Assessing the Risk of Crew Injury Due to Dynamic Loads during Spaceflight

J. Somers[1], M. Gernhardt[2], N. Newby[1]
[1]Wyle Science, Technology & Engineering Group, Houston, TX
[2]NASA Johnson Space Center, Houston, TX

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Overview

- **NASA Environment**
  - Vehicles and Dynamics
  - Space Suits
  - Spaceflight Deconditioning
  - Injury Context
- **Acceptable Injury Risk**
- **Selecting the Right Anthropomorphic Test Device**
  - Critical Injury Definition
  - Injury Metrics
  - THOR

Crew Vehicle Comparison

Current System

Soyuz TMA-M

Multi-purpose Crew Vehicle Program

Orion

Commercial Crew Program

SpaceX Dragon

Boeing CCT-100

Introduction

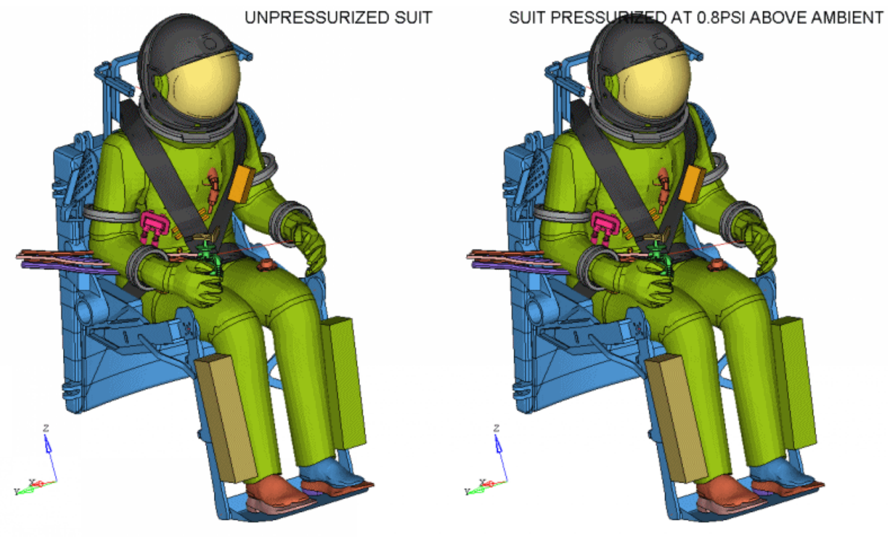
- **Dynamic Phases of Flight**
  - Launch
    - All proposed vehicles launch with crew laying on their backs (eyeballs in accelerations)
  - Abort
    - Primarily X-axis loads (Eyeballs in)
    - May have significant oscillatory components
  - Reentry
    - Primarily X-axis loads (Eyeballs in)
    - May have transient dynamics due to parachute deploy
  - Landing
    - The landing mode is specific to the vehicle design
      - Water Landing
      - Land Landing

NASA Occupant Protection Considerations

- **Anthropometrics**
  - 1st to 99th percentiles (current requirement)
- **Sex Differences**
- **Flail**
- **Suit-related issues**
  - Point loading, restraint interactions, blunt trauma from suit interaction, etc.
- **Crew Deconditioning**
  - Physiological effects of long duration spaceflight may lead to increased risk of injury
  - Loss of BMD for each month of exposure to microgravity – Extremely subject dependent
  - Muscle loss
- **Anatomical Localization & Severity of Injuries**
  - Crew must be able to perform certain tasks post-landing and not have permanent injury
- **Launch, Abort, Reentry and Landing Loads**
  - Multi-axial loading. Varies with each vehicle
  - Dynamic loading occurs on every flight, so low risk of injury needed
  - Must consider nominal and off-nominal conditions

Suit Considerations

- **Helmet Mass**
  - Helmet can increase neck loads and moments
  - Without proper padding, head can impact interior of helmet
- **Rigid Elements**
  - Previous research has shown that rigid suit elements such as mobility bearing can case injury
- **Suit Pressurization**
  - Although the suit should not be inflated at landing, residual pressure may exist and could interfere with the restraints
  - Previous pressurized suit testing during Apollo resulted in injury to the subject



Spaceflight Deconditioning

- **Prolonged exposure to reduced gravity affects bone and muscle**
- **Bone mineral density (BMD) has been shown to decrease by ~1% per month**
- **Recent improvements to exercise have reduced the loss of BMD**
- **Even so, there are significant changes in bone architecture, particularly in the trabecular bone**
- **<u>Varies significantly by subject</u>**
- **Unclear how these changes affect returning crewmember's <u>tolerance to impact</u>**

