Restraint Harness Performance During Flight Maneuvers: A Parametric Study

Cheng-Fei Du; Xiao-Yu Liu; Li-Zhen Wang; Song-Yang Liu; Yu-Bo Fan

INTRODUCTION: Modern super agile fighter aircraft are capable of producing an increasing multiaxial acceleration environment which can adversely affect the pilot. An evaluation of the performance of the restraint system during flight maneuvers will benefit restraint designs and, thus, the safety of pilots.

METHODS: A finite element model of a mannequin with PCU-15/P harness restraint was used in this study to investigate how the factors, such as strap material stiffness, friction, and belt tension, affect the performance of restraint systems during impact along the $-G_x$, $-G_y$, and $-G_z$ directions. The corresponding maximum displacement of the mannequin's torso was computed.

RESULTS: The mannequin moved beyond 74 mm sideways. The change in friction coefficient (FC) from 0.1 to 0.4 decreased the displacement of the lower torso by less than 6.7%. The displacement of the torso decreased as the stiffness of the strap or tension increased. Displacement decreased by 9.3%, 6.0%, and 2.7% for the lower torso under the G_x impact, as the tightening force increased from 20 N to 80 N gradually. However, this changed slightly when the stiffness arrived at 1 E or the tension increased to 60 N.

DISCUSSION: PCU-15/P harness has the poorest performance during side impact and friction plays an unimportant role in affecting its performance. The stiffness of the webbing used in the PCU-15/P harness is sufficiently high. The lap belt has more effect on limiting the movement of the pilot than the shoulder straps, and a tension of 60 N during the adjustment may be enough for conventional flight maneuvers.

KEYWORDS: biomechanics, finite element, restraint harness, flight maneuver.

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Developments in engine performance and aerodynamics have enabled the modern fighter aircraft to increase its agility and maneuverability, thus exposing the pilot to an increased multiaxial acceleration environment. According to the previous report,[15] an attack maneuver with an angle of attack of 80° and a roll rate of $100° \cdot s^{-1}$ produces an acceleration exceeding 3 G in the G_y and G_z directions. Under such conditions, it is essential for the seat restraint system to keep the pilot firmly attached to the seat. Without adequate restraint, under the high acceleration produced, the pilot may feel a sensation of buoyancy, shakiness, discomfort, and may even lose the ability to fly the aircraft safely.[11] Inappropriate restraint systems and poor sitting posture, which may be affected by the former, both contribute to the spinal injuries of the pilot in an ejection scenario.[6,18,19]

Performance of the restraint harness may be affected by the harness configuration, material properties, tension of adjustment, and other factors.[7] Some investigators experimentally studied the effect of changing harness configuration on the dynamic response of a mannequin during impact loading. The addition of a negative strap to the restraint harness reduced the off-seat displacement and provided a better occupant-seat coupling during vertical impact. Moreover, this reduced the tendency of submarining in forward-facing impact.[9,11] Compared to the PCU-15/P harness, the X-Band 90 restraint harness was

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found to cause lower head acceleration and chest acceleration during $+G_z$ impact.[3]

The finite element method (FEM) is a useful tool in studying the performance of restraint systems. FEM is widely applied in the automobile safety field. The performances of traditional three-point seat belts and four/five-point restraint configurations were compared using FEM.[10,12] A parametric study was also conducted to evaluate the performance of child restraint systems in side impacts.[2] However, the application of FEM to investigate the performance of restraint systems for aircraft has not been reported.

Accordingly, the aim of this study was to investigate the performance of restraint systems in a flight maneuver scenario. This paper introduces a multibody model of a 50th percentile adult male occupant constrained in a seat restraint system and presents a parametric study of the strap material stiffness, friction between the belt and pilot, and tensioning force of belt adjustment. In the parametric analysis, how these factors affect the harness restraint and the dynamic response of the pilot were investigated to better understand the performance of aviation restraint systems and benefit the development of future restraint designs.

