Critical Review of Head and Neck Injury Criteria in the Escape Community

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MBA Approach to Influencing New Programmes

1) **What problem are we trying to solve?** Both fatality-wise and injury-severity-wise.
   - What injury mechanism(s) or predominant cause(s) for fatality is the programme trying to mitigate?
   - Agree to a set of **anatomical regions** that must form part of the CES physiological assessment and their associated **injury mechanism** as part of a **specific escape phase**

2) What recordable physiological data or injury metrics exist to assess such a risk?
   - Biomechanical attributes (strengths and limitations/caveats)
   - Are these predicting a fair real-world representation of the assessed risk?
   - Verification methods (synthetic versus physical and their limitations)

3) What should be the airworthiness criteria for assessing that risk?

4) What is deemed an “acceptable” risk for that injury?
   - Injury thresholds; injury criteria limits based on crew anthropometry
   - Relaxation of limits based on speed and hazard risk assessments

6) What seat performance and design versus physiological trade off exist?

Injury Criteria Key Biomechanical Attributes

- Key biomechanical attributes for physiological injury criteria have been identified:
  - Developed within an escape loading context
  - Developed for a specific type of injury
  - Probability distribution function of injury risk (for duty holders and safety risk assessments)
  - Validated against in-service escape data
  - Account for occupant size

- Understanding of the biomechanical foundation of physiological requirements and capabilities of verification methods (crash test dummies)
  - i.e., specific conditions used to develop the criteria, data limitations, or caveats to be aware of.
  - Helps identify the optimal airworthiness requirements to be used to evaluate occupant and system safety
  - Decision makers to be best equipped to gauge the real human risk accordingly

Head and Neck Injury Mechanisms / Risks

Initiation and Propulsion

- Retraction (if Out of Position crew)
- Tension/Flexion (Catapult)
- Tension (Windblast)
- Compression/Flexion (head impact through canopy escape)
- Head linear and angular accelerations (recoil into headrest)

