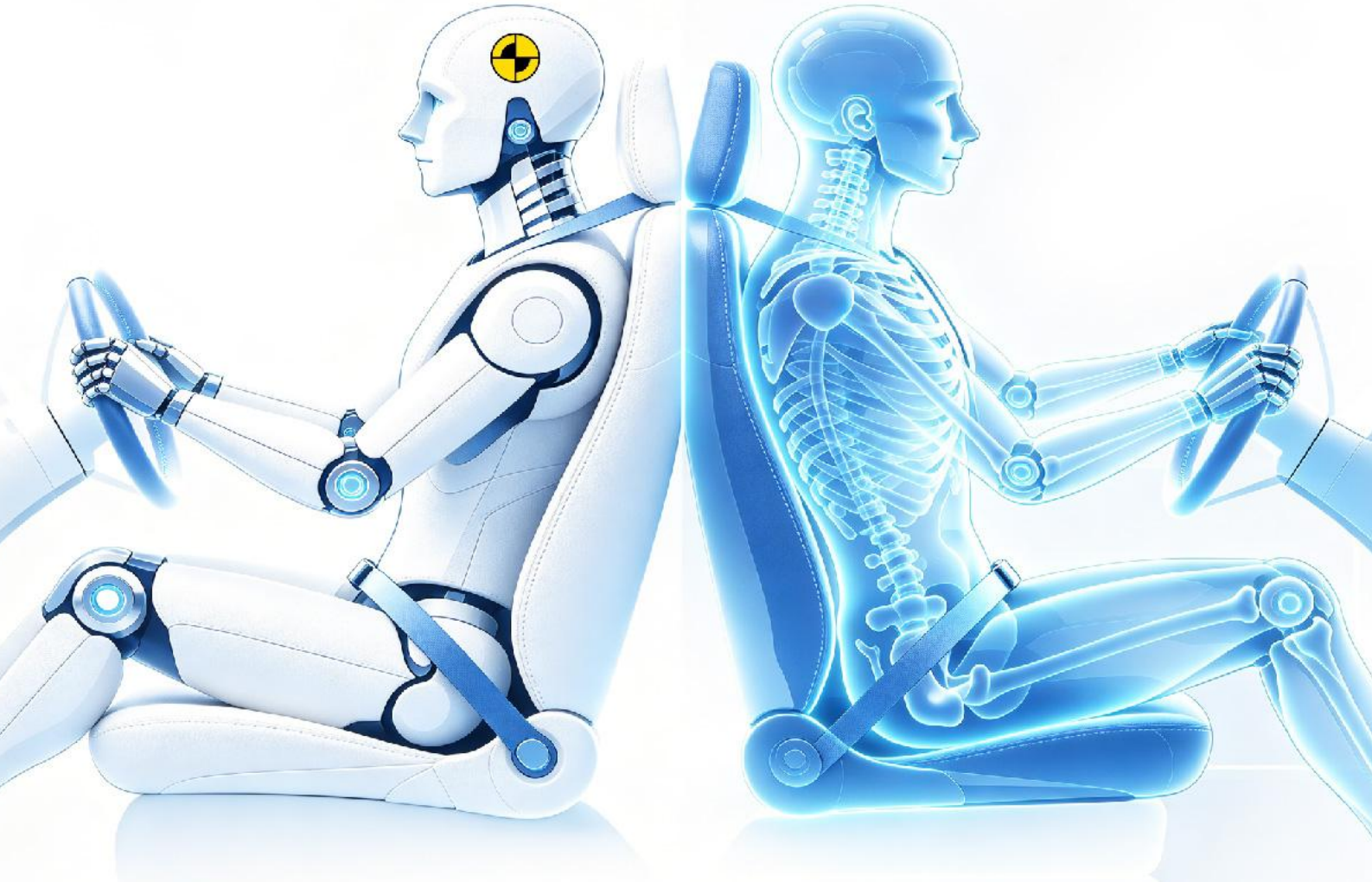
人体模型：生命安全新量具

White Paper on Human Body Models: Applications and Outlook

第一期 人体模型与假人：从区别到协同

Part 1 Human Body Models vs. Crash Test Dummies: From Differences to Synergy



聚焦汽车安全与虚拟测评

Focusing on Automotive Safety and Virtual Testing

CAERI & Euro NCAP 联合发布

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JOINT STATEMENT

联合声明

中国汽车工程研究院股份有限公司（CAERI）与欧盟新车安全评鉴协会（Euro NCAP）基于共同的道路安全愿景，联合编制《人体模型：生命安全新量具》白皮书。双方本着客观、开放、协同的原则，围绕人体模型与假人的区别与协同、开发与验证技术体系、虚拟测评应用与路线图三个主题，系统梳理行业共识与技术趋势，为汽车安全从业者、研究机构与决策者提供参考。本白皮书不构成任何一方的机构立场承诺，亦不替代相关法规与测评规程。

CAERI and Euro NCAP jointly publish this white paper series based on a shared vision for road safety. The series aims to provide an objective and open reference for engineers, researchers, and decision-makers, and does not replace any regulation or assessment protocol.

