} + 1.96 \times S/\sqrt{n}, \qquad \text{Eq. 3}$$

Then all 256 pilots in subgroup B underwent the measurement protocol one by one.

Firstly, the height, weight, sitting height, sitting eye height, and interocular breadth were measured according to the methods of GJB4856-2003. The instrument precision was ±1.0 mm. Secondly, the pilot was asked to sit in the simulator with the belt fastened and to select a cruising posture with two hands on the throttle and stick. It was important that the pilot was able to be sufficiently observed through the simulation HUD. The experimenter encouraged the pilot to imagine actual flight operation and readjust any equipment to ensure that he had obtained a stable operational posture. After the pilot simulated an operational posture, the experimenter recorded the eye landmark location with the Romer probe.

Statistical Analysis

The IBM SPSS statistical software package 20.0 was used for the data analysis and all of the test data were expressed in means ± SD ($\bar{x} \pm$ SD) or percentile (%). The difference between the anthropometry data and norm was compared using the one-sample *t*-test. An alpha level of 0.05 was used as the threshold for significance.

RESULTS

Results of Investigation on the Cruising Posture During Flight

All 48 pilots in subgroup A completed the questionnaire and their answers were collected and summarized. The cruising posture was extracted from 81.3% (39/48) of the pilots surveyed, which was defined as the sitting posture while cruising with two hands on the stick and throttle, the back leaning against the seat back, the neck and upper shoulder leaning front by 10° to 15°. Almost all of them agreed that the erect posture was often not the cruising posture and only while landing or searching would they sit in an erect position in order to acquire a better external view.

Comparison of the Anthropometry Data and GJB4856 Data

The results are shown in **Table I**. The single sample *t*-test showed that the statures and weights of the pilots were significantly higher than those of the GJB4856 norm. The sitting height, sitting eye height, and interocular breadth were not statistically different from those of the GJB4856 norm.

Results of 3D Measurement

The plot of the cruising eye point in the sagittal plane is shown in **Fig. 2**. According to the 3D data of the cruising eye point, which is shown in **Table II**, Dv is 759 mm, which is the z-value of the mean. Dv is 36 mm less than that in GJB35B-2008 (795 mm) and 29 mm less than that in MIL-STD-1333B (788 mm). According to Eq. 2 and Eq. 3, we can calculate the 95% CI of Dv as:

Table I. Comparison of Anthropometry Data and Data from GJB4856 (mm).

ITEMS	MEASUREMENT ($\bar{x} \pm$ SD) $N = 256$	MEASUREMENT (P_{50}) $N = 256$	GJB4856 ($\bar{x} \pm$ SD)	GJB4856 (P_{50})	*t*-VALUE	*P*-VALUE	P_{50} DIFFERENCE	CHANGE RATIO (%)
Stature	1718.3 ± 32.2	1715.0	1705.0 ± 36.6	1704.0	6.585	<0.001**	11.0	0.6
Weight	69.4 ± 6.8	69.6	68.0 ± 7.6	68.0	3.256	0.001**	1.6	2.4
Height, Sitting	924.7 ± 20.0	926.0	924.3 ± 21.9	928.0	0.303	0.762	−2.0	−0.2
Eye height, sitting	814.7 ± 22.5	815.0	812.3 ± 21.4	813.0	1.685	0.093	2.0	0.2
Interocular breadth	36.8 ± 3.3	37.0	36.8 ± 3.7	37.0	0.004	0.997	0.0	0.0

** $P < 0.01$

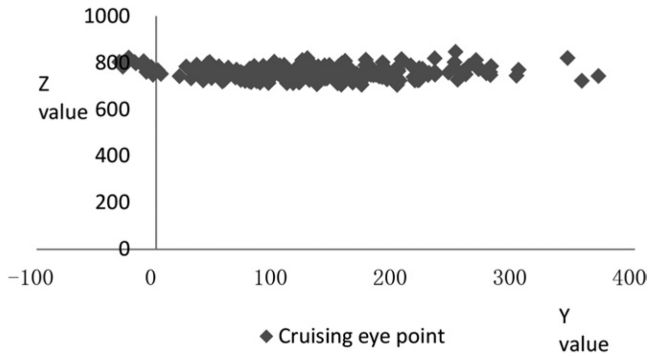

Fig.2. Plots of cruising eye point in the sagittal plane (mm).

$$CI\ Lower\ endpoint\ of\ Dv = 759 - 1.96 \times 1.6 = 756mm,$$

and

$$CI\ Upper\ endpoint\ of\ Dv = 759 + 1.96 \times 1.6 = 762mm.$$

Dh is 131 mm, which equals the y-value of the mean, as shown in Table II. Dh is 24 mm less than that in GJB35B-2008 (155 mm) and is 24–65 mm less than that in MIL-STD-1333B (155–196 mm). According to Eq. 2 and Eq. 3, we can calculate the 95% CI of Dh as:

$$CI\ Lower\ endpoint\ of\ Dh = 131 - 1.96 \times 4.6 = 122mm$$

and

$$CI\ Upper\ endpoint\ of\ Dh = 131 + 1.96 \times 4.6 = 140mm.$$

Therefore, the design value of Dv is 759 ± 3 mm and Dh is 131 ± 9 mm.

