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System Level Crash Sled Simulations for Evaluating Helicopter Adaptive Seat Damper

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ABSTRACT: This research study focuses on the finite-element based nonlinear dynamic model development and analysis for virtual evaluation of adaptive seat dampers for enhanced occupant protection during vertical crash landings of a helicopter. The current state-of-the-art helicopter crew seat has passive safety mechanisms that are highly limited in their capability to optimally adapt to each type of crash scenario due to variations in both occupant weight and crash severity level. While passive crash energy absorbers work well for a single design condition (50th percentile male occupant and fixed crash severity level), they do not offer adequate protection across a broad spectrum of crash conditions by minimizing the load transmitted to the occupant. This study reports the development of a finite-element based seat-occupant system level model using LS-DYNA3D for rotorcraft crash injury simulation. This finite element simulation model of a seated occupant with five-point belt and stroking seat is used to study occupant kinematics and spinal injury assessments to support crash sled evaluations of seat energy absorbers. The injury criteria and tolerance levels for the biomechanical effects are discussed for each of the adult-sized occupants with respect to thoracic lumbar loads. The desired objective of this analytical model development is to develop an analysis tool to study the performance effectiveness of adaptive seat energy absorbers for enhancing rotorcraft occupant crash protection.

KEYWORDS: Adaptive seat energy absorber, Crash dynamic model, Rotorcraft crashworthy safety seat, Helicopter crash injury simulation.

NOTATIONS:

A:	Current, Amps
ATD:	Anthropomorphic Test Device
FSMREA:	Fail-Safe Magnetorheological Energy Absorber
G:	Acceleration in g's
IARV:	Injury Assessment Reference Value
MREA:	Magnetorheological Energy Absorber
ft/s:	Feet per second
ms:	Milli-seconds
ΔV_z:	Change in vertical impact velocity

I. INTRODUCTION

Rotorcraft crew seats generally use passive energy absorbers to attenuate the vertical crash loads that are transmitted through the fuselage structure of the rotorcraft to the seated occupant [1] during a crash or hard impact landing event. These energy absorbers (EAs) include fixed-load energy absorbers (FLEAs), shown in Figure 1 or variable load energy absorbers (VLEAs) [1-3]. These passive energy absorbing devices are not capable of automatically adapting their load-stroke profile as a function of occupant weight or as a function of varying degree of impact severity during a crash or hard landing event.

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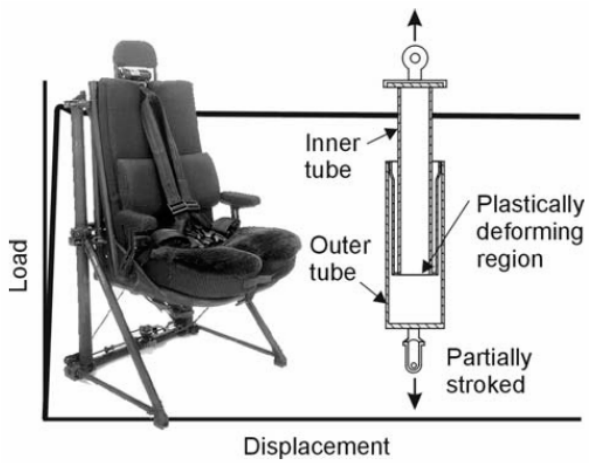


Figure 1. FLEA utilized in SH-60 Seahawk crew seat [15]