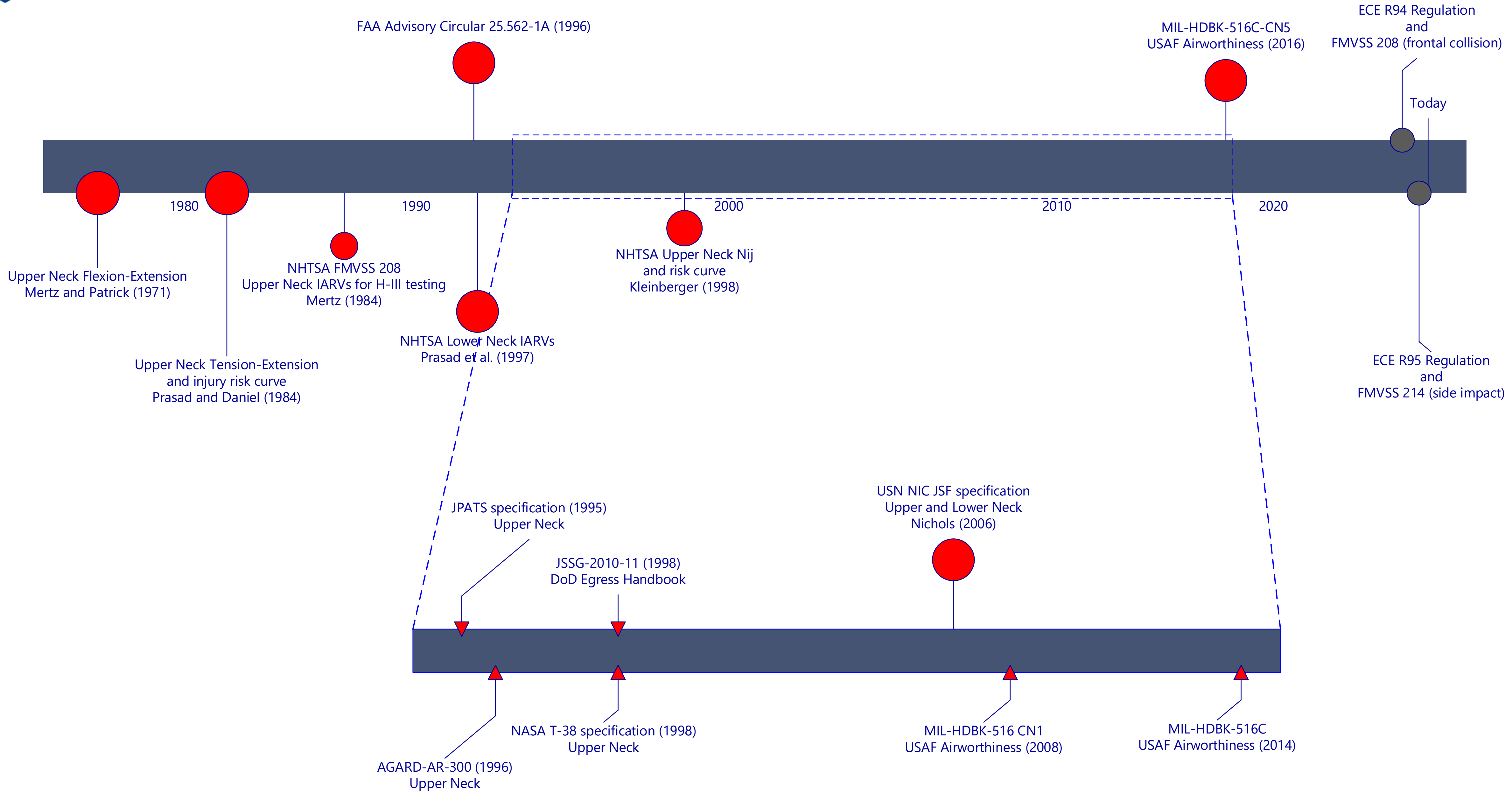
Drogue Stabilisation

- -Gx deceleration
- Seat stability (pitch, yaw, roll)
- Head recoil into headrest