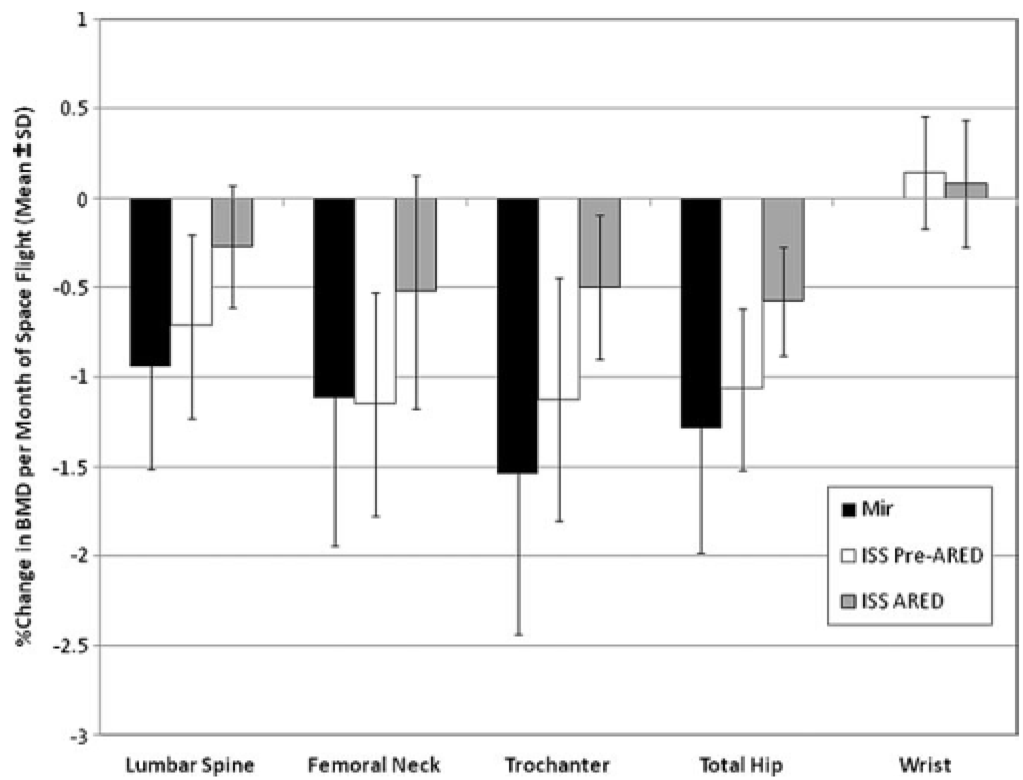
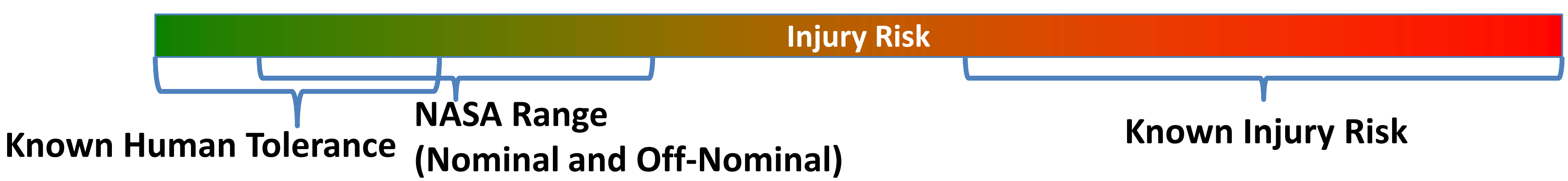


Figure reproduced from J. D. Sibonga, "Spaceflight-induced bone loss: is there an osteoporosis risk?," Curr Osteoporos Rep, vol. 11, pp. 92-8, Jun 2013.

Injury Risk

Environment	P(impact)	P(inj)	P(total)
Military	Low	Medium	Low
Automotive	Remote	Med-High	Low
Race Car	Low	Medium	Low
Spaceflight	Certain	Low	Low

- **The Brinkley Dynamic Response Criterion is based on human volunteer testing**
  - Low risk level is based on human tolerance, but was not developed using statistical methods
- **Current ATD injury assessment reference values (IARVs) are based on automotive injury risk functions**
  - These functions are optimized for more severe and higher probabilities of injury than are needed for NASA use
  - Less information is available between the range of known human tolerance and injury risk