In the recent times, smart adaptive energy absorbing devices, such as magnetorheological energy absorbers (MREAs), have emerged as an innovative solution for providing active crash protection by utilizing a continuously adjustable load-stroke profile EA in a controlled manner during a crash event[4-8]. MREAs can adapt their stroking load as a function of occupant weight and also can respond to various impact/shock excitation levels in combination with a feedback controller. By intelligently adjusting the load-stroke profile of the MREA as the seat strokes during a hard landing or crash event, MREAs have the capability of providing an optimal combination of a short stroking distance coupled with minimal lumbar loads with varying occupant weight and impact severity level. Furthermore, MREAs offer the unique ability to use the same seat suspension system for both shock isolation during hard landings or crash impacts, and for vibration isolation during normal and extreme manoeuvring flight conditions. References [6] and [7] have explored the use of MR seat dampers to reduce the vibration level and also mitigate the severity of end-stop impacts. Flow-mode (Poiseuille flow) [9] in linear stroke has been typically utilized in MREAs that have been developed for seat attenuation applications. However, due to compact sizing and packaging in seat design considerations, shear mode (Couette flow) has become the design choice in the recent MREA implementations for seat shock and vibration attenuations [10-12]. Compared to the linear stroke flow-mode MREA, the rotary vane shear-mode MREA offers less weight, compact design, and cost effectiveness. A shear mode MREA has been developed for rotorcraft crash safety seat application to demonstrate the ability of the MREA in reducing occupant injury during crash events, as well as reducing vibration level during normal and extreme manoeuvre operations [13]. Reference [14] reports the development of a fail-safe rotary MREA by incorporating permanent magnets into a shear mode based magnetorheological (MR) fluid rotary vane energy absorber. The use of permanent magnets in MR seat dampers can be used to achieve a fail-safe force to a specific load requirement, for example, stroking load for a 50thpercentile male in a maximum crash deceleration condition as per military specifications. With the same device, an adjustable stroking load (for occupants from 5thpercentile to 95th percentile under varying crash severity conditions) can be obtained by cancelling or augmenting the magnetic field with the help of electromagnetic coil in combination with permanent magnets. Based on the determined maximum and minimum limit loads required for a rotorcraft crashworthy seat attenuation system, the design parameters of the permanent magnets and electromagnetic coil can be optimized. Due to existing magnetic bias in the damper system, continuously varying attenuation is possible with a smaller, light weight electromagnetic coil design. In addition, in case of electric power loss, this damper device would act as a passive device providing the required load attenuation for a 50thpercentile occupant. Reference [14] has a detailed report of the development of a fail-safe rotary vane MREA and component testing.

In this paper, an analytical evaluation technique is presented to determine the performance benefits of adaptive damper devices as compared to passive energy absorbers. This analysis method can help to fine tune the design of these adaptive systems for different crash scenarios. This model can also help in evaluating control algorithms that can be used in rotorcraft crashworthy seat adaptive systems. In this study, a detailed finite-element seat-occupant system level model has been developed for crash injury assessment simulation. Typical rotorcraft crash pulses, as recommended by rotorcraft crashworthiness requirements are used to assess crash injuries in different segments of the body of the seated occupant. The injury criteria and tolerance levels for the biomechanical effects are discussed for the most commonly identified vulnerable body region, mainly focusing on spinal column injuries as indicated by thoracic lumbar loads.

II. MODEL DEVELOPMENT

A crash sled model, as shown in Figure 2 was developed. The sled model uses a Hybrid III ATD (Anthropomorphic Test Device) crash dummy finite-element model that is available from LSTC (Livermore Software Technology Corporation) [16]. The crash dummy finite-element model is compatible with LS-DYNA software, which is a nonlinear, large deformation impact dynamics analysis solver that was used to conduct simulations.

Seated Occupant Model

The Hybrid III finite element crash dummy model closely represents the Hybrid III Anthropomorphic Test Device (ATD) that is typically used in crash sled testing for injury assessment evaluations. The stroking seat model, shown in Figure 2, was modelled to have a maximum stroke of 15 inches before it hits the end-stop mechanism on the seat support rails. The maximum stroke limit of 15 inches is in line with the proposed hardware design of the seat for this research. A 5-point finite element seat belt was used to restrain the occupant model. The seat support structure, and occupant's foot-rest were modelled to simulate a typical seated occupant inside a helicopter cockpit. The occupant-seat system was developed for three different occupant sizes, namely, 5th percentile small female, 50th percentile mid-size male, and 95th percentile large male to study the performance adequacy of seat dampers for different sized occupants for prescribed crash deceleration profile conditions.