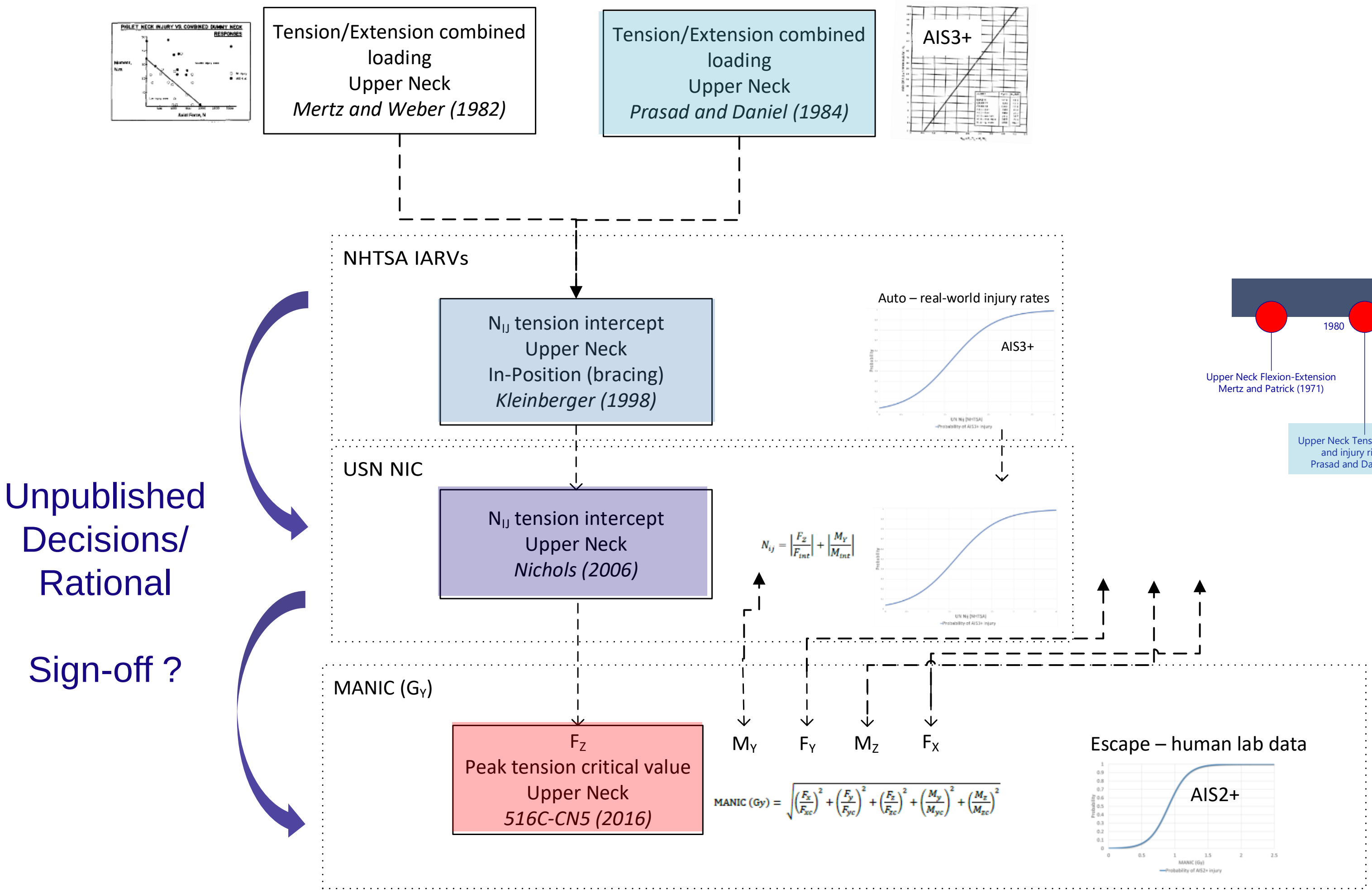
Parachute Deployment and Inflation

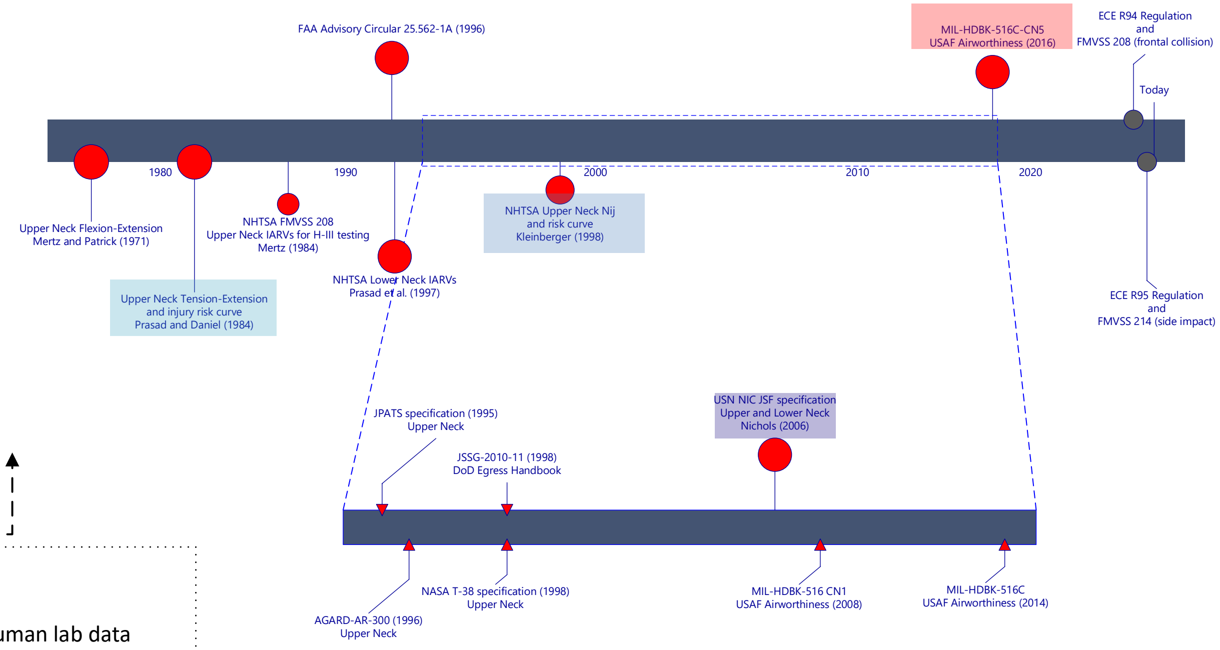
- Parachute deployment
- Parachute opening shock
- Parachute risers out of neck alignment
- Parachute riser snag on helmet

Requirements Historical Timeline



Example of Requirement Biomechanical Foundation Traceability (1/2)





Example of Requirement Biomechanical Foundation Traceability (2/2)

YES
PARTIALLY
NO

			Accounts for occupant size?	Accounts for multi-axiality?	Associated probability of injury risk function (AIS)?	Developed with legacy helmets, HMDs or none?	Applicable to human (H) or manikin (M) measurements?	Biomechanical rationale for limits?	Developed with human data?	Developed with manikin data?	Developed with cadaver data?	Developed with animal data?	Developed within which industry?	