Operationally Relevant Injury Scale

- The Operationally Relevant Injury Scale (ORIS) was developed to address NASA's unique operational environment. Because the Abbreviated Injury Scale (AIS) was developed for passenger car incidents, it was determined that a new injury classification system was needed for NASA. The new scale combines the injury severity from the AIS, a measure of a crewmember's ability to self-egress, and a measure to estimate the time to return to flight status. All three factors are used to calculate the final classification of the injury.
- Example: A clavicle fracture (AIS=2) could prevent crewmembers from egressing (SE = 3), so it would be classified as a Class III Injury using the ORIS

Injury Severity (IS)

0	1	2	3	4	5	6
None	Minor	Moderate	Serious	Severe	Critical	Maximal

Self-Egress Capability (SE)

0	1	2	3	4
No Impact	Able with Minor Impact (within req)	Able with Major Impact (not within req)	Unable without assistance	Unable, requires rescue and/or stabilization

Return to Flight Status Estimate (FS)

0	1	2	3	4
No Delay in Return	Short Delay in Return (<3mo.)	Intermediate Delay in Return (<1y)	Long Delay in Return (>1y)	Ended Flight Status/ DQ'd

Operationally Relevant Injury Class

0	I	II	III	IV
No Injury	Minor Injury	Moderate Injury	Severe Injury	Life-Threatening or Fatal Injury

Acceptable Risk

- **An expert panel was convened to determine what level of injury would be acceptable for NASA. The team used a systematic approach to buy down the risk to an acceptable level for nominal and off-nominal scenarios. To provide context, the team considered other analogous environments such as previous spaceflight, military aircraft, and automotive race cars. To assist in understanding the consequences of injury, the team considered generic tasks that crewmembers would be required to perform after landing.**
- **Once the team reviewed this information, the highest risk that would be acceptable was determined. This risk was then bought down using driving criteria, such as: ethical, medical, political, and programmatic considerations**

	Injuries Per Crash or Off-Nominal Landing				Injuries Per Sortie (Exposure Risk)			
Program	Class I	Class II	Class III	Class IV	Class I	Class II	Class III	Class IV
NASCAR	0.36%	0.58%	0.39%	0.04%	0.02%	0.03%	0.02%	0.00%
IRL	1.58%	2.28%	2.46%	0.35%	0.07%	0.09%	0.10%	0.01%
USAF Fixed Wing	57.0%	5.6%	7.0%	8.5%	0.006%	0.001%	0.001%	0.001%
USN Rotary Wing	59.27%		17.16%	23.57%	0.054%		0.015%	0.021%
USN Fixed Wing	68.4%		12.3%	19.3%	0.09%		0.02%	0.03%
USA Rotary Wing	36%	40%	9%	16%	0.0027%	0.0029%	0.0007%	0.0012%
USA Fixed Wing	48%	35%	14%	3%	0.040%	0.030%	0.012%	0.002%
Shuttle	N/A	N/A	N/A	N/A	0.75%	0%	0%	0.88%
Soyuz	15.9%	1.6%	0%	1.6%	4.1%	0.4%	0%	0.4%

Injury Description	*Injury Class*	*Nominal Probability of Injury*	*Off-Nominal Probability of Injury*
Minor	I	4.8%	19.1%
Moderate	II	1.0%	3.9%
Severe	III	0.27%	1.1 %
Life-Threatening	IV	0.03%	0.11%

Injury Assessment Method Comparison

	Humans		Human Surrogates			Numerical Models		
	Human Volunteers	Human Exposure	PMHS	ATD[2]	Animal	Brinkley Dynamic Response Model	ATD[2] Numerical Model	Human Numerical Models
Extrinsic Injury Risk Factors								
Vehicle Dynamic Profile	Yes	No[3]	Yes	Yes	Yes	Yes	Yes	Yes
Seat & Restraints	Yes	No[3]	Yes	Yes	No	No[4]	Yes	Yes
Suit & Helmet	Yes	No[3]	Yes	No[5]	Partial	No[4]	Yes	Yes
Intrinsic Injury Risk Factors								
Age	Yes	No[3]	No[6]	No	No	No	No	Possible[7]
Gender	Yes	No[3]	Yes	No	No	No	No	Yes
Anthropometry	Yes	No[3]	Yes	Yes	No	No	Yes	Yes
Spaceflight Deconditioning	No	No	Possible[8]	No	Yes	No	No	Possible[7]
Other Considerations								
Anatomy	Yes	Yes	Yes	Partial	No	No	Partial	Yes
Physiologic Response	Yes	Yes	No	No	Yes	No	No	Yes
Injurious Testing	No[3]	Yes[3]	Yes	Yes	Yes	Yes	Yes	Yes
Direct Observation of Injury	No	Yes	Yes	No	Yes	No	No	No
Technology Readiness Level[9]	High	High	High	High	High	High	Moderate[9]	Low