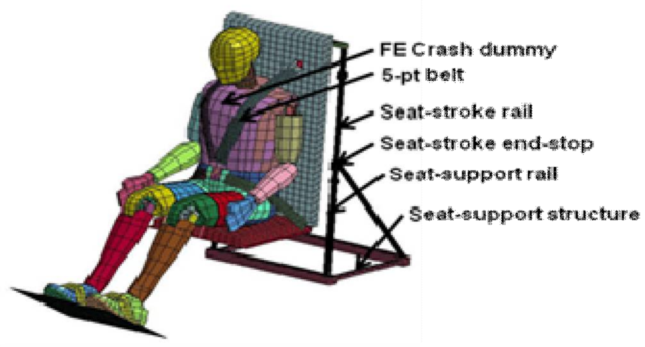


Figure 2. Finite Element seat-occupant system level model

Crash Pulse

Typical symmetrical triangular crash pulse per MIL-S-58095A [17], as shown in Figure 3 for vertical impacts of helicopters with ΔVz of 42ft/s for military rotorcraft was used to perform simulation runs. This crash impact velocity of 42 ft/s is represented as a triangular input with a deceleration input peak pulse of 46g - 51g within 36ms - 51ms according to MIL-S-58095A (see Figure 3).

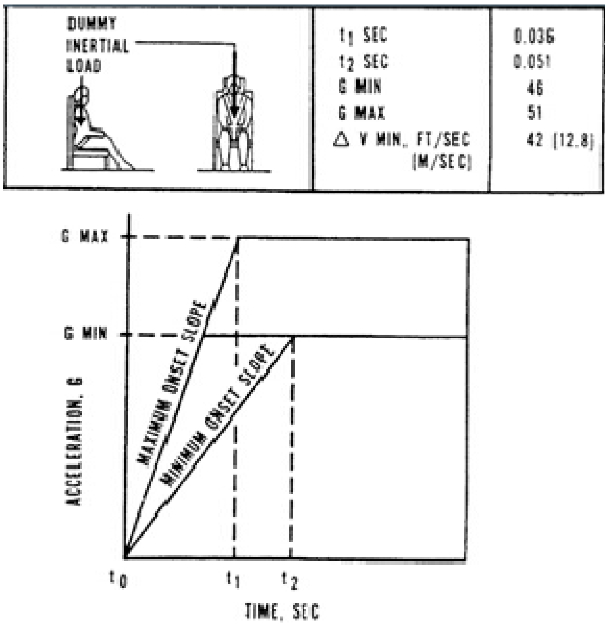
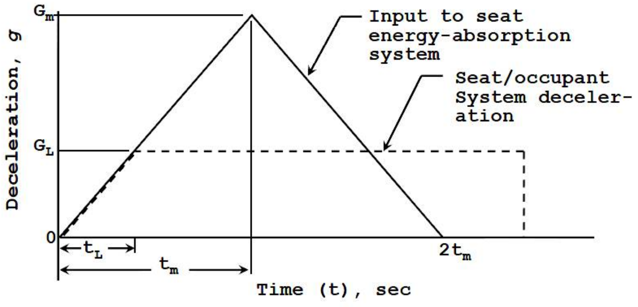


Figure 3. Triangular crash pulse for 42 ft/s sink rate [17]

Figure 4 shows the same vertical impact crash pulse with notional limit loads that can be obtained with a seat energy absorption system [15]. Load-deflection characteristics of seat dampers can be tuned in an adaptive manner to study the injury assessment evaluations for different sizes of occupants and different crash severities. The key injury assessment parameter such as the lumbar loads would be the primary focus in comparing the performance benefits of passive EA and adaptive EA. Published injury criteria for tolerable limits were used for comparison of performance between the passive and adaptive EAs.



G_m – maximum acceleration
G_L – limit acceleration (14.5g)

Figure 4. Typical rotorcraft pulse profile and deceleration limit for seated occupant [15]

III. PERFORMANCE CRITERIA

Different methods are available for assessing occupant injury probability. These include the Eiband criteria, the dynamic response index (DRI) and the peak measured lumbar spinal load. Both the Eiband criteria and DRI are based on the measured acceleration on the seat pan. They do not take into account the effects of the seat pan cushion or the occupant size. But, the measured lumbar load provides a direct measurement of the spinal column injury probability. Since, the main objective of incorporating the vertically stroking seat energy absorber is to mitigate or prevent spinal injuries, the lumbar load criterion is commonly used currently. Table 1 shows the lumbar load tolerances for various adult occupant sizes.