Developed with real-world ejection data?	Developed with real-world automotive field data?	Accounts for muscle tone?	Validated against escape operational experience
Upper Neck	Mertz Flexion Corridor	Upper Corridor Moment	YES	NO	NO	None	H,M	YES	YES	YES	YES	NO	AUTO	NO	NO	NO	NO
		Lower Corridor Moment	YES	NO	NO	None	H,M	YES	YES	YES	YES	NO	AUTO	NO	NO	NO	NO
	Mertz Extension Corridor	Upper Corridor Moment	YES	NO	NO	None	H,M	YES	YES	YES	YES	NO	AUTO	NO	NO	NO	NO
		Lower Corridor Moment	YES	NO	NO	None	H,M	YES	YES	YES	YES	NO	AUTO	NO	NO	NO	NO
	Prasad/Daniel	NTE	YES	PARTIALLY	YES	None	M	YES	NO	YES	YES	YES	AUTO	NO	NO	YES	NO
	NHTSA Nij		YES	PARTIALLY	YES	None	M	YES	YES	YES	YES	YES	AUTO	NO	YES	YES	NO
	USN NIC	Nij intercept values	YES	PARTIALLY	PARTIALLY	Legacy	M	PARTIALLY	NHTSA				AV	NO	YES	YES	NO
	MANIC	MANIC (Gy)	YES	PARTIALLY	YES	HMD	H	YES	YES	NO	YES	NO	AV	NO	NO	NO	NO