SERIES OVERVIEW

系列总览

本白皮书采用三期连载形式。第一期聚焦人体模型与假人的区别与协同；第二期系统介绍人体模型的开发与验证技术体系；第三期探讨人体模型在虚拟测评中的应用路径与发展路线图。三期内容相互衔接，共同构成从基础概念、技术方法到测评应用的完整知识框架。

This white paper is published in three parts: Part 1 focuses on the differences and synergy between human body models and crash test dummies; Part 2 introduces the development and validation system; Part 3 discusses applications in virtual assessment and the roadmap.

PREFACE

序　言

CAERI 序　Preface by CAERI

汽车安全评价的最终目的，是为不同道路使用者提供更可靠的生命安全保护。当前，这一评价正在经历一次方法上的转变：从以物理试验为主，走向物理试验与虚拟仿真相互结合的虚实融合评价。人体模型（Human Body Model，HBM）是这一转变中的关键工具。它把损伤生物力学与工程开发连接起来，使安全评价从整车的运动与受力，进一步深入到骨骼、软组织和器官层面；也使过去难以覆盖的群体、姿态和工况，有可能被纳入评价范围。对行业而言，人体模型带来的不只是一个新的仿真工具，更是一种更接近真实道路使用者的评价方式。

近年来，中国汽研围绕中国体征人体模型持续开展工作：构建中国人体骨骼几何与材料参数数据库，开展节段级、整人级生物力学验证，推进事故重建与工程应用，并牵头建设人体模型联合应用与创新中心。目前已形成系列模型，未来仍将围绕多体征、多姿态和工程适配持续完善。我们深知，模型的价值不只在几何精度，更在数据基础、验证证据和工程可用性。

这份白皮书由中国汽研与 Euro NCAP 共同发布。我们希望把 Euro NCAP 在新车评价中的经验，与中国道路交通事故和车型开发的实际结合起来，帮助企业看清人体模型当前能做什么、在哪些条件下还不能做什么，避免把模型精度直接等同于评价结论的可信度。书中不展开所有技术细节，重点是把基本概念、能力边界和行业共识讲清楚。欢迎整车企业、零部件企业、高校和科研机构共同参与，推动人体模型在明确边界内得到规范应用。

中国汽研总经理

刘安民

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Euro NCAP 序　Preface by Euro NCAP

Euro NCAP has been at the forefront of introducing human body models into virtual safety assessment. We believe these models offer important opportunities to improve our understanding of injury mechanisms and complement what can be learned from conventional crash test dummies. At the same time, their wider application requires careful consideration of model validation, qualification and the conditions under which results can be used with confidence.

This white paper series is an important contribution to that discussion. It provides a better understanding of the capabilities and limitations of human body models and the challenges that still need to be addressed before they can be more widely adopted in safety assessment.

Through our cooperation with CAERI, we hope to build a common technical understanding between the European and Chinese safety communities and encourage further exchange across the industry. We look forward to continuing this work together and supporting the development of more effective tools for improving vehicle safety.

General Secretary

Michiel van Ratingen

A B S T R A C T

摘　要

人体模型（Human Body Model，HBM）是以有限元方法构建的数字化人体替代物，能够输出传统物理假人难以测量的组织级响应，为损伤机理研究、防护装置开发和测评体系扩展提供新工具。本册为系列第一期，围绕“人体模型与假人：从区别到协同”展开：先界定人体模型的定义与技术特点，梳理全球主流模型谱系；再从模拟对象、能力输出和评价用途上厘清其与物理假人、假人仿真模型的区别；随后分析物理测评体系的成就与边界，说明虚拟测评的必要性与可行路径，并讨论三类工具在测评中的协同前提与三阶段推进路径。

本册在介绍技术能力的同时，着重说明人体模型与物理假人、假人仿真模型各自的角色与协同条件。人体模型的价值不在于替代物理试验，而在于与物理假人、假人仿真模型协同，把已经建立的可重复评价基准延伸到更广泛的人群、更多碰撞工况和更深入的组织响应层面。这些认识也为第二期的开发与验证技术体系、第三期的虚拟测评应用与路线图奠定讨论基础。

> A finite element human body model (HBM) is a digital surrogate of the human body that can provide tissue-level responses not directly measurable with physical dummies, offering a new tool for injury mechanism research, restraint development, and the expansion of assessment systems. This first part, under the theme "Human Body Models and Crash Test Dummies: From Differences to Synergy," first defines HBMs and their technical characteristics and reviews the global model landscape. It then distinguishes HBMs from physical and digital dummies in terms of modeled object, outputs, and assessment use, before examining the achievements and boundaries of physical testing, explaining the need for and feasibility of virtual testing, and discussing the preconditions and three-stage pathway for collaboration among the three tools.

> While introducing technical capabilities, this part focuses on the roles of, and collaboration conditions among, human body models, physical dummies, and dummy models. The value of human body models is not to replace physical testing, but to complement physical and digital dummies, thereby extending established evaluation benchmarks to broader populations, more crash scenarios, and deeper tissue-level responses. These conclusions also provide a basis for Parts 2 and 3.