Table 1. Lumbar load limits as per JSSG-2010-7 [18]

Occupant Size	Lumbar Tolerance Load
5th %ile female	1281 lb (~5.70 KN)
50th %ile female	1610 lb (~7.16 KN)
50th %ile male	2065 lb (~9.19 KN)
95th %ile male	2534 lb (~11.27 KN)

On the other hand, Full Spectrum Crashworthiness Criteria for Rotorcraft, published by the U.S. Army Research, Development & Engineering Command, Aviation Applied Technology Directorate (RDECOM, AATD) [19] states more stringent injury performance criteria guidance for future occupant safety systems in rotorcraft. In this research, the injury criteria as stated in JSSG-2010-7 (Table 1) were used for performance evaluations.

IV. ENERGY ABSORBER LOAD PROFILE

For the passive EA representing a Fixed Load Energy Absorber (FLEA), a constant load-stroke profile as shown in Figure 5 was used. This basic EA load profile is designed to reach the desired limit based on a pre-set occupant size/weight setting as soon as possible and to remain at that limit load for the duration of the seat stroke without any further loading to the occupant. However, in practice, some small stroking distance is required to achieve the limit load due to the elastic properties of the EA, the EA attachments, and the seat frame. For the crash dynamic model simulation, the passive EA was modelled as reaching the limit load at 0.25 inch of stroke and keeping a constant limit load until the stroking hits the end-stop on the seat rails. This idealized passive EA load-stroke profile is shown in Figure 5. The stroking distance limits were set to a maximum of 15 inches on the seat model to represent proposed seat hardware design.

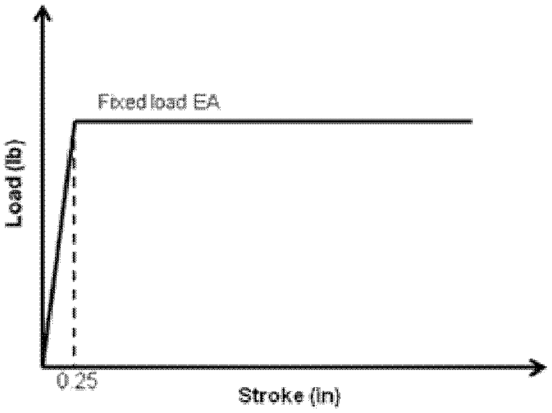


Figure 5. Passive EA load-stroke profile for modelling

Adaptive EA Component Testing

For the adaptive EA modelling, a linearly varying load-stroke profile to absorb the crash energy within the available stroke limit was used. The initial load level can be programmed to start with a load applicable to a 50th percentile male and then modulated with a linear increase or decrease based on occupant size/weight sensor on the seat as well as an accelerometer at the seat base measuring the crash severity level. Such an adaptive EA load-stroke profile as shown in Figure 6 was used for modelling purposes.

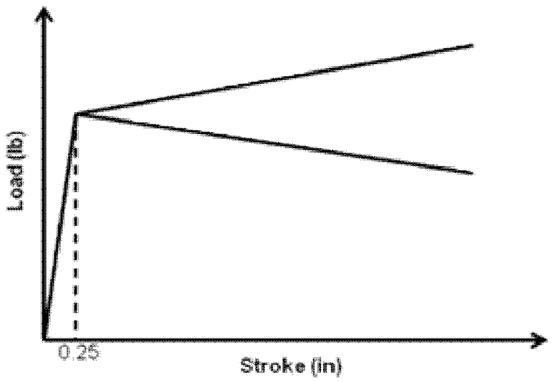


Figure 6. Adaptive EA load-stroke profile

Connected with this research project, an adaptive damper was developed using a rotary vane magnetorheological energy absorber (MREA) concept that is fail-safe (electric power fail-safe) [14]. The prototype Fail-safe Magnetorheological Energy Absorber (FSMREA) that was developed is shown in Figure 7. This device uses a combination of permanent magnet and electro-magnetic coil to achieve a continuously varying damper load capability by adjusting the current to the electro-magnet. A schematic sketch showing the cross-sectional view of the magnetic circuit for FSMREA is shown in Figure 8.