METHODS

Equipment

CAD software (Solidworks 2007; Dassault System SolidWorks Corp, Waltham, MA) was used to develop the model of an ejection seat. CAE preprocessing software (Hypermesh 11.0; Hyperworks Co., Troy, MI) was used to convert the geometrical model of ejection and the mannequin to a finite element model and adjust their relative position. The corresponding boundary loading conditions were also set in this software. A workstation (ThinkStation D20, Lenovo Corp, Beijing, China) was used to perform the numerical simulation. All the simulations were conducted using explicit dynamic software (Ls-dyna 971 R5; LSTC Corporation, Livermore, CA).

Procedure

The facet mannequin model consists of interconnected rigid segments, which were designed based on the general model of a male subject captured using a 3D scanner. These segments included head, neck, upper trunk, lower trunk, thigh, leg, foot, upper arm, forearm, and hand. They were connected through spherical joints. The physical properties of each segment, such as size, mass, center of mass, and moment of inertia, were consistent in the 50th percentile Hybrid III mannequin. To achieve the interactions of a higher degree of accuracy between the body and restraint systems, two layers of soft tissue representing the skin and flesh were added on the outer surface of the upper torso, lower torso, and thighs. The skin and flesh were linear elastic and viscoelastic materials, respectively, and their values can be found elsewhere.[17] Joint properties, such as the range of motion, stiffness, friction, and dampening, representing the nonlinear, rate-dependent characteristics of the human joints were based on the data of a Hybrid III mannequin and obtained from published literature.[1,16]

The ejection seat, satisfying the major characteristics of the Advanced Concept Ejection Seat II seat with a back angle of 30° and a design of side stick, was modeled using Solidworks 2007. The models of the mannequin and seat were meshed as shell 3-node or 4-node elements in the Hypermesh 11.0. The mannequin model and seat were configured to the body posture of a pilot in flight. The clearance between the body and seat restraint systems was adjusted to about 2 mm to avoid penetration. The PCU-15/P harness restraint was modeled in Hypermesh, and its geometrical and material properties were in agreement with the military specifications (MIL-W-25,361). The complete model is shown in **Fig. 1**.