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CHAPTER 01

什么是人体模型

01

本章给出人体模型的定义与术语界定，梳理全球主流人体模型谱系和开发生态，并对比人体模型、物理假人、假人模型三者的能力差异。

1.1 人体模型的定义与特点

1.1.1 定义

人体模型（Human Body Model，HBM）在不同学科与工程应用中具有不同含义，既可指物理人体模型或解剖标本，也可指数字化人体模型。本书所讨论的人体模型，特指汽车碰撞安全领域的人体有限元模型（Finite Element Human Body Model，FE-HBM）。文献中，“人体数字模型”“人体数值模型”等术语有时与 HBM 混用，但其内涵和适用范围可能更为宽泛。除特别说明外，本书后续所称“人体模型”或“HBM”均指 FE-HBM。



图 1　人体模型

FE-HBM 是以有限元方法为主要手段、在计算机环境中构建的数字化人体替代物，用于模拟人体在车辆碰撞等外界载荷下的组织变形与生物力学响应。该类模型通常包括骨骼、肌肉、内脏器官和脑组织等主要解剖结构，并根据研究目的进行不同程度的简化，为各结构赋予相应的材料本构参数。其基本原理是将人体连续结构离散为有限单元，基于连续介质力学描述各组织的变形、损伤与失效，通过求解动力学方程，获得人体在载荷作用下的运动学响应以及组织的应力、应变场。与物理假人（Anthropomorphic Test Device，ATD）相比，FE-HBM 能够提供脑组织应变、骨骼应力和器官变形等 ATD 难以直接测量的组织级响应，为损伤机制研究与损伤风险评估提供依据。

1.1.2 主要技术特点

1）**高生物逼真度**。人体模型以人体解剖学和真实人体医学影像数据为基础，对骨骼、肌肉、皮肤、内脏、脑组织、韧带等组织结构分别建模，并赋予如弹塑性、粘弹性的具有组织特异性材料本构参数。基于遗体捐献者（Post-Mortem Human Subjects，PMHS）试验数据进行组件级-节段级-整人级的系统化验证，保

证人体模型从整人运动学到骨骼、器官、软组织等结构层级生物力学响应的逼真度，可模拟正碰、侧碰、追尾等不同外界载荷下人体力学传递与损伤机制。

2）**详细的组织级响应数据。**人体模型支持在任意指定位置提取位移、速度、加速度、力、压力、应力、应变、能量等多物理量，能够获取物理假人因传感器布设限制而无法测量的组织级响应，例如脑组织应变、骨骼应力、器官变形等，为损伤机理分析与损伤指标构建提供丰富的数据支撑。

3）**体型与姿态扩展性。**以参数化人体几何描述为基础，人体模型可通过缩放技术对单一基准模型进行各向异性缩放与局部形变，实现身高、体重、年龄、性别多维人群体征的连续可控生成，为人群差异性研究与个性化安全设计提供基础。同时，同一模型可调整为行走、骑行、乘坐和斜躺等姿态，用于研究斜躺乘员保护、骑行者碰撞等问题。

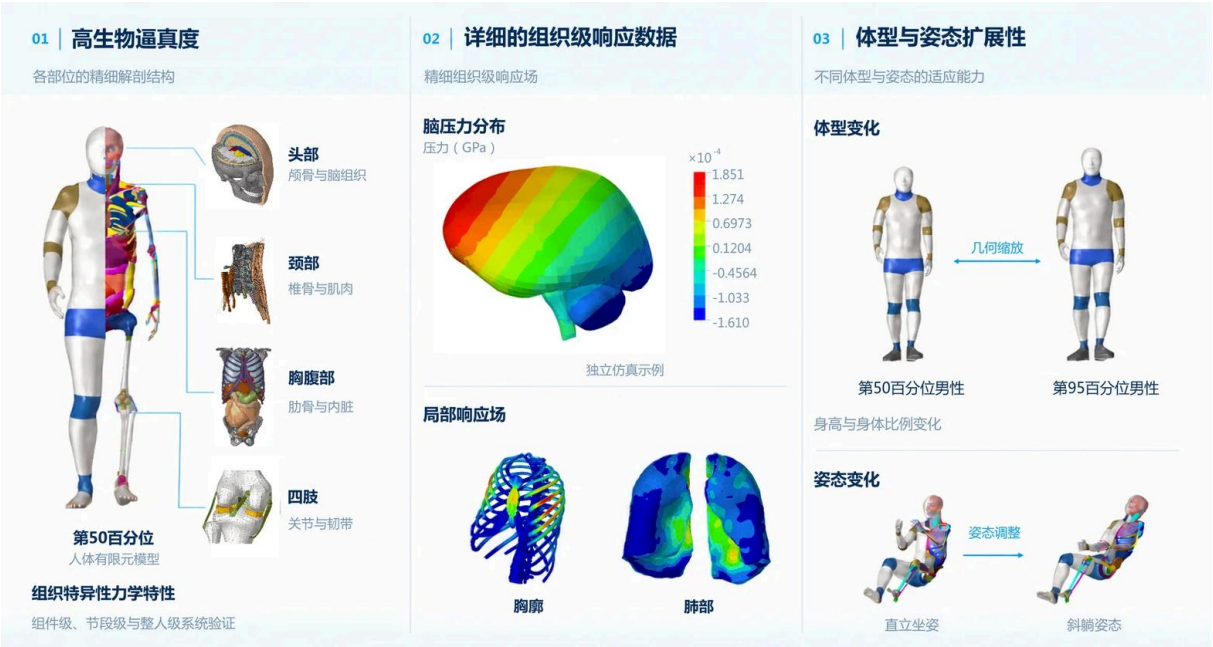

图 2　人体有限元模型特点

须注意，人体模型的预测能力取决于几何结构、材料属性、建模假设、数值方法及验证范围，仅靠几何缩放无法准确反映不同人群的生物力学响应，仿真结果应在已验证范围内解读，不可视为人体损伤的直接测量数据，因此在现行法规体系中通常作为物理试验的补充。