[2] Anthropomorphic Test Devices
[3] Not possible prospectively
[4] The Brinkley Dynamic Response Model was validated using specific seat and restraint setups and dynamics. The model may not predict injury accurately when extrapolating beyond this setup and dynamics.
[5] Not possible to assess localized injury potential
[6] Although possible prospectively, very difficult in practice due to limited subject pools
[7] Currently Available Human numerical models do not specifically address these factors, but could be modified to simulate the increased risk of injury
[8] Selection criteria could be used to select only subjects with similar bone mineral density (BMD), although this is not a true representation of spaceflight deconditioning.
[9] Technology Readiness Level (TRL) is a measure of how ready each method is for immediate NASA use. ATD models are at various levels of TRL depending on the solver, ATD family and size

Critical Injury Definition

- **Working with experts within NASA, the team developed a list of "critical" injuries. This list of injuries is not all inclusive, nor is it a list of "expected" injuries.**

- **Instead, the list is intended to be comprehensive, such that if the risk for each injury is mitigated, then the risk for other related injuries would also be mitigated.**

- **The list of injuries was also divided anatomically to ensure that every region of the body was represented.**

Region	***Injury***
Head	Concussion w/o LOC Concussion w/ LOC Skull Fracture TBI
Face	Eye Ear Fracture
Chest	Rib Fracture Lung Contusion Hemothorax Pneumothorax Hemopneumothorax
Upper Extremity	Shoulder Dislocation Joint Injury Skeletal Fracture
Lower Extremity	Joint Injury Fracture
Spine	Brachial Plexus injury Cord Contusion Fracture Herniated Disc Disc Rupture

Selecting Injury Metrics and ATDs

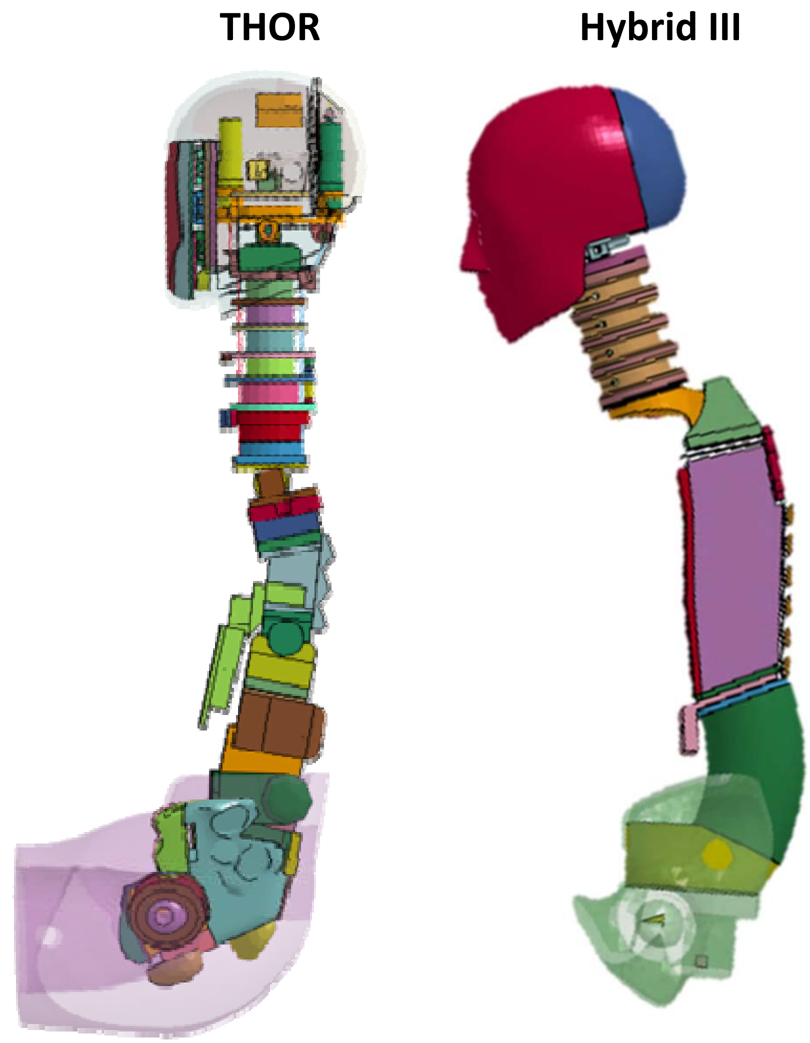
Collaborating with experts within NASA, the FAA, and NHTSA, the team developed a table mapping critical injuries to various injury metrics available for Anthropomorphic Test Devices (ATDs or crash test dummies). Using this framework, the THOR ATD was selected for use.