DISCUSSION

DEP is the key issue in cockpit design and ergonomic evaluation[29] since it is critical for obtaining an accurate reading of the information and symbols displayed. The most difficult and controversial issue is how to define the design data for the DEP. Usually, the design data are obtained from the structural anthropology data measured directly in the standard posture, especially the sitting eye height and head length. Pilots who are in the 50th percentile point for the sitting eye height of average stature should attain the DEP when the seat is in the neutral position. Pilots who are below P_{95} or above the P_5 point for the sitting eye height could attain the DEP through adjustment of their seats.[18]

Table II. Three-Dimensional Digital Measurement of Cruising Eye Point (mm).

	X	Y	Z
Mean	2.8	130.6	759.0
Standard deviation	4.1	74.0	25.9
Standard error	0.3	4.6	1.6
P_5	−5.1	0.7	717.5
P_{50}	4.0	125.5	756.9
P_{95}	7.0	267.5	806.9

The factors considered differ among various standards. The structural anthropology data and back angle factors are considered in MIL-STD-1333B and GJB35B-2008. But Jung et al.[19] argued that the structural anthropology data measured from the standard sitting posture were not sufficient to define the DEP since the erect sitting posture is different from the actual posture in the ejection seat. They considered the trunk extension angle and neck flexion angle to be necessary parameters in the calculation of the DEP height. Additionally, the estimated posture data should be validated by the pilots' real postures. As we know, human body dimensional data of the typical work posture are used in other occupations.[9] However, those data in the ejection seat cannot be measured through use of the classical anthropometry tools. To obtain these essential data for the design of the DEP, some researchers have focused on 3D measurement technology as a way to measure the actual eye location of the pilots in real aircraft. In the development of the Comanche RAH-66 helicopter, to check whether the Comanche cockpit was too small, the engineers used FaroArm, which can measure a point location in three dimensions to 2-sigma accuracy, to determine the accuracy of the actual measured DEP by placing 20 subject aviators in a full-scale Comanche simulated cockpit. The evaluation concluded that the DEP of the two prototype aircrafts could not adequately predict the real eye position.[2] Crawford[4] also used the FaroArm to measure the actual eye location of seven subjects sitting in an AV-8B. But the experimenter asked the subjects to sit upright with their hips against the seat back. This is the standardized anthropometrical posture and not the cruising posture. Also, the small sample size was insufficient for development of a database.

In our study, we used the Romer to locate the eye position while in the cruising posture as simulated by pilots according to the definition obtained through the investigation in the simulated cockpit. During the study, interviews and questionnaires were combined to ensure that the pilots adequately and accurately understood the aim. They could visualize the actual flight posture before finishing the questionnaire and thus the quantized data were obtained.

In MIL-STD-1333B, the erect posture is assumed when the seat back angle is 10°; it is also assumed that the trunk extends with the seat back as the seat back angle increases. But as a matter of fact, this is not the pilots' actual postures. Jung et al.[19] argued that the changes in the trunk extension angle and neck flexion angle with the seat back angle are also both important to the DEP. If we consider the influence of these two factors when we design the DEP with a back angle of 17° according to the norms of GJB35B-2008 and MIL-STD-1333B, respectively, the Dh (155 mm) in GJB35B-2008 should be increased and the Dh (99 mm) in MIL-STD-1333B should be reduced. Therefore, the Dh (131 mm) calculated from real 3D measurement data should be more accurate.

Dv (759 mm) was calculated based on the 3D measurement to be 36 mm less than that from GJB35B-2008, which is 795 mm. Since the sitting eye height is not significantly different according to the GJB4856 norm, the difference is caused by posture difference but not by sample bias. Two possible reasons may account for this difference. One is the difference between the erect and relaxed postures. According to MIL-HDBK-759C,[6] the sitting eye height may be reduced as much as 65 mm when a person sits in a relaxed or slumped position. In Mil-STD-1472d,[8] the P_5 and P_{95} data of aviator eye height are, respectively, 736 mm and 861 mm when the studied aviators are sitting erect and straight. Correspondingly, the P_5 and P_{95} data of the eye height are, respectively, 716 mm and 841 mm when the studied aviators are sitting in a relaxed manner. It is obvious that the difference between the erect and relaxed postures of the same study subjects is 20 mm. The other cause is the difference in seat back angles. The Dv data in GJB35B-2008 and MIL-STD-1333B are calculated with an assumption of 13° SBA. But the Dv is 780 mm and 773 mm, respectively, which is derived from Eq. 1 with the condition that SBA is 17° and the difference is 15 mm.