1.2　全球人体模型概览

丰田汽车公司是人体建模领域的先驱之一，在推动人体模型用于汽车安全研究方面发挥了重要作用。早期人体模型通常以单一体型为代表，随着生物力学研究与建模技术的发展，逐步形成覆盖不同性别、年龄、体型及姿态的模型谱系，以更好地反映道路使用者的多样性。与此同时，中国也在推进基于本国人群特征的自主人体模型研发，为中国人群的交通损伤研究与安全评价提供支持。

为系统梳理当前主流人体模型的技术水平与适用边界，选取四个代表性模型进行对比分析。样本框定采用“地域—模型”对应的方式，在中国、日本、美国和欧洲四个主要人体模型研发区域中各选取一个模型，以体现不同区域在建模思路、验证数据与工程应用上的差异。具体筛选遵循以下原则：其一，模型须具备完整

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的解剖结构与全面的试验验证；其二，模型在汽车安全和生物力学领域具有较高影响力，并有文献引用或工程应用基础。

本次比较并未穷尽所有模型。目前市场上还有其他代表性人体模型，例如PIPER儿童人体模型，源于DYNAmore研发的 Ansys Hans，Humanetics开发的HBM Connect，查尔姆斯理工大学、Autoliv和Volvo Cars等合作开发的SAFER HBM等。这些模型未纳入本次比较，并不意味着对其技术能力或特定应用适用性存在任何负面评价。

表 1　全球主要人体有限元模型分类矩阵

模型	开发机构	最早时间	开放程度	模型家族覆盖	主要特点
THUMS	丰田汽车公司，丰田中央研发实验室	1997年	免费开放使用（许可条件以官方协议为准）	AM50，AM95，AF05，AF50，3岁、6岁、10岁儿童，老年人，行人，乘员，大倾角模型	解剖结构精细，含骨骼、器官、软组织；V5—V7含主动肌肉控制；支持倾斜姿态工况研究
GHBMC	全球人体模型联盟	2006年	符合条件的学术机构可申请许可；具体条件以授权协议为准；商业许可需授权	AM50，AM95，AF05，AF50，6岁儿童，老年人，行人，乘员	提供精细和简化双版本；全身具备实体肌肉详细建模；支持组织级损伤预测
VIVA+	查尔姆斯理工大学	2022年	开放获取 / 开放科学模式	AM50、AF50、行人、乘员	强调性别差异和开放式虚拟安全评价；颈部具备主动肌肉力
AC-HUMs	中国汽车工程研究院	2022年	学术免费；商业许可需要授权	中国AM50，AM95，AF05，AF50，行人，乘员，大倾角模型	来源于中国人体体征数据，参照GB/T 10000-2023；颈部具备主动肌肉；提供精细和简化双版本；通过中国交通事故验证

下面分别阐述各模型的开发定位、技术特点和应用情况。

1）**THUMS（Total Human Model for Safety）**：由丰田汽车公司与丰田中央研发实验室于1997年联合启动研发，旨在计算机中还原车辆碰撞中的人体全身损伤响应。2000年发布Version 1（骨骼建模），历经二十余年迭代，依次在面部骨骼（V2，2005）、脑组织（V3，2008）、内脏器官（V4，2010）、全身肌肉（V5，2015）及内脏-肌肉耦合（V6，2019）等方面持续精细化[1][2]，2023年发布Version 7，进一步提升了模型几何精度，并新增面向自动驾驶场景的斜躺乘员姿态建模[3]。2021年1月起，丰田将THUMS向全球免费开放使用[4]，进一步推动了THUMS在行业中的应用。

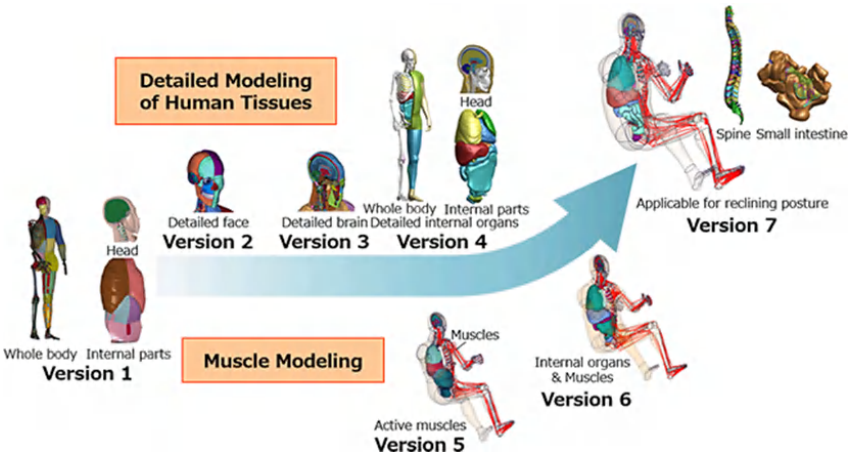

图 3　THUMS 发展历程

2）**GHBMC（Global Human Body Models Consortium）**：是由汽车制造商和供应商于2006年联合组建的国际联盟，旨在整合各成员分散的人体建模资源，建立行业共享、全面验证的人体模型体系[5]。模型开发由5所大学分部位协同承担，提供精细版模型与简化版模型。精细版模型完整重建了骨骼、内脏器官及全身肌肉，生物逼真度较高[6][7]，简化版模型大幅降低单元数量，计算效率显著提升[8]，更适于参数化研究与工程应用。