Figure 7. Prototype FSMREA hardware [14]

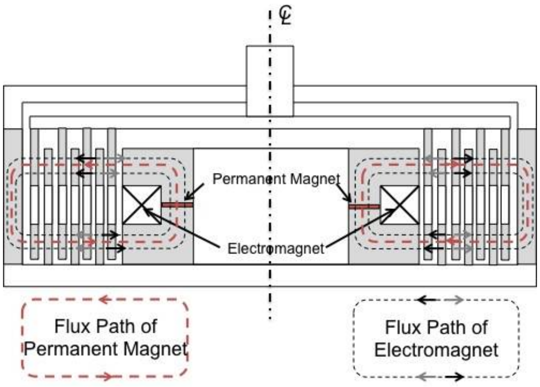


Figure 8. Cross-sectional view of magnetic circuit for FSMREA [14]

The FSMREA that was developed for a vertically stroking crew seat, was subjected to cyclic testing using the MTS machine to evaluate the linear motion behaviour of the FSMREA. The testing results were also used to verify the analytical force level range that could be possible with this hardware. Typical results of the force-displacement and force-velocity hysteresis behaviour at frequency of 1 Hz subjected to 5 different currents are presented in Figure9, in which the predicted results of the electro-magnetic flux simulations are also shown for comparison. It is shown that the experimental hysteresis behaviour matches the modelling results quite well. The varying force levels by adjusting current were used to determine the range of variability that is possible for the adaptive EA load-stroke profile in the finite-element based crash dynamic simulations.

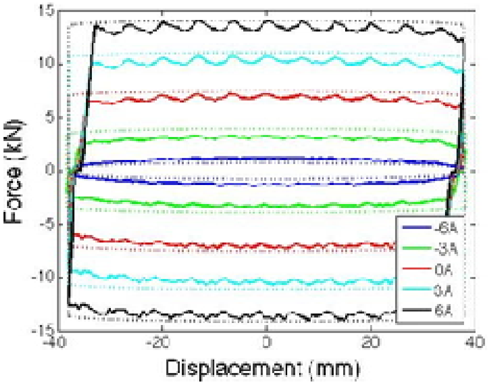
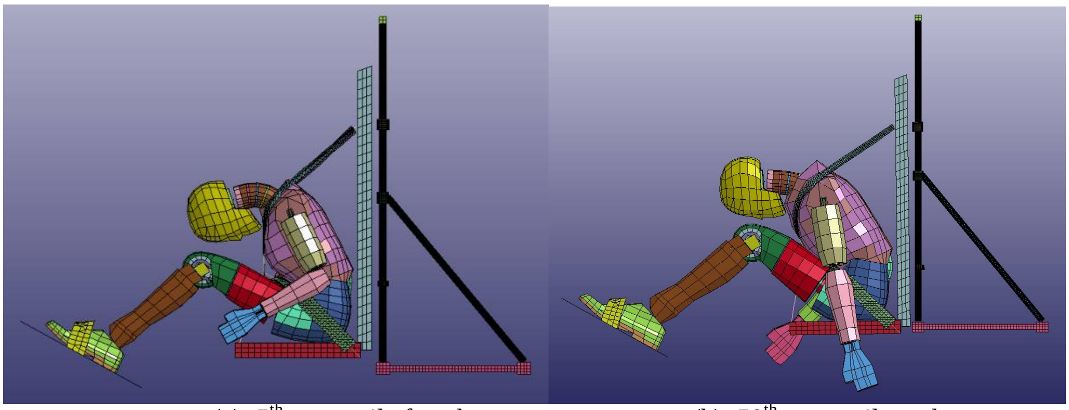


Figure 9. Hysteresis behaviour of FSMREA (solid lines-experimental; dotted lines – Model) [14]

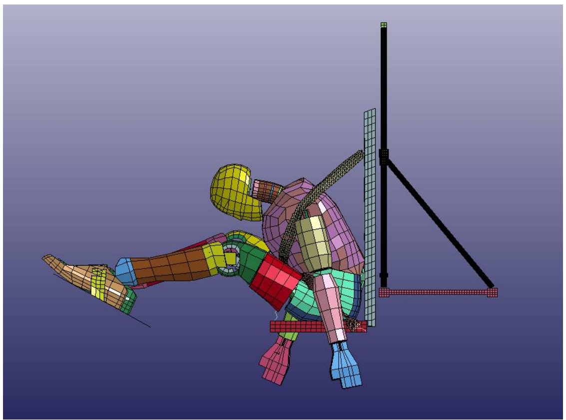
V. SIMULATION RESULTS AND DISCUSSION

The baseline simulations using the developed finite-element seat-occupant model was conducted utilizing the passive, fixed load energy absorber (FLEA) with a maximum possible stroke distance of 15 inches. Figure 10 shows the occupant kinematics of 5th percentile female, 50th percentile male, and 95th percentile male occupants from the crash dynamic simulations for a triangular crash pulse with a peak acceleration of 46g keeping the time of occurrence of peak acceleration at 51ms according to MIL-S-58095A.