H – Hybrid III
T – THOR
W - WorldSID
X – Design Constraint

	Head Injury	Facial Trauma	Cervical Spine Trauma	Blunt Trauma	Lung Contusion	Rib Fracture	Hemo/Pneumo-thorax	Upper Extremity Joint Injury	Upper Extremity Fracture	Thoracic Spine Trauma	Lumbar Spine Trauma	Lower Extremity Joint Injury	Lower Extremity Fracture
HIC36	T/H												
BRIC	T/H												
Neck Axial Tension			T/H										
Neck Axial Compression			T/H										
Max Chest Deflection					T	T	T						
Lateral Shoulder Force (Contact)					T/W	T/W	T/W	T/W	T/W				
Acetabular Lateral Force												T	T
Lumbar Axial Compression										T/H	T/H		
Ankle Moments												T	
Contact Limits / Restraints (Design Constraint)		X		X				X	X			X	X

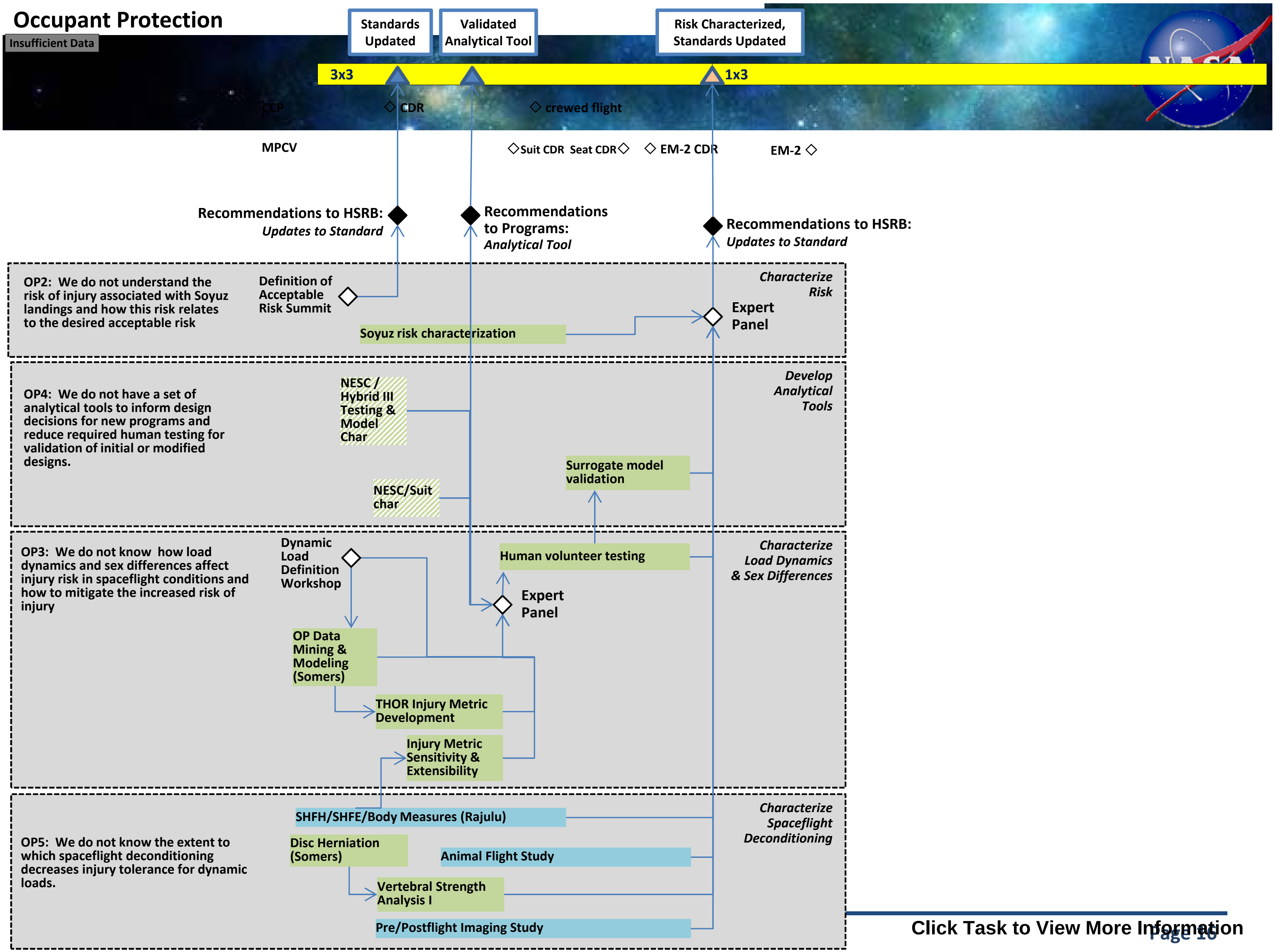
THOR

- **Benefits for NASA**
  - Improved biofidelity
  - Better multi-axial response
  - More sensitive to lower energy dynamics
  - More instrumentation
  - Appropriate seating posture for spaceflight applications
- **Limitations for NASA**
  - Limited Availability
  - Cost
  - Only available in one size