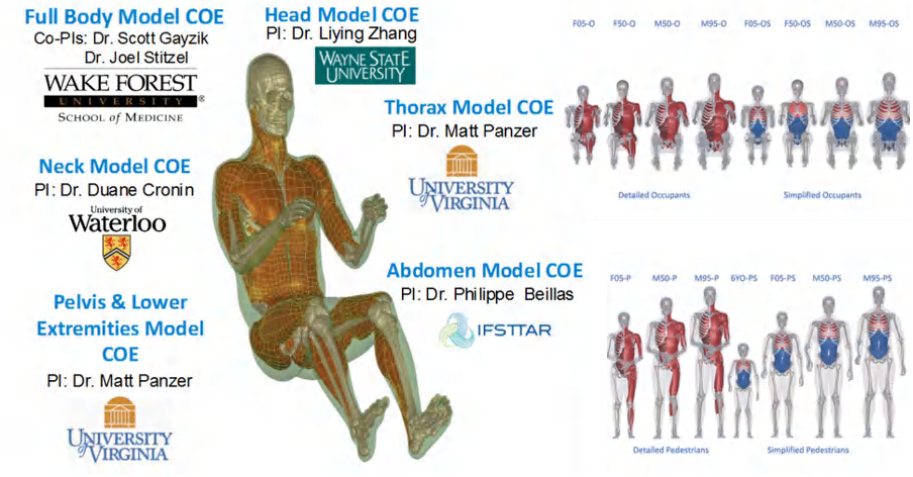

图 4　GHBMC 系列模型

3）**VIVA+：**采用开放科学模式发布模型及验证资料，其2022年发布的模型族以平均体型女性和男性为基础，采用一致的单元定义和网格拓扑，通过六面体主导的网格设计兼顾计算效率与数值稳定性，旨在支撑碰撞保护中的性别差异研究[9]。

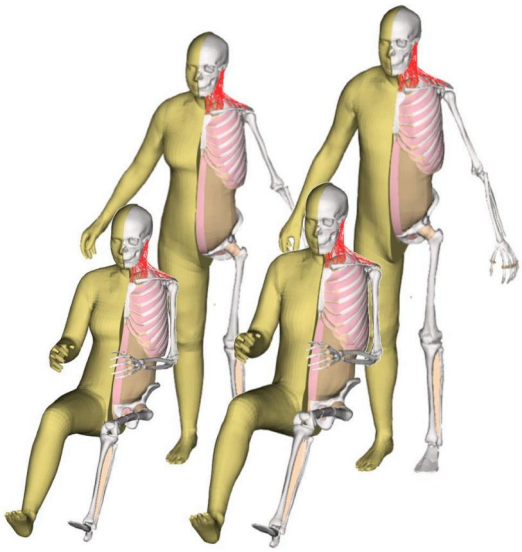

图 5　VIVA+ 系列模型

4）**AC-HUMs（Advanced Chinese Human Body Models）**：由中国汽车工程研究院股份有限公司牵头，联合10所高校单位于2022年启动开发，旨在建立面向汽车安全测评、代表中国人体特征的人体模型体系。模型以中国第50百分位男性人体为起点，几何构建依托于本土人群测量数据[10]，材料数据经中国人体骨骼力学测试与参数识别获取[11]，各部位建模[12][13]均重现重要解剖学结构特征并通过生物逼真度验证，整人模

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型进一步通过中国真实道路交通事故重建验证[14]，从数据基础到验证场景均立足本土。同时，AC-HUMs不局限于中国体征，还开发了欧美体征男性模型，其中AC-HUMs OS US-M50（LS-Dyna）已列入Euro NCAP CP550合格人体模型名单[15]。未来将持续向多体征人群拓展，构建覆盖更广范围人群的模型体系。