(a) 5th percentile female

(b) 50th percentile male



(c) 95th percentile male

Figure 10. Occupant kinematics from simulation (passive EA)

For the same passive seat energy absorber, (FLEA), Figure 11 shows the dynamic seat stroke profiles for the three occupant cases. Figure 12 shows the lumbar load responses for the three different types of occupants for the passive seat energy absorber case. As stated earlier, the primary goal of this research is to establish a high fidelity finite-element based seat-occupant model that can be used to evaluate seat EAs, and aid in the optimized design of adaptive energy absorbers for rotorcraft crashworthy safety seat application. The developed models will be verified with test data and will be fine-tuned in the future efforts of this research. At present, to gain confidence with the model, the baseline analysis results were compared with test data published in reference [1] and good agreement in lumbar force data and seat stroke time history profile were noted for the case of 50th percentile male occupant. So, the developed model was further used to evaluate linearly varying adaptive seat energy absorber with load-stroke profiles as shown in Figure 6 to carry-out the feasibility study of mitigating lumbar loads for all three occupant sizes with the isosceles triangular crash pulse of maximum 46g's with a time duration of 102 ms (or time of maximum acceleration at 51ms as per MIL-S-58095A). In Figure 12, it is clearly shown that for the case of the 95th percentile male occupant, with the FLEA the stroke exceeds the design limit of 15 inches by hitting the end-stop on the seat rails resulting in a spike of lumbar load at around 120ms. With a continuously varying adaptive EA load profile, it could be possible to limit the lumbar load to a safe level within the available stroke limit of 15inches for the heavy 95th percentile male occupant case under the given crash severity condition. The established model after careful tuning with test data will be ultimately helpful in the evaluation of different types of control schemes for the efficient control of adaptive dampers to meet crew safety requirements for varying occupant sizes and vertical impact sink rates.

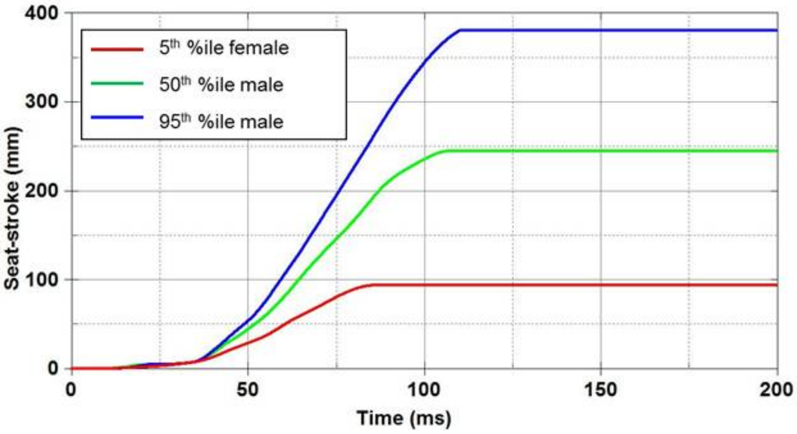


Figure 11. Dynamic seat stroke profiles from simulation (passive EA)