Live Ejection versus Physical Test Data

- A total of **162 NACES ejections** in F-18s and T-45s
  - MANIC(G_Y) predicts a 44% probability of AIS2+ neck injury, even in the heart of the ejection envelope (50th crew at 250 knots)
  - **In-service injury rate**: discounting "First Aid" neck injuries due to ejection forces (<AIS2) and discounting through-canopy neck injury: = **1.7% risk of AIS2+ neck injury**
- **Why such a disparity?**
  - Metrics not validated against modern escape in-service data
  - Lack of biofidelity in ATDs
  - MANIC(Gy) has been derived from human data and a transfer function for ATDs has yet to be developed
- Ultimately we need to ensure **we are designing for humans** and not ATDs
- Injury risk functions need corroborating against modern seat performance for them to be a **useful injury risk evaluation tool** to work towards real design/technology safety needs
  - Need for in-service ejection medical data AIS-coding classification
- Importance of physical testing in the **middle of the envelope** (speed) with **50th-ile** dummies

Critique of Escape Physiological Requirements

- Historical review, requirements traceability, live ejection and test data analysis have led Martin-Baker to put together a set of **recommendations** for injury criteria.
  - Biomechanical foundation rationale, key biomechanical attributes, limitations or caveats, as well any proposed direct amendments identified, and future work for consideration with various programme dependencies.

				Key Attributes											
Escape Phase	Body Region - Injury Mechanism	Injury Criterion	Nude weight (lower and upper bounds)	Attribute 1	Attribute 2	Attribute 3	Attribute 4	Attribute 5	Attribute 6	Strengths	Limitations	Future Work - Proposed Amendments	Physiological versus Design Trade Offs	Verification Method	Validation / In-Service (Human injury risk)

Fit-for-use "as is"

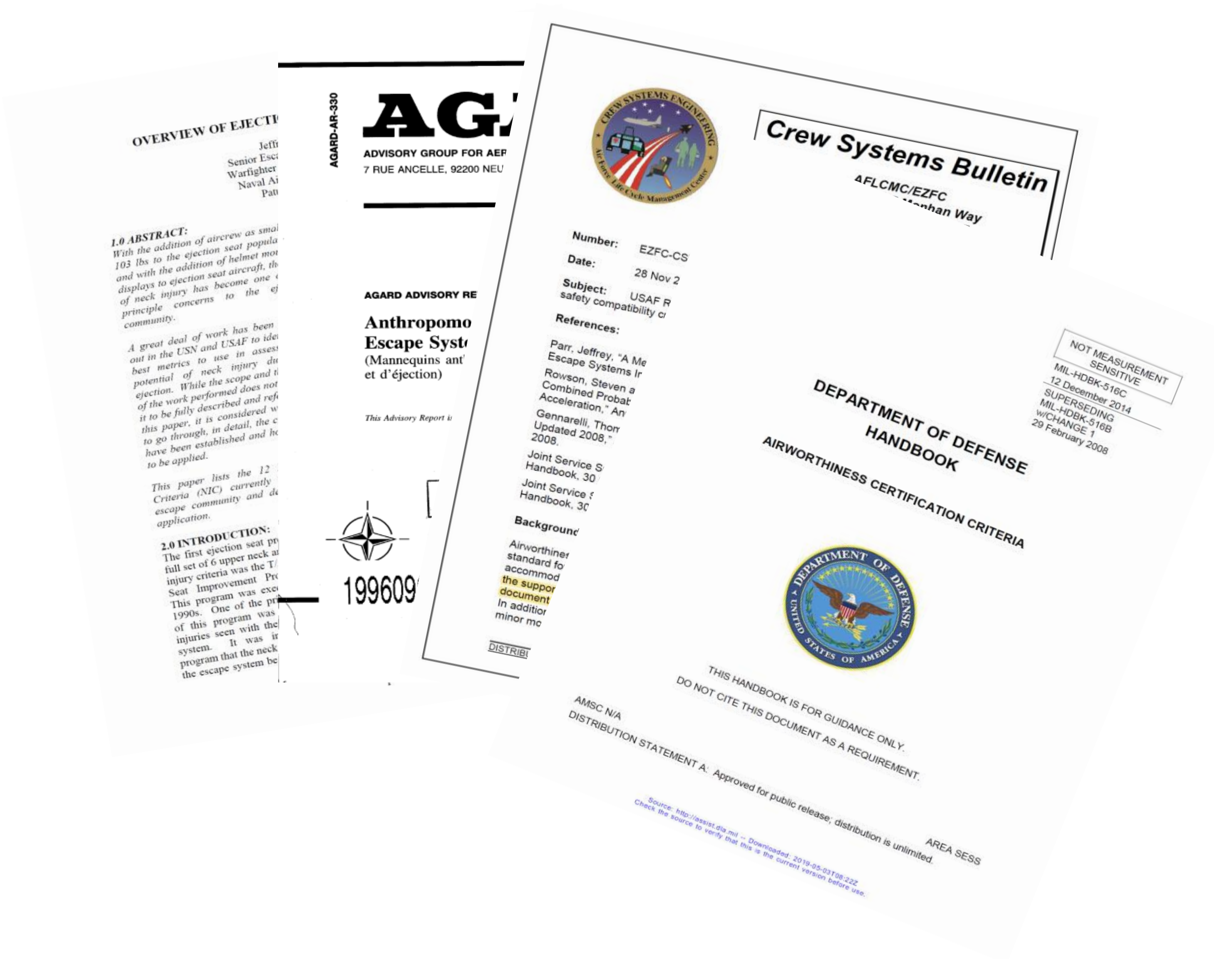
Recommend fit-for-use, with identified amendments required and awareness of limitations/caveats