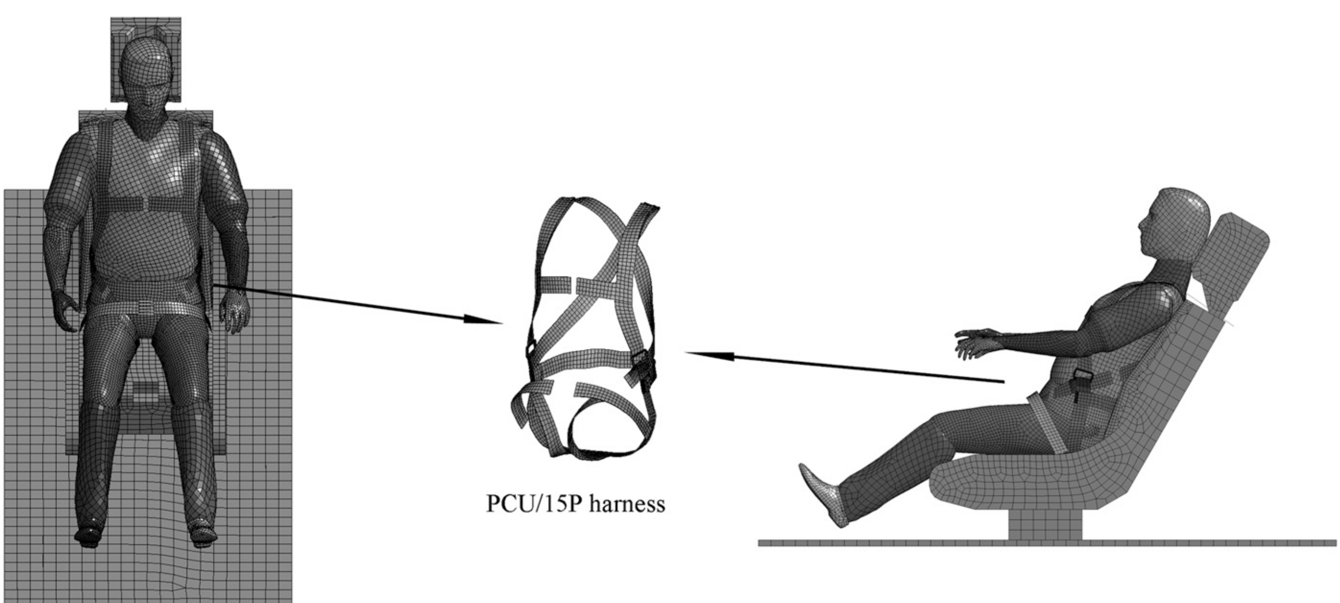

Fig. 1. Model of the mannequin and PCU-15/P harness used in the experiment.

The shoulder strap and lap belt were modeled using membrane elements which closely represent the almost noncompression property of a seatbelt. The inertia reel was also included and the trigger condition for activating the retractor to lock was set at an acceleration of 2 G. The adjustment buckle was modeled as a cable discrete beam. All the interactions between the mannequin, seat, and restraint harness were represented as automatic surface-to-surface contacts with a friction coefficient (FC) of 0.3. The dynamic response of the pilot during the impact was analyzed using an Ls-dyna 971 R5 system.

The model was validated by comparing its predictions to the results from the previous experiments[4,11] in which the same restraint system was used. Only the test data in the G_x and G_z directions were used because the response information of subject or mannequin during sideways impact was not available. The load-constraint boundary conditions should be comparable to those recorded under experimental conditions. A left-handed coordinate reference system was used during the data analysis. In this coordinate system, the +x axis is directed forward, the +y axis is directed from left to right, and the +z axis is directed upward. After validation, the proposed model was used to predict the dynamic response of the mannequin under acceleration in the –x (back to chest), −y (left to right), and −z (pelvis to head) directions separately. The acceleration profile was trapezoidal in shape and the magnitude of maximum acceleration was 3 G with an onset rate of $6\ G \cdot s^{-1}$ over a time interval of 2 s. This was done to simulate the impact loading experienced by a pilot during a flight maneuver.[15] During the simulation, the movement of limbs relative to the seat was constrained considering the effect of stick and pedal on the hands and feet.

A parametric study was then undertaken to analyze the material properties of the harness (stiffness and friction of the strap) and tightness during adjustment on the performance of the PCU-15/P harness. The stiffness E (1260 MPa for lap belt and 1080 MPa for shoulder strap), representing the base elastic modulus of webbing, was varied from 0.25 E to 2 E (0.25 E, 0.5 E, 1 E, 1.5 E, and 2 E) during the dynamic simulation. Similarly, the friction coefficient between the restraint harness and mannequin or seat was varied from 0.1 to 0.4 (with an increment of 0.1 per step) with a baseline of 0.3, and the tension force was varied from 20 N to 80 N (an increment of 20 N per step) with a base value of 40 N. First, the tension was assumed as the same for both lap belt and shoulder strap, and then the tension was taken as different values between these two different parts of restraint harness.

Then a quasi-static loading was conducted to impose the preload of gravity and tightening forces before the dynamic simulation for elimination of the initial gap between the mannequin and seat or the mannequin and restraint harness. This procedure was conducted using the function of dynamic relaxation and the duration was set at 1 s. At the end of 1 s, the dynamic relaxation analysis was terminated and the current state became the initial state for the subsequent step of normal dynamic analysis.

Data Analysis

The displacements of the upper torso of the mannequin under different conditions were recorded as the major index to evaluate the effects of the factors influencing the performance of harness restraint. For the case with different tension values in lap belt and shoulder strap, the displacement of the upper torso was also measured. Because the aim of this study was to compare the response of the same model under various conditions, no statistical analysis was conducted.

RESULTS

The peak values of the displacement of the lower torso (buttocks) under G_z acceleration during the simulation were compared to the experimental data reported by Leupp[11] (**Fig. 2**). The simulated displacements were in agreement with those of this experimental data except for some minor deviations during the impact loading of 3 G and 4 G, as shown in Fig. 2. The response of the mannequin to $-G_x$ impact was validated by comparing the simulation response time history with the experiment of Buhrman.[4] **Fig. 3** shows that the historical data of acceleration of the chest predicted from the model are in good agreement with the experimental results.