Summary

- **The spaceflight dynamic environment is unique**
  - Loading direction
  - Low Injury Risk
  - Space Suit
  - Spaceflight Deconditioning
- **To address these considerations, NASA has**
  - Developed a risk posture for impact injury
  - Identified critical Injuries
  - Identified appropriate ATD metrics to address these injuries
  - Selected the THOR for use in future Standards and Requirements



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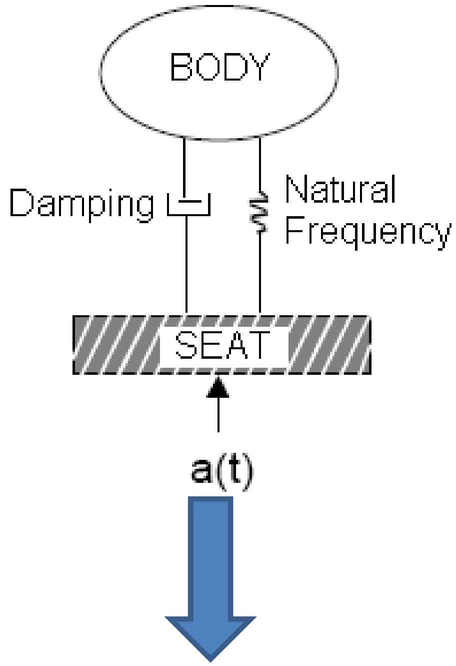
  - NASA Biomedical Research and Environmental Division
  - NASA Astronaut Office

Backup Slides

Current Occupant Protection Standards: Brinkley Dynamic Response Model

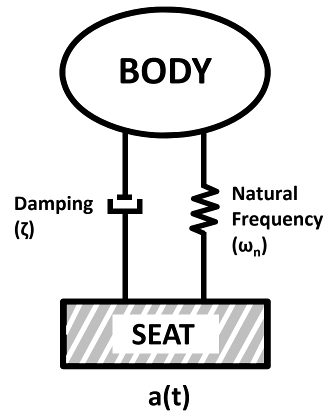
- **NASA currently uses the Brinkley Model for Occupant Protection**
  - Found in NASA-STD-3001 Vol II, HSIR, and Commercial Crew Requirements
- **Drawbacks:**
  - Likely too simple a model of a complex dynamic system
  - Estimates the likelihood of an injury, not the nature or severity of an injury
  - Does not account for the suit (extra head supported helmet mass, rigid suit elements, etc.)
  - Injury levels not determined using statistical approaches
  - Is not sensitive to changes in seat/suit design
  - Model based largely on young, male, military pilots
    - Does not account for age, gender, anthropomorphic differences
    - Does not account for spaceflight deconditioning
- **New model with higher biofidelity is needed to replace the Brinkley Model**
  - Model development will be based on:
    - Data mining from relevant environments
    - Dummy testing
    - Mathematical modeling
    - Human Testing

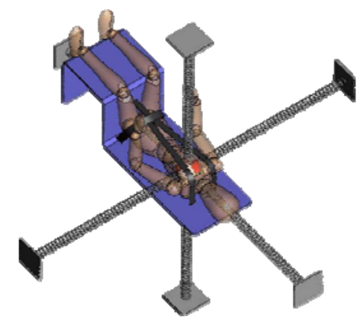


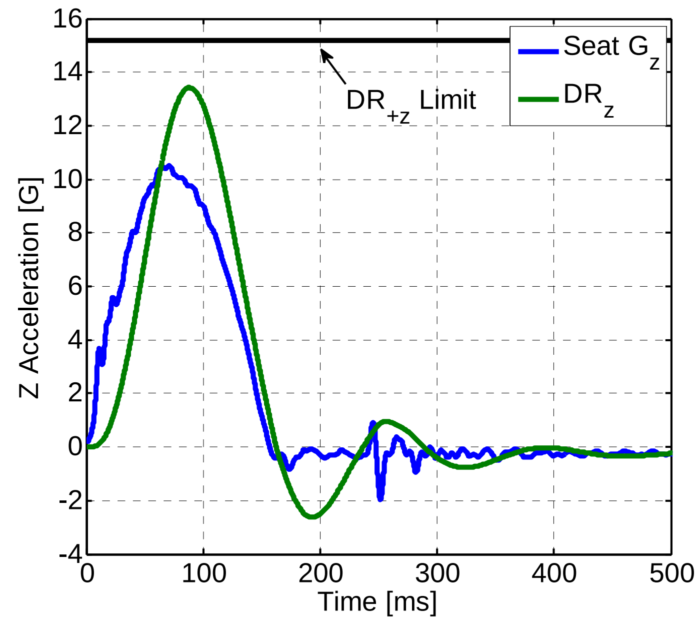
Brinkley Dynamic Response Criterion (BDRC)