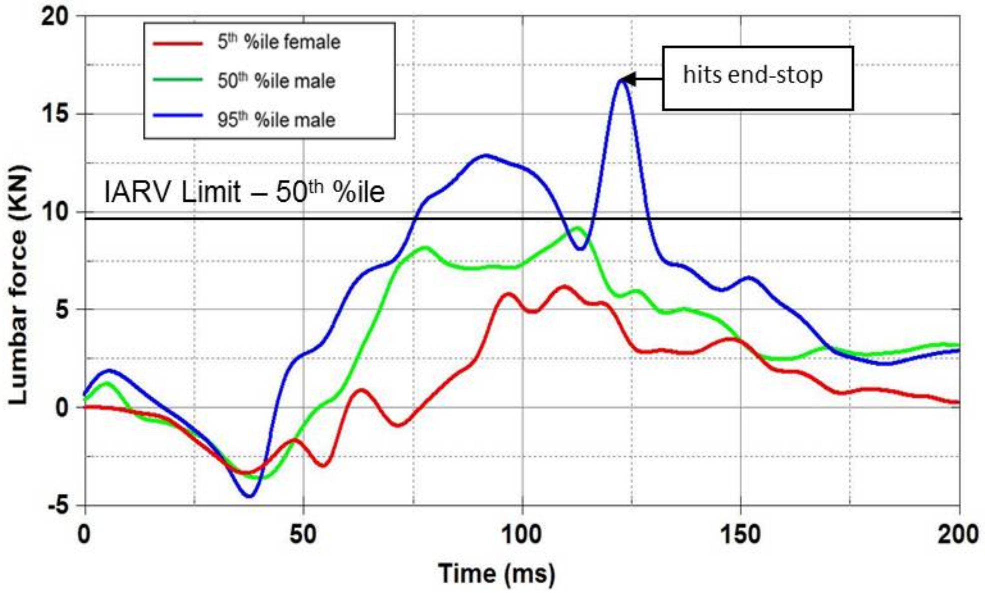


Figure 12. Lumbar load responses from baseline simulation (passive EA)

The simulation results, such as lumbar force vs. time and seat stroke vs. time, from the adaptive EA for the 5th percentile female occupant case are shown in Figures 13 and 14 and also compared with the passive EA case. The results show that it will be viable to efficiently manage the crash energy with a continuously varying linear adaptive load EA profile damper without exceeding the lumbar force limit and keeping the seat stroke within the allowed stroke limit.

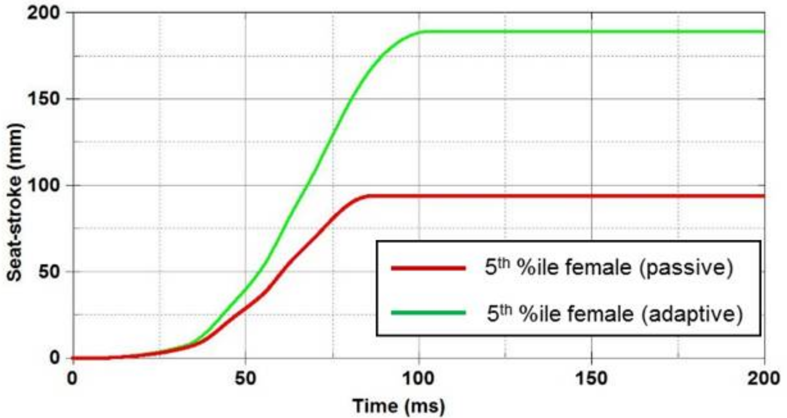


Figure 13. Dynamic seat stroke profiles from simulation (passive EA & adaptive EA – 5th percentile female case)

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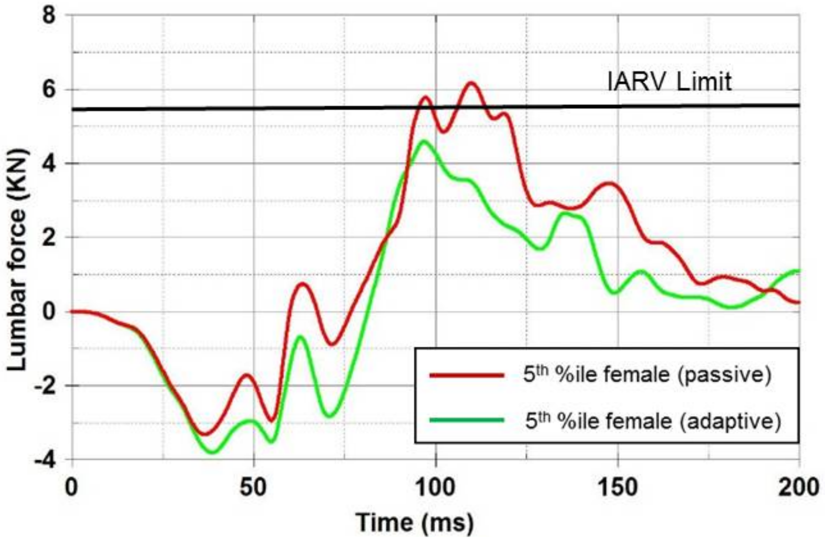

Figure 14. Lumbar load responses from simulation (passive EA & adaptive EA – 5th percentile female case)

The analysis results for the adaptive EA with a 95th percentile seated occupant are shown in Figures 15 and 16 and also compared with the results of the baseline case simulation. The Figures 15 and 16 show that it would be possible to design a continuously varying load EA profile damper that would be able to mitigate the lumbar force within the tolerance limit while keeping the seat stroke within the allowed design space.