The resultant displacements of the upper torso and lower torso in the three directions of impact with various material properties of the restraint harness are shown in **Table I**. Evidently, the mannequin moves most during the lateral impact and least in the front direction, indicating that the performance of the PCU-15/P is poor during side impact. It can be seen that the pilot's body moved less as the stiffness or FC decreased. However, the influence of FC became very slight on the restraint system because the decrease in the displacement of the lower torso was less than 6.7% as the FC increased from 0.1 to 0.4 in all directions of impact. While in the range of stiffness

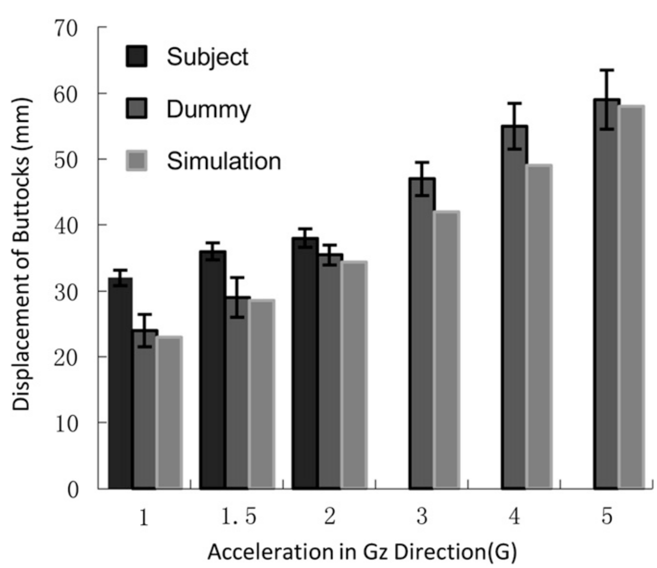

Fig. 2. Comparison of results obtained by simulation and from the experiments by Leupp;[11] the experimental results are represented as mean ± SD.

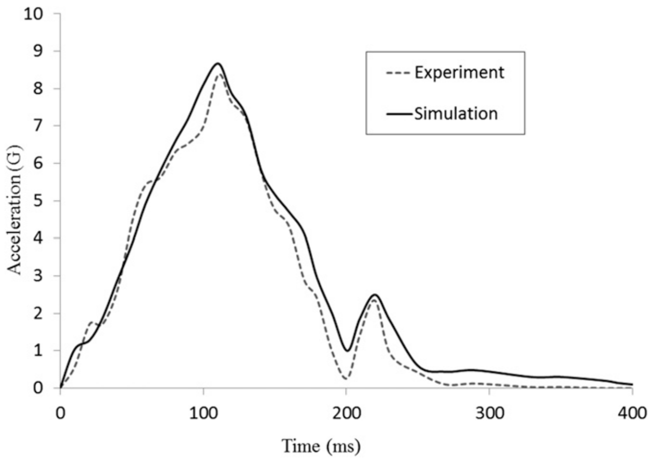

Fig. 3. Comparison of chest acceleration during $-G_x$ impact in the simulation and Buhrman et al.'s experiments.[4]

considered, this displacement decreased by about 30% in the $-G_x$ and $-G_z$ directions as the stiffness changed from 0.25 E to 2 E. However, this changing tendency of the lower torso movement became gradually weak as the stiffness increased.

For the same tension values in lap belt and shoulder strap, the impact of tension on the displacement of the torso is also shown in Table I. The upper torso moved more than the lower torso except in the $-G_x$ direction. The lateral impact has the least effect on the movement of the pilot's body, consistent with the parametric study on the material properties of webbing. For the impact in the $-G_x$ direction, the motion of both the upper torso and lower torso decreased as the adjustment became tighter. The displacement decreased by 9.3%, 6.0%, and 2.7% for the lower torso under the $-G_x$ impact as the tightening force increased gradually from 20 N to 80 N. This shows that the variation in the displacement became negligible during the incremental increase in tightening in the $-G_x$ direction, and a similar tendency was observed in the other directions of impact.