The slump factor should be considered when selecting the range of movement for adjustable seats, as well as in locating the displays, optics, and vision ports.[6] The results of our experiment's 3D data show that the slump factor was not taken into enough consideration in GJB35B-2008. Suitable allowances should be made for postural variation using the anthropometric data. In our study, allowances have been made through the pilot's posture imitation, so the data are more valid and reliable for use in guiding the design of the DEP.

The deviation of Dv from the real eye position can be compensated for through a larger vertical adjustment range of the seat to some degree. However, it would increase the height of the canopy. The seat height is adjusted to allow sufficient clearance between helmet top and canopy, especially under the very low canopy. This distance, canopy to DEP, is a cockpit design feature. The deviation of Dh is hardly to be compensated for in the fighter cockpit since the seat is not adjustable horizontally. This factor is also very important in the DEP design of modern aircraft with HUD, which can decrease the attention resources and increase the workload of pilots. The study results show that the current regular design size of the eye box of the HUD is not large enough, especially for fighters. Although the size of the eye box should be large enough to ensure visibility in all expected flight conditions, an increase in size would sharply increase costs. For maximum optical efficiency, every pilot's eyes should be set into the design eye-box in the entire expected seat adjustment range. To obtain proper visibility of all information in the HUD, distribution of the pilot's eyes around the DEP, human body size, and postural variation must be taken into account while designing the range of the eye box.[16]

According to AC 25-11B[12] and regular update of CS-25,[10] the DEP must be centered within the minimum design eye box dimensions, which are defined as the following: Lateral, 1.5″ left and right from the DEP (3.0″ wide); vertical, 1.0″ up and down from the DEP (2.0″ high); and longitudinal, 2.0″ fore and aft from the DEP (4.0″ deep). Wood indicated that the actual dimensions must be larger than the minimum criteria and modern HUD eye box dimensions are typically 5.2″ laterally, 3.0″ vertically, and 6.0″ longitudinally.[32]

However, these design criteria still cannot fulfill the needs of fighter pilots since the super maneuverability requirement will affect the operational posture and eye position. The pilot's head will move away from the DEP during maneuvering. Postures assumed to relieve fatigue are also a challenge for the eye box. Davies et al.[5] found that considerable head movement to relieve muscle fatigue is a common practice in train driving. Such extreme head motions will exceed the range of the designed eye box of much current equipment. The most practical solution is to increase the HUD head box and/or employ HUD technologies associated with larger head boxes. In our study, the range of the cruising eye position varies in the longitudinal dimension from P_5 to P_{95} at 267 mm, which is larger than in Wood's opinion (152 mm).[32] It is hard to compensate for in the fighter cockpit since the seat of the fighter cockpit is not adjustable horizontally. Thus, some pilots must adjust their comfortable postures to adapt to the HUD and it is very unlikely for them to always be able to maintain a comfortable posture during air combat, which has been proven by some other studies. Green and Brown[13] found that during air combat, the head of the pilot was away from the neutral position 68% of the time, predominantly in extension or rotation plus extension. This is associated with high levels of muscle activation and fatigue. Thoolen and van den Oord[30] found that the sitting posture was reported as 50% of the cause for flight-related neck pain and 89% of the cause of back pain. Alagha[1] also agreed that poor neck posture during air combat maneuvers is the cause for neck pain, which is very common among pilots. These symptoms may significantly limit flight performance and disqualify the pilot from flight duty. The prevalence of backaches in aircraft pilots is 42.1% (56/133)[24] to 64.02%, among which pain in the cervical region is 47.2%.[14] Therefore, we think a more suitable DEP may be of benefit for pilots in maintaining neutral head postures and subsequently reducing the level of associated neck injury. Better design of the DEP using 3D data may reduce these problems.

There are also two limitations for this study. First, the imitated posture in the simulator may be different from that used in actual flight. For example, the G effect may reduce eye height in flight. Second, the subjects were all men, so the body dimension differences between male and female pilots have not been studied. The results of this study should be validated in further studies and aircraft design practice.

In this study, we applied a 3D measurement method to collect data regarding eye position while in the cruising sitting posture of the aircraft cockpit to guide the design eye point. The results show that current DEP data cannot fulfill the needs of fighter pilots and should be amended according to the results of the 3D measurement so that pilots can acquire optimal cruising posture in flight. This new method has the value of practical application to investigate cockpit ergonomics and the measurement data can guide the DEP design.

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