- **Dynamic Response (DR)**
  - Estimates the acceleration of the human body
  - A single degree of freedom lumped mass model
  - Calculated independently in each direction
  - Responses are highly specific for seat used in development
- **Injury Risk Criterion (β)**
  - Preset DR limits in each direction estimate the injury risk
  - Limits based on limited statistical analysis of injury data
  - Estimates an injury risk but not severity
    - Low: 0.05 to 0.5%
    - Moderate: 0.5 to 5%
    - High: 5 to 50%
- **Model Accuracy Varies by Direction**

Direction	DR (Response)	β (Injury Risk)
+X (rear)	Insufficient data, so –X model used	Human injury exposure
-X (frontal)	17 male subjects only at 10G, age 22-35	Human injury exposure
±Y (lateral)	11 male, 2 female, only at 8G, age 22-34	Expert opinion
+Z (spinal)	57 yo cadaver (ω_n) and 8 males (ζ), age 29-47	Ejection injury rates
-Z (headward)	11 male, 1 female, only at 10G, ages 22-37	Expert opinion







Brinkley Model Ground Rules

- **The following ground rules are intended to assure a vehicle design meets the underlying assumptions necessary to apply the Brinkley Dynamic Response Model (BDR)**
- **Proper restraint**
  - The BDR was developed with a specific restraint configuration. Similar restraints must be correctly used to apply the model
- **Flail considerations**
  - The model was developed with arm and leg restraints. Injury due to flail is not captured by the BDR injury prediction, so flail protection is required in addition to the BDR
- **Seating support**
  - The model was developed with data obtained through human subject testing in specific seat geometry. Changes in seat geometry has been shown to increase the risk of injury (not captured in model predictions).
- **Amplification**
  - Improper seat cushioning has been demonstrated to cause amplification of loads transmitted to the crewmembers which can invalidate the BDR predictions
- **Suit Considerations**
  - Research and testing have shown that suit elements (e.g. metallic mobility joints, helmets, etc.) can produce injuries not predicted by the model.
- **Deconditioning**
  - Additional deconditioning factors are needed to protect crews due to long-duration spaceflight deconditioning (unless countermeasures are demonstrated to mitigate the effects on impact tolerance)

Brinkley Model Limitations

- **Even with the ground rules, there are limitations of the model that necessitate supplemental requirements**
- **Model validation**
  - The model is well validated in some directions, but not others
- **Sex differences**
  - The model was developed primarily with young, male military volunteers. Females are known to be at greater risk of injury (particularly in the neck)
- **Age effects**
  - Older occupants are at a greater risk of injury due primarily to changes in BMD.
  - We feel this risk is controlled by the current BMD flight selection standards
- **Anthropometry effects**
  - Smaller occupants have a greater risk of some particular injury given the same dynamics
- **Military training**
  - Military subjects have been shown to have a 15-20% higher BMD than the general population.
  - Because astronauts are more like the military population than the general population, this risk is believed to be controlled
- **Head Supported Mass / Helmet Mass**
  - The helmet can be a source of injury if it is not within the original constraints used during model development (Mercury helmet was used in many of the original tests)

- **Current approach is to address these limitations using the Hybrid III Anthropomorphic Test Device (ATD)**

Hybrid III Anthropomorphic Test Device (ATD)

- **The Hybrid III was developed in the 1970's for frontal car crash testing**
- **It has been adapted over the years for various industries**
- **Several configurations are currently available including**
  - Available in 5th female, 50th male and 95th male adult sizes
  - Straight and curved spine designs
  - Sitting and articulating pelvis designs
  - Various heads available

- **Several commercial numerical models are available for the Hybrid III**
  - COTS FE models of ATDs do not include some of the configuration options
  - Evaluate of the fidelity of the various COTS models is needed
  - FE ATD models which include pressure suit elements do not currently exist
- **Limitations**
  - The Hybrid III is not intended for lateral use
  - The neck responses are not biofidelic in any direction
  - Chest is very stiff

	Height	Weight
5th Female	5'	110lb.
95th Male	6'2"	223 lb.