Table I. Displacement of the Lower Torso Under Impact with Different Stiffnesses of Strap, Friction Coefficients (FC) Between the Belt, and the Mannequin and Tension Values for the Adjustment of the Restraint Harness (mm).

VARIABLES	$-G_X$	$-G_Y$	$-G_Z$
Friction coefficients			
FC = 0.1	33.62	76.53	46.22
FC = 0.2	32.03	75.80	45.21
FC = 0.3	31.33	75.61	45.10
FC = 0.4	31.36	75.00	44.1
Stiffness of strap			
0.25 E	42.31	76.22	61.73
0.5 E	32.80	75.80	50.38
1 E	31.33	75.61	45.10
1.5 E	30.57	75.12	43.80
2 E	29.20	75.21	43.18
Tension			
20 N	36.48	77.63	48.80
40 N	31.33	75.61	45.10
60 N	29.10	74.58	43.81
80 N	28.01	74.18	43.49

With different tension values in different parts of the restraint system, the tension in the lap belt was found to exhibit more influence on restraining the pilot than the shoulder strap. For example, control of the displacement of the lower torso by the two variables of lap belt and shoulder strap is shown in **Fig. 4**.

DISCUSSION

Maneuverability is an important factor in the evaluation of modern fighter aircraft. A better maneuverability provides the aircraft more positional advantage to fire and higher survival probability in evading an enemy missile. However, the great inertial force induced in the acceleration environment may produce several negative effects on the pilot. The conventional fighter aircraft has a G environment predominantly along the G_z axis.[14] The exposure to $+G_z$ may result in loss of consciousness, which has attracted the attention of researchers for decades.[5,13] With the advent of super agile aircraft with high maneuverability, the overall G environment experienced by the pilot of this aircraft became multiaxial. The large magnitude multiaxial inertial force induced in this environment would probably cause vibration or sliding of the pilot body, fatigue of the muscles, and even injury when the restraint harness fails to provide the expected performance. These effects may impair the operation of the aircraft and increase the risk to the pilot in combat operations. A centrifuge study showed poor performance of the pilot under combined $+G_z$ and $+G_y$ than under $+G_z$ alone in a tracking task.[8,20] This is probably because of the poor ability of a pilot to accurately control the movement of his arms which is induced by the complex acceleration environment. On the other hand, the movement of the upper torso or lower torso may alter the curvature of the spine, resulting in a higher risk of spinal injury in the case of possible emergency ejection.[6,18]

This study developed a facet finite element model of a restrained pilot and conducted a parametric study on the dynamic restraint performance of the PCU-15/P service harness. The results show that the restraint of the harness is insensitive to the friction coefficient between the harness and pilot. It was confirmed that the tendency of relative slip between the belt and pilot is not appreciable, and that the major interaction between them is a normal force. The predicted results displayed an obvious effect from the stiffness of the strap on the performance of the restraint harness. However, the reduction in the displacement of the pilot torso became small when the stiffness of the webbing increased. This indicates that the stiffness of the service restraint harness is strong enough and its improvement has only a slight impact on the performance of the restraint system during flight maneuvers.

The tension of the harness in the adjustment stage is indispensable because of the large differences in the anthropometric parameters of the pilot. This procedure eliminates the gap between the restraint harness and the body and produces pressure on the skin simultaneously. Theoretically, a higher tension in the harness permits an improved restraint performance of