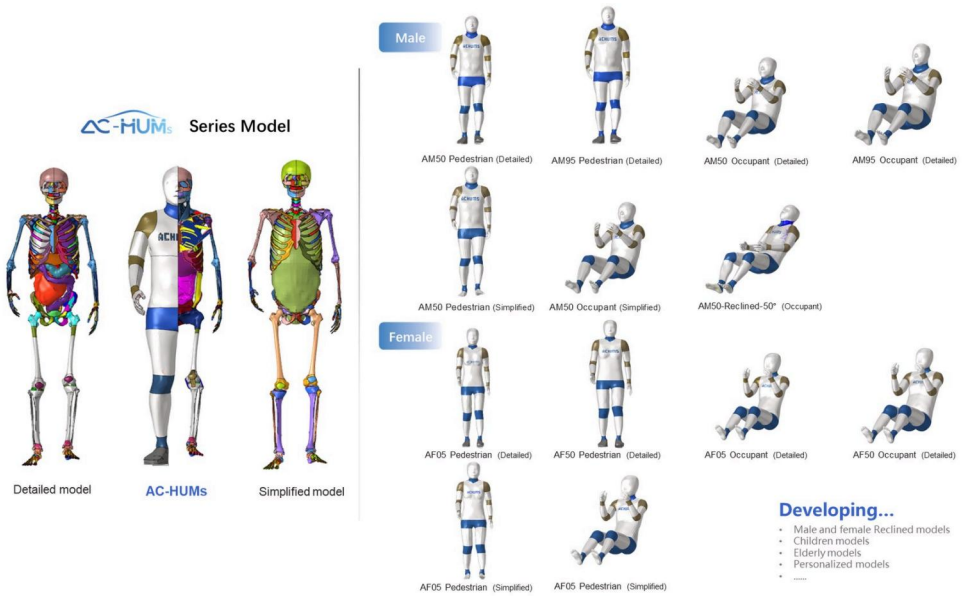

图 6　AC-HUMs 系列模型

综合来看，国内外人体模型经过长期迭代，已形成覆盖多性别、年龄、体征、姿态并且支持主动肌肉响应的模型谱系，基于不同的开发需求衍生出精细版、简化版或者适用于预碰撞-碰撞全序列仿真的模型等。通过遗体捐献者试验、志愿者试验对标验证模型的逼真度。

1.3　人体模型与假人的区别

在梳理了人体模型的发展谱系与技术特点之后，还需进一步明确其在测评体系中的位置，即人体模型与长期使用的物理假人及假人仿真模型有何区别、如何分工。测评对工具的要求，不仅在于能够评估更广泛的场景、计算更多工况，还在于能够提供适用范围明确、经过验证且可复现的评价证据，这在物理试验和虚拟测评中都至关重要。物理假人、假人仿真模型与人体模型应在统一的评估框架内发挥互补作用，围绕同一评估任务形成分工：物理试验提供真实车辆及约束系统响应的基准，假人仿真模型支持对应试验的分析与工况扩展，人体模型补充经验证的人体运动和组织损伤信息。不同工具的结果应在工况、指标定义和验证依据明确的前提下进行衔接，并依据具体评价规程确定其使用方式。

1.3.1　角色与定位

在试验时，物理假人被安放于车辆乘员位置，通过布置在头部、胸部、骨盆等部位的传感器，记录碰撞过程中的运动与受力响应。其标准化测量依赖于明确的型号规范、标定要求和试验程序。通过对假人状态、安装姿态及测量通道的统一控制，实车碰撞与滑台试验可获取客观且可比的响应数据，从而对不同保护方案进行评估。在此基础上，可针对具体型号建立假人仿真模型，也称数字假人，通过描述其几何、材料、关节和测量部件，预测对应物理假人在碰撞中的运动与测量响应。假人仿真模型需要与同型号物理假人的部件及整体试验结果进行对照，确认其在目标工况中的适用性，进而支持方案筛选、参数分析和试验结果解释。从

物理假人到假人仿真模型，延伸的是假人在虚拟环境中的应用方式，其模拟对象仍是具有规定机械结构的假人。

人体模型则以人体解剖结构和组织力学特性为建模依据，通过骨骼、关节、肌肉、软组织和器官等结构，计算碰撞载荷下人体的运动与变形。与假人仿真模型复现特定机械装置不同，人体模型着重描述载荷在各部位之间的传递，以及不同组织对载荷的响应。在模型所包含的结构与功能范围内，人体模型不仅能够输出整体运动和接触力，还可提取局部组织的应力、应变等信息，为分析内部的受载过程及潜在损伤机制提供依据。