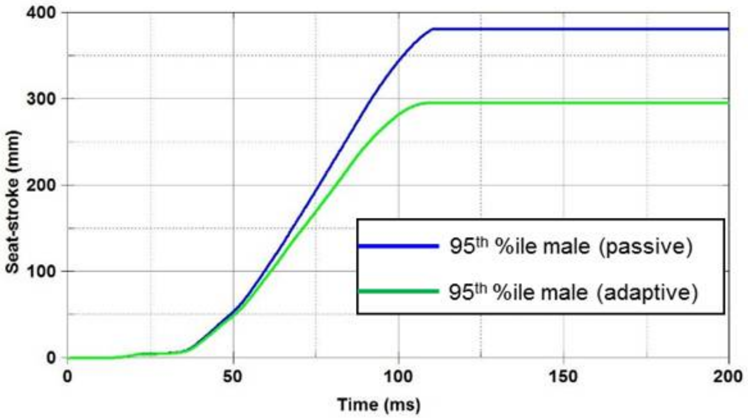

Figure 15. Dynamic seat stroke profiles from simulation (passive EA & adaptive EA – 95th percentile male case)

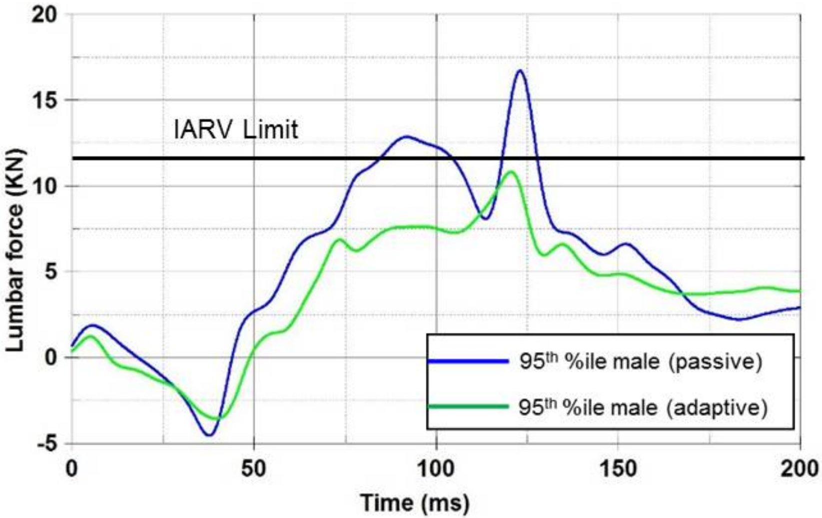

Figure 16. Lumbar load responses from simulation (passive EA & adaptive EA – 95th percentile male case)

VI. CONCLUSION

A finite-element based nonlinear dynamic model was developed for virtual crash evaluations of adaptive seat dampers to study their effectiveness in enhancing occupant protection during vertical crash landings of a helicopter. Baseline simulations with fixed load energy absorber showed that while this passive damper could be tuned for a 50th %ile occupant, it may not work adequately for a 5th%ile female occupant or a 95th %ile large male occupant. The results from the adaptive EA cases showed that it is viable to mitigate lumbar injury for varying occupant sizes/weights by using a continuously varying linear load-stroke profile energy absorber. Further correlation and tuning of this developed finite-element model will be accomplished after completing crash dynamic sled tests as part of this ongoing research work.

FUTURE WORK

System level dynamic crash sled testing is planned to evaluate the fail-safe rotary vane magnetorheological energy absorber integrated to a typical helicopter crew seat. The crew seat will also be integrated with a suitable control module to continuously vary the damper load as the seat strokes during the sled testing. After completing the sled tests, the developed seat-occupant finite element model will be verified and tuned with the test data. This model will then be used for future study and development of advanced, adaptive seat energy absorbers for crashworthy seats in military helicopters.

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