Recommend considering with further work needed

Do not recommend

Head and Neck Requirements on Martin-Baker Programmes

- Legacy programmes: no head and neck requirement
  - Even though some of these platforms fly with an HMD
  - Who underwrote that risk?
- Introduction of smallest occupant 103lbs Case 1 and HMDs
  - U.S. at the forefront of escape biomechanics research and head and neck injury metrics development
  - In close proximity with Airworthiness organisations
  - AFRL – USAARL – NAWCAD …
  - Who is the European counterpart?
- Plethora of H&N requirements (JPATS – T-38 – F-35 …)
  - Evolution (for the better?) -driven
  - Or due to disagreements, lack of common standard?
- However, none of them are predicting real-world in-service injury rates
  - Overly-conservative: closing the window opportunity in safe escape system design
  - Not to be used without further assessment
  - **Tread carefully, be aware, seek advice**

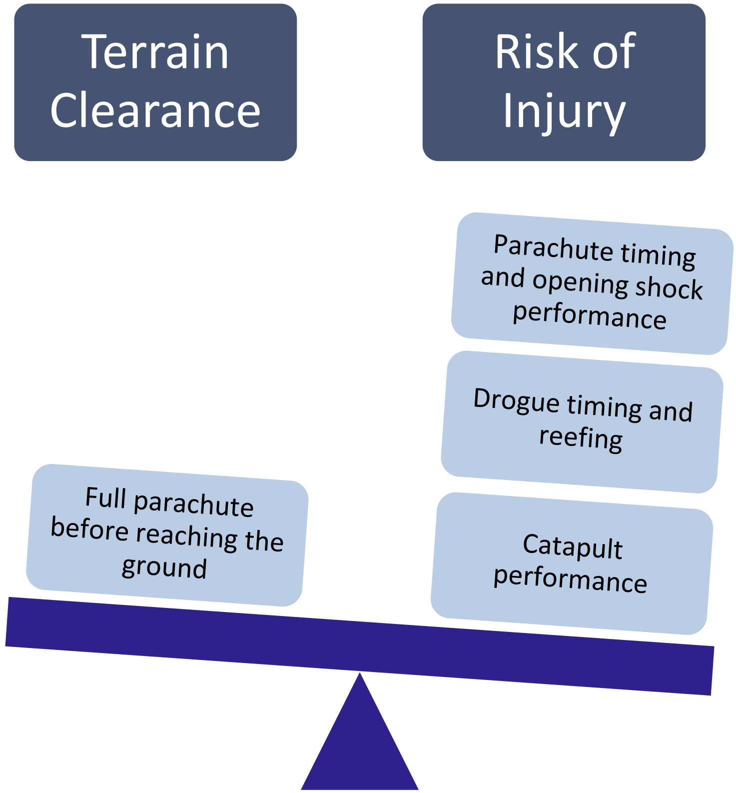


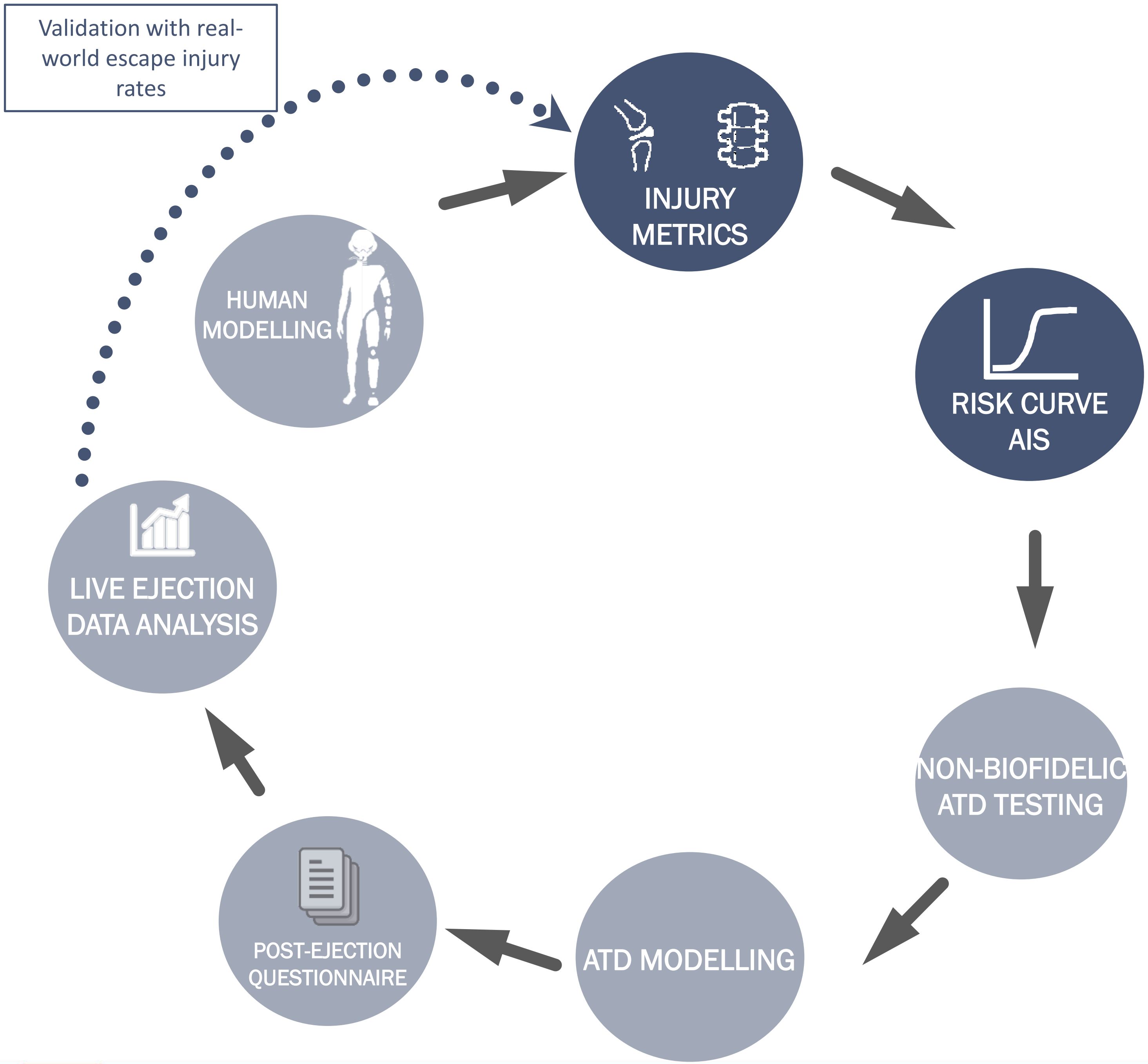
Design and Physiological Safety Trade Off

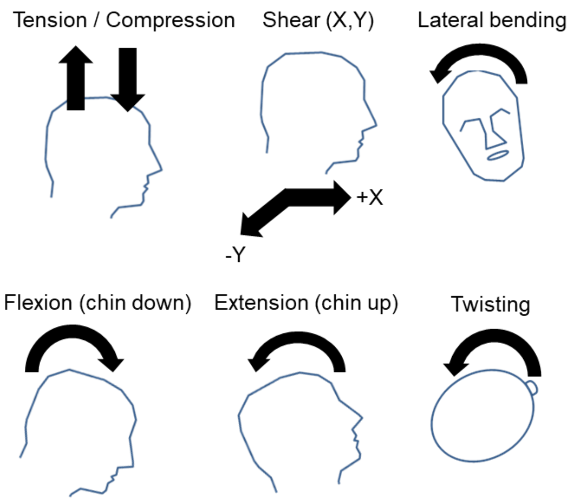
- **Risk of injury** versus **certainty of being under full parachute before hitting terrain**
  - Which is a higher priority?

- Decades old trend of **improving terrain clearance by shortening parachute timing**
- Lowering occupant mass (103lbs) + HMD
  - Risk of head and neck injuries at parachute inflation has caused increase in parachute timing
  - Reduction in terrain clearance

- Catapult performance requirement and design trade-off: lowest acceleration with the highest velocity
  - Lowest acceleration (light aircrew)
  - Highest velocity (heavy aircrew)