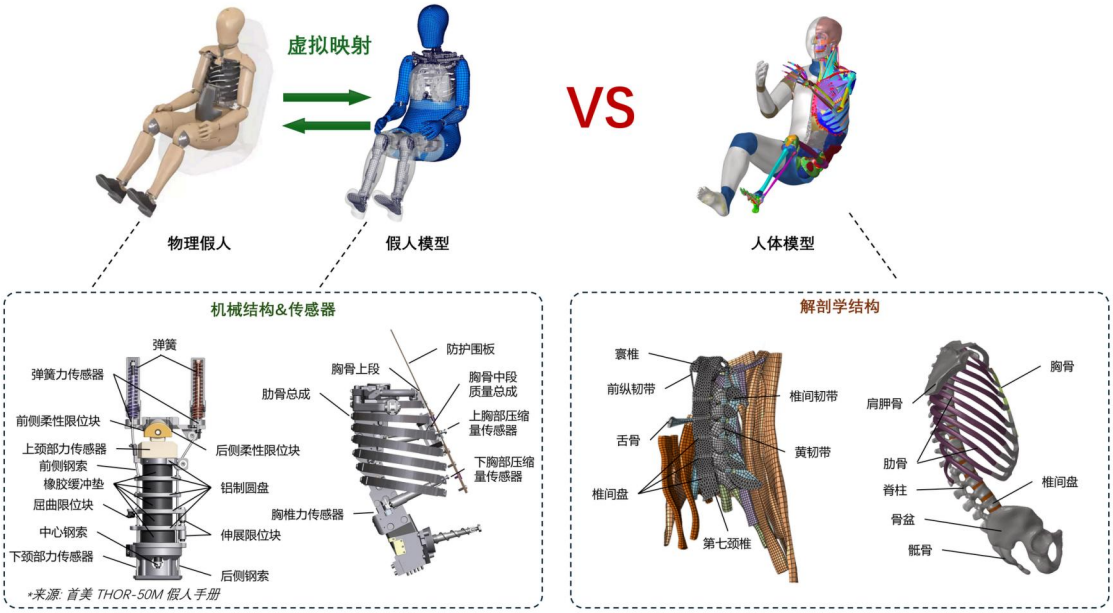

图 7　ATD、ATD Model及HBM

因此，物理假人、假人仿真模型和人体模型应作为三类工具加以区分：前两者分别通过实体测量和仿真预测获取假人响应，人体模型则依据解剖结构及组织力学特性，计算模型所描述的人体响应。假人仿真模型不会因采用更精细的建模方式而成为人体模型，二者的区别在于模拟对象及其力学表征。

1.3.2　能力对比

测评工具的能力差异应结合具体评价任务理解。物理假人及其仿真模型主要围绕既定测量指标，支持规定工况下的车辆保护性能比较；人体模型则通过人体解剖结构和组织力学特性的描述，补充组织损伤、人群差异及不同姿态下的响应信息。比较的重点在于工具能否有效回答相应的评价问题。

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表 2 假人与人体模型能力对比

比较维度	物理假人	假人仿真模型	人体模型
主要作用	在实体试验中提供标准化测量	预测对应假人的运动和测量响应	研究人体运动及模型所描述的组织响应
主要验证依据	规定的标定、认证及相关生物力学依据	对应型号假人的部件及整体试验	适用的人体生物力学试验等资料
主要输出	规定测点的加速度、变形及载荷	对应假人测量通道的预测值	运动学、组织应力应变等
人群与姿态扩展	受型号和设计适用范围限制	受对应假人及模型验证范围限制	可进行参数化扩展，但需说明扩展依据与验证范围
重复性与复现条件	受标定、装配和试验控制影响	需控制版本、求解设置及边界条件	还需控制姿态生成、材料和损伤后处理方法
成本构成	硬件、维护、场地及试验成本	模型、相关性验证及计算成本	模型准备、验证、计算及损伤分析成本
生物逼真度依据	通过适用的人体生物力学试验响应评价；表现受身体部位及加载条件限制	主要验证其对对应物理假人响应的再现能力；与假人吻合不等于与人体响应吻合	利用适用的PMHS、志愿者等试验资料，对整体运动及局部响应进行验证；损伤预测还需相应损伤数据支持
规程认可与使用条件	按具体规程采用指定型号，并满足标定及试验要求	是否可用及其用途由具体规程确定，通常需满足模型资格与试验对照要求	是否可用及其用途由具体规程确定，需明确模型资格、适用范围与评价指标；通过验证不等于可直接用于评分

在损伤评估中，碰撞假人依赖预设位置的测量数据，借助加速度、胸部压缩量和施加载荷等指标来评估乘员保护效果并估算损伤风险；人体模型可进一步提供局部组织响应，为分析损伤位置及其力学原因提供依据。例如，假人胸部指标可用于比较不同约束方案，人体模型则可结合适用的损伤风险函数开展肋骨骨折风险分析[16][17]。

在人群覆盖方面，假人及其仿真模型主要以既定体型型号代表不同乘员群体，人体模型则可通过调整人体几何、组织材料等参数，并结合相应的损伤耐受性数据，研究更广泛的人群差异。年龄相关的肋骨耐受性便可纳入此类分析[18]。

在碰撞方向与姿态适应性方面，假人及其仿真模型受到机械结构、关节特性和设计用途的约束，正面碰撞假人、侧面碰撞假人以及后向碰撞假人等还无法通用；人体模型则能够通过所描述的人体结构及组织间相互作用，研究多方向载荷、后仰和离位等情形。这些应用能力的差异，需要结合具体碰撞场景进行比较。在侧面及远端侧碰工况中，假人及其仿真模型主要反映特定机械结构下的整体运动和规定测点响应，人体模型则可进一步描述胸部、骨盆等区域的载荷传递与组织变形。因此，两类工具的比较既要考察整体运动，也要关注局部响应，相近的运动轨迹并不必然意味着相同的局部受载[19][20]。对于AEB引起的离位，假人的响应主要取决于其机械关节及被动结构特性，具备主动肌肉功能的人体模型还可研究肌肉作用对碰撞前姿态的影响[21]；对于后仰乘坐，假人模型与HBM均可用于分析乘员运动和下潜行为，两者对骨盆结构及其与安全带相互作用的不同表征可能影响预测结果，需要结合相应的遗体捐献者试验进行比较和验证[22]。