- **New Occupant Protection requirements levied on MPCV and CCP include the use of the 5th and 95th percentile Hybrid III**
  - Further investigation of sensitivities to variations in ATD configurations, seated versus articulated pelvis and straight versus curved spine, is needed

Hybrid III Limits

Injury Assessment Reference Values (IARV) Limits

ATD Metric	ATD Size[1]	Non-Deconditioned		Deconditioned	
		Nominal	Off-Nominal	Nominal	Off-Nominal
HIC 15	5th Female	375	525	375	525
	95th Male	325	450	325	450
Head Rotational Acceleration [rad/sec^2]	5th Female	2,500	4,200	2,500	4,200
	95th Male	2,100	3,600	2,100	3,600
N_{ij}	5th Female	0.5	0.5	0.4	0.4
	95th Male	0.5	0.5	0.4	0.4
Peak Neck Axial Tension Force [N][2]	5th Female	890 – 1,840		765 – 1,580	
	95th Male	2,000 – 3,390		1,720 – 2,910	
Peak Neck Axial Compression Force [N][2]	5th Female	890 – 2,310		765 – 1,990	
	95th Male	2,000 – 4,360		1,720 – 3,750	
Flail	5th Female	Pass			
	95th Male	Pass			
Peak Lumbar Axial Compression [N][3]	5th Female	3,500	4,200	3,000	3,600
	95th Male	6,600	7,800	5,700	6,700

[1]The following ATDs shall be used to evaluate the metrics:

5th percentile female automotive Hybrid III

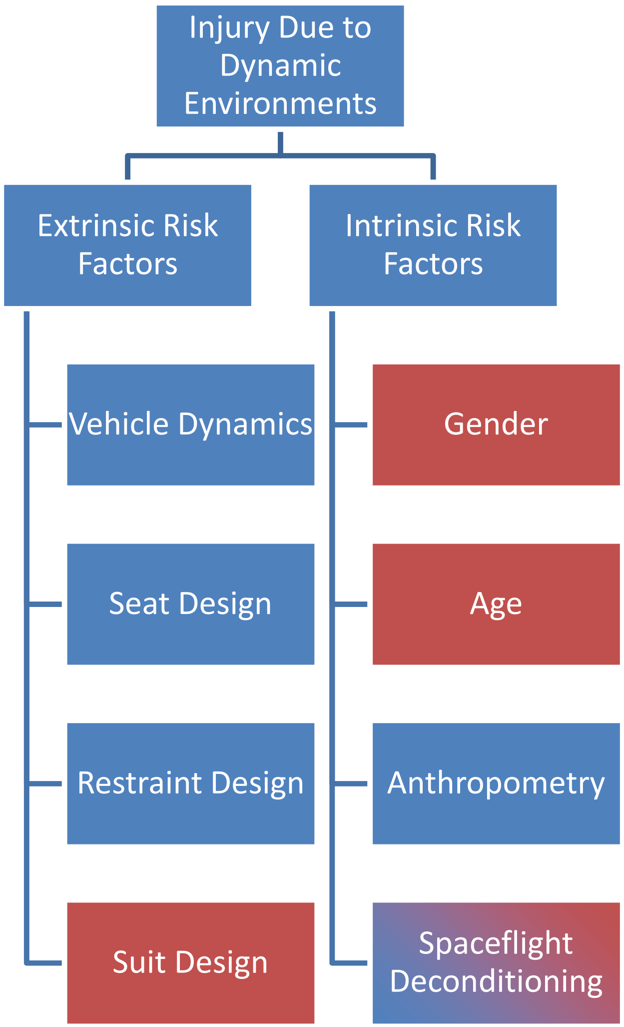
95th percentile male automotive Hybrid III with straight spine

[2]Values in table are evaluated at varying time durations as specified in J

[3]Required only if Occupant Response Amplification ground rule is not met by the design

Limitations with Current Approach

- **Current requirements do not adequately address all of the risk factors (red boxes)**
  - BDRC primarily addresses vehicle dynamics
  - Hybrid III ATD addresses vehicle dynamics, seat and restraint design, and anthropometry
  - FE ATD models which include pressure suit elements do not currently exist
  - Current mitigations do not directly address gender and age differences
  - Spaceflight deconditioning factors are based on DXA data and may not be indicative of the true risk
- **Because of these limitations, certification for flight requires human testing for ALL vehicle designs (per SA-13-061 HMTA Position Memo)**
- **Current operational experience with Soyuz shows a risk of injury due to dynamic loads to be >1% (Partially controlled)**
  - More information is needed to understand how the current requirements relate to the Soyuz and whether the current injury rate is predicted by these requirements



Reentry and Landing Scenarios