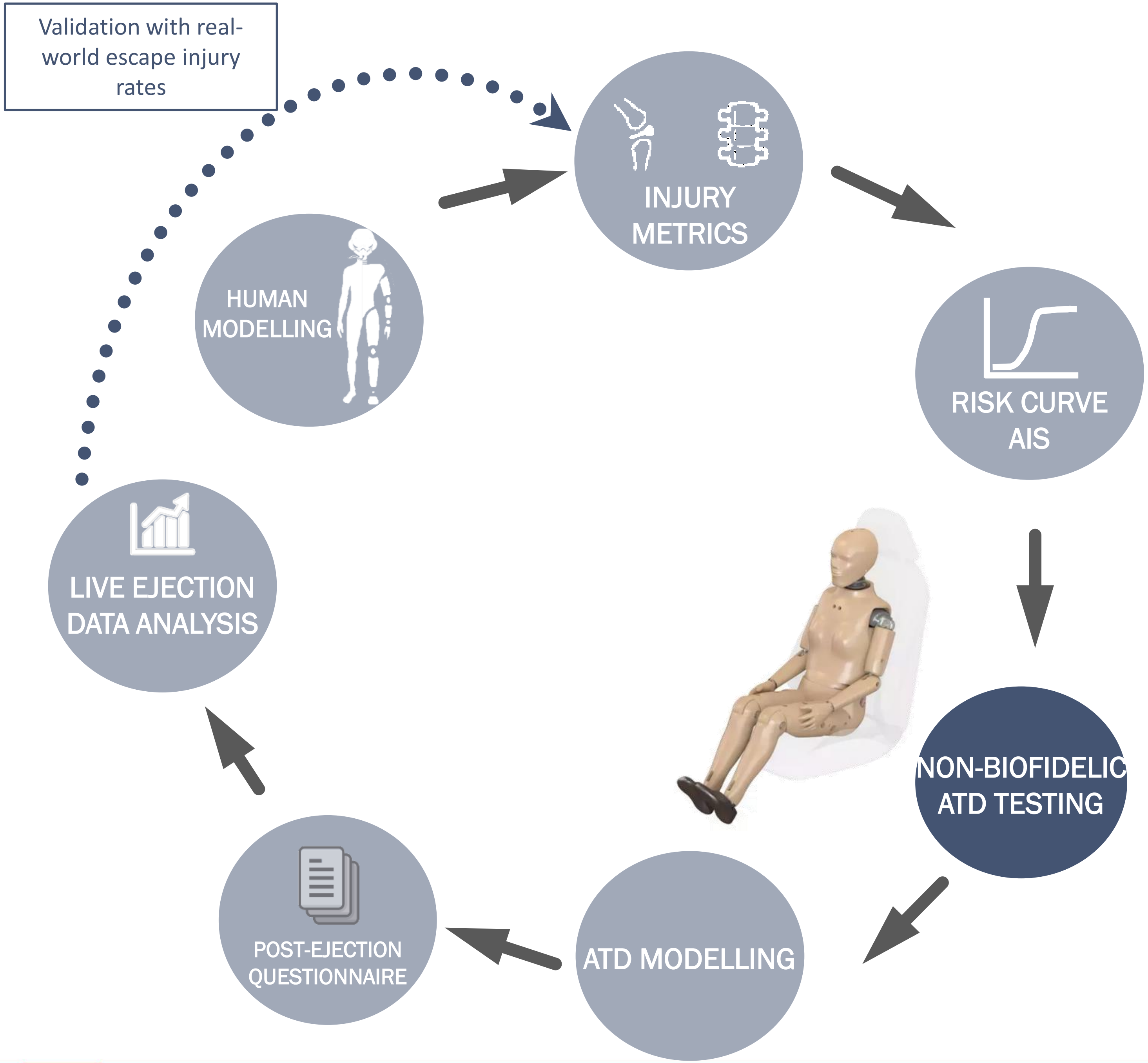


Physiological requirements derived from biomechanics research:
- Automotive, aviation, sport, emergency egress
- Most not developed in the context of an escape environment

Variety of data sources – spectrum in data quality:
- PMHS, human, ATD
- Escape system legacy performance

Injury risk curves associated to injury metrics
- **Correlation to injury severity index AIS**

No validation against modern escape system in-service performance
- Challenge physiological criteria



Aerospace H-IIIs
- Originally developed for the automotive industry
- Frontal crash testing
- Straight lumbar spine (erect posture behind car wheel)

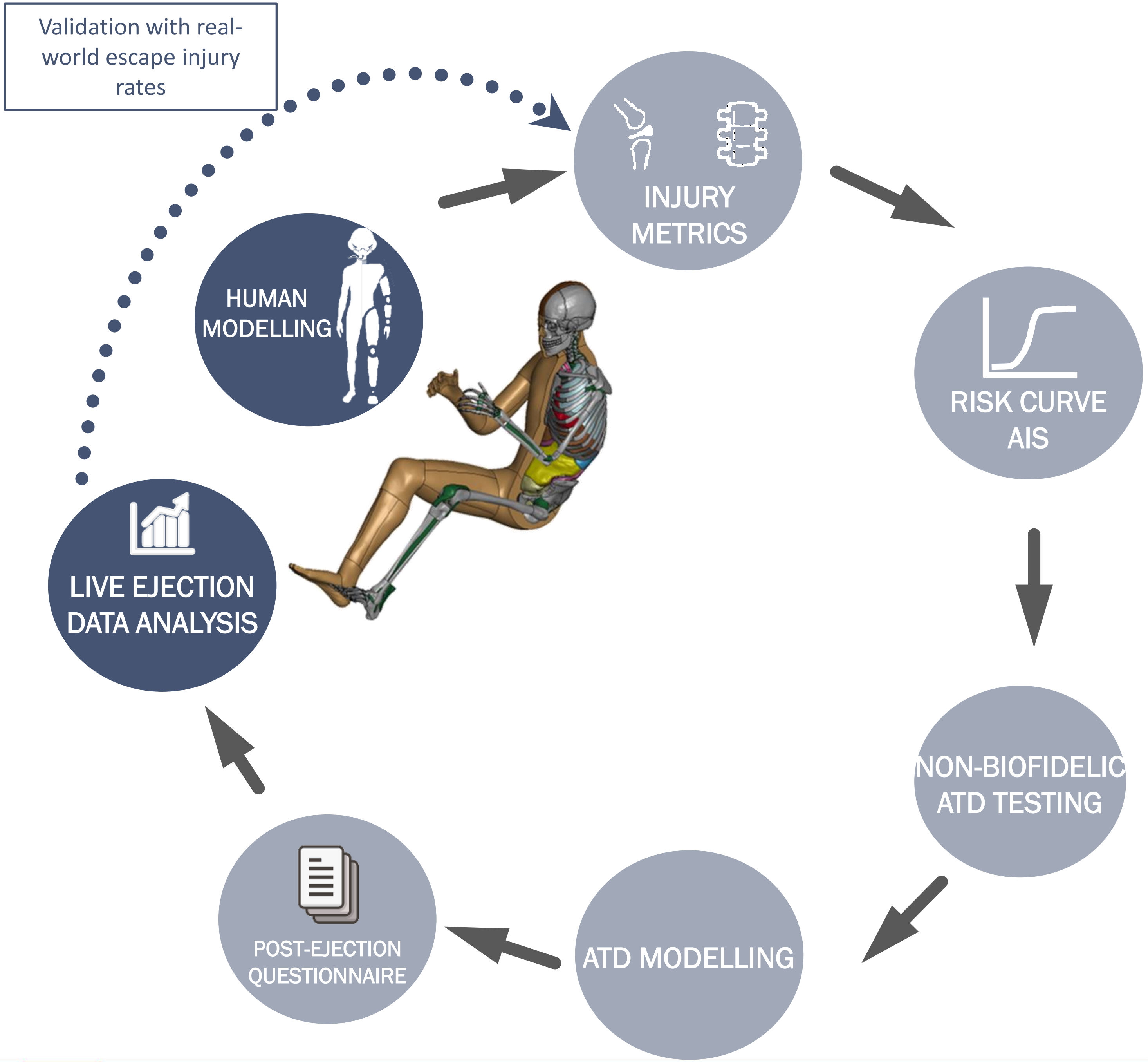
Lack of biofidelity in current ATDs is as important as appropriate choice in injury metrics and their tolerance levels