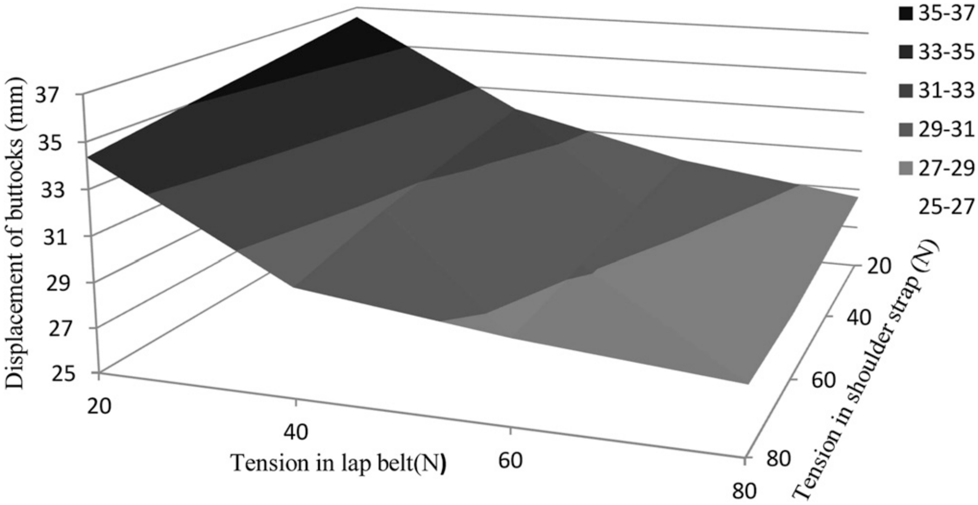

Fig. 4. Displacement of upper torso and lower torso of the mannequin with different tension values in the lap belt and shoulder strap under impact in the $-G_z$ direction.

the occupant in a vehicle and that was also confirmed by the constrained mannequin model in this study. However, most of the subjects are inclined to keep the belt rather relaxed during a flight according to a survey conducted with a questionnaire. This is because an overtight belt causes discomfort to the pilot and may even limit his performance.[11] Therefore, it is necessary to seek a balance between comfort and safety. The results of the model presented in this paper reveal that the effect of tightening on the movement of the pilot trunk becomes negligible as the tension increases, especially when the tension is beyond 60 N. Accordingly, 60 N may be a good tension to use during the adjustment of harness for a conventional flight maneuver. However, probably the best way to solve this problem is to use an automatic adjustable buckle for the restraint harness based on the impact loading imposed on the pilot.

This parametric study shows that the pilot trunk moves to a greater degree during side impact than in the other two directions of impact. The restraint harness of the PCU-15/P showed a poor performance in the direction of the G_y axis, and it is necessary to improve this aspect. Notably, a tendency to submarining was found in the $-G_x$ environment in this study. This phenomenon indicates the movement of the torso under the lap belt during forward-facing impact loading and it presents the risk of abdominal trauma.[9] For this reason, the upper torso moves to a lesser extent than the lower torso during $-G_x$ impact, as observed in this study. The reasons for submarining may be related to factors such as seat back angle, sitting posture, and restraint harness. Further investigation will be conducted on this issue.

It is important to note that this study has several limitations. It represents a preliminary FEM model of a human seat restraint system to analyze the performance of a selected harness; as such, the findings cannot be generalized and applied to other types of harness restraints. Similarly, G impact loading with a specific peak magnitude and onset rate was used in this study. Thus, the predicted results cannot be used for any other G environment with a different peak value and onset rate. Furthermore, the clothing on the pilot was not considered in this model and it may produce a gap between the belt and body and result in underestimating the predicted displacement of the torso. Finally, muscle force was not considered in the study because it is not known which muscle would be activated nor the magnitude of force produced under various acceleration conditions. Further improvements to this biomechanical model of a restrained pilot should be made in future research and also tested to validate it.

In conclusion, a finite element model of a mannequin in conjunction with a seat system was developed and a parametric study on the material properties of the restraint harness and tightening during adjustment was conducted. The PCU-15/P harness restraint revealed a poor performance during side impact loading compared to the other two directions of acceleration impact. The friction coefficient between the harness and the body of the pilot has negligible influence on the performance of the restraint harness. The performance of the restraint harness decreased as the stiffness of the strap and the tensioning force increased. This varying tendency became weak as these two factors increased. The tension of the lap belt plays a more important role in affecting the PCU-15/P harness performance compared to that of the shoulder strap. The lap belt has more effect on limiting the movement of the pilot than the shoulder strap and tensioning them with 60 N during the adjustment may be sufficient during a conventional flight maneuver. This biomechanical model of a mannequin can be used to study the response of a restrained occupant under impact loading for assessing the effectiveness of a restraint system design.

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