Need for the development of an **egress-biofidelic** ATD

FAA H-III 50 Male
- Allows for abdominal compression and lumbar flexion

Some Considerations for Hybrid III Aerospace Dummies

- **Lack of sufficient biofidelity** in current state-of-the-art aerospace manikins
  - **Discrepancies** between physical testing predictions and real life injury rates (slide 8)
  - Choice of ATD and lack of biofidelity in ATDs is **as important as** the injury metric tolerance levels themselves.
- Hybrid III might react to a short high-level duration pulse, whilst a human neck would not.
- Biofidelity requirement for automotive industry: 50^{th} %-ile male surrogate to meet **flexion and extension** response corridors.
  - with and for frontal and rear impact (sagittal plane motion)
- Not biofidelic in environments in which loadings come from **multiple directions** such as those seen in **rollovers** (or escape)[2,3]
  - Injury rates occurring in rollover tests were shown to be two orders of magnitude more frequent than that seen in the real-world accidents[2]



Criteria that do not adequately represent the real-world human data

- Appear very conservative if used without further assessment
- Suspect ATDs play a part in over-prediction of injury risk

With in-service ejection data: re-validation of metrics should take place

The objective is to have a set of airworthiness criteria that quantify more accurately the risk to aircrew personnel

Live ejection data to be AIS-coded to link back to requirement definitions

- **AIS lacks post-ejection escape and evade risk**[1]

Transfer function between dummy response and human response

Final Considerations

- How do we evaluate **physiological safety during ejection** (requirements definition, airworthiness risk acceptance process)
  - New aircraft platform: off-the-shelf escape system, or new bespoke escape system?
  - A legacy escape system?
  - A legacy aircraft platform with a retrofitted modern escape system?

- Development of new and improved requirements?
  - Maybe existing ones are good enough – and only need recalibrating (injury thresholds and acceptance levels)
    - When assessed against modern escape system performance
    - Crash test dummy to human transfer functions

- Is a legacy system safe to fly with a helmet and HMD? Evaluated under which physiological requirements?
  - Legacy programmes (e.g. Rafale, Typhoon, Gripen) have no head and neck requirements
    - Even though some of these platforms fly with an HMD
    - Who underwrote that risk?
    - Without useful live ejection data, route forward to HMD introduction would be through a risk analysis and acceptance process.
  - Future helmet designs should follow certain identified design considerations (physiological / enhanced performance trade space)
    - Helmet design criteria exist to channel physiological safety considerations

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Lives saved to date

THANK YOU

Any questions?

References

- [1] Bilger C., and Hughes K. Standardisation of Post-Ejection Reporting: A Questionnaire Approach, International Conference of Aerospace Medicine, Paris, 2022.
- [2] Herbst B., Forrest S., Chng D., Sances A., Fidelity of anthropometric test dummy necks in rollover accidents, Paper Number 98-S9-W-20.
- [3] Paver J.G., Friedman D., Mattos G., and Caplinger J, The Development of IARVs for the Hybrid III Neck Modified for Dynamic Rollover Crash Testing, ICRASH, Washington, D.C., 2010.