CHAPTER 02

从区别到协同，为什么需要人体模型

02

本章回顾物理测评体系的成就与边界，说明虚拟测评的必要性与可行路径，并阐述人体模型与假人在测评中的协同前提和三阶段推进路径。

2.1 测评方法：从物理测评到虚拟测评

2.1.1 物理测评的成就

过去数十年，车辆安全法规（如 GB、FMVSS和联合国法规）与Euro NCAP等新车评价规程、IIHS、C-IASI等消费者安全评价项目，共同构建了可重复、客观且可比较的碰撞安全评价框架。标准化碰撞假人始终是这些评价的核心工具，并有明确的试验条件、假人定位程序和性能评价准则作为支撑。这一体系使不同制造商、不同车型的安全性能得以比较，同时为法规符合性判定和消费者获取安全信息提供依据，推动了车辆结构、约束系统与乘员保护技术的持续改进。

上述努力在事故伤亡数据上得到印证。中国道路交通事故死亡人数在 2002 年前后达到约 11 万人的峰值，此后持续下降[23]，2019年以来在6万人左右波动[24]，2024年为59,280人[23]。全球层面亦呈相似趋势：据世界卫生组织（WHO）统计，全球道路交通年死亡人数从2010年约125万人降至2021年约119万人，下降约5%，总体改善仍显不足[25]。尽管自动驾驶和主动安全技术迅速发展，但仍存在一定的能力边界，无法完全避免交通事故的发生。

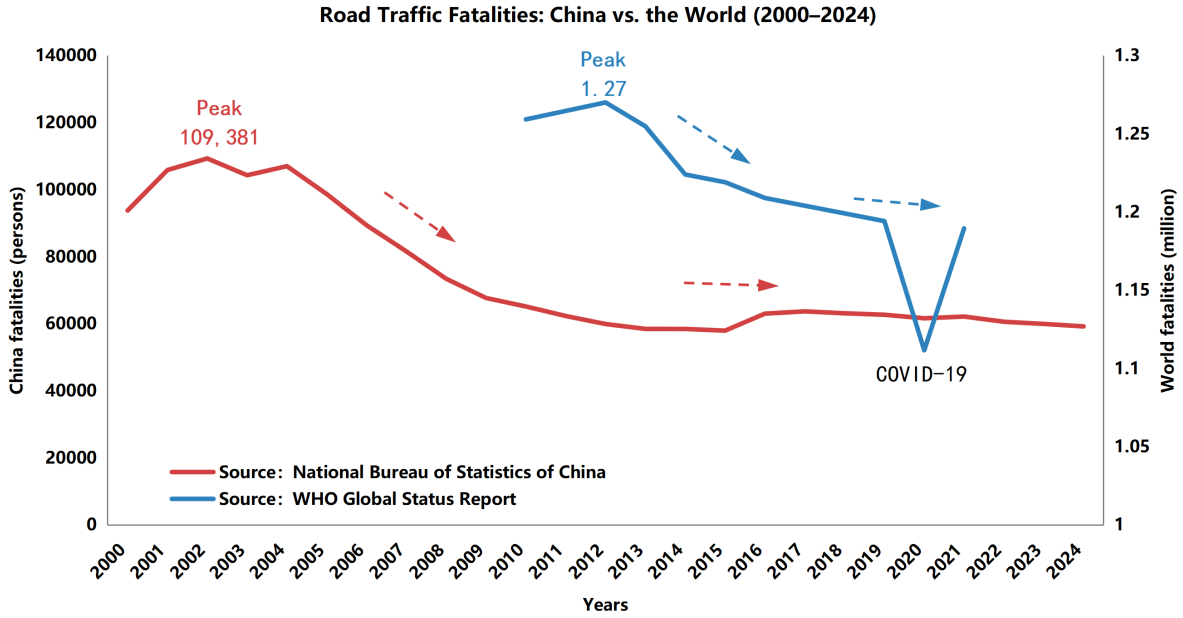

图 8　中国及全球道路交通死亡数据趋势

2.1.2 物理测评的边界

道路伤亡减少的进展受多种因素影响，要进一步提升车辆安全水平，需采用超越传统物理试验能力的评

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估方法。尽管物理试验的价值已得到充分验证，但其在反映道路交通使用者的多样性、覆盖更广泛的碰撞工况，以及评估组织层面的损伤响应等方面，仍存在固有局限。这些局限为以虚拟评估方法补充物理试验提供了充分依据。具体表现为以下三点：

评价对象的体征覆盖有限。现行法规与测评规程所用假人家族包括 Hybrid III、THOR、WorldSID、SID-IIs 及 Q 系列儿童假人等，其核心基准体征仍以50 百分位成年男性为主；部分小体格型号（如 Hybrid III 族第 5 百分位女性假人）以几何缩放为主构建，许多碰撞假人最初基于 20 世纪 70—90 年代的生物力学知识与试验数据开发，虽经后续改进，但其设计与生物力学响应特性已未必能充分体现当前人体解剖、损伤机制及人群多样性的理解。这些假人普遍未针对女性、老年、肥胖及儿童群体的生理结构、组织力学特性与损伤耐受阈值开展系统标定，以单一标准体征假人进行的测评，可能低估甚至错判弱势乘员的损伤风险。

坐姿与工况覆盖有限。法规与测评工况高度标准化、参数固定，与真实事故的随机性之间存在"工况脱节"：中国事故深度调查数据显示，大部分真实碰撞事故超出法规与测评规程的典型工况范围[26]。与此同时，自动驾驶技术的发展可能带来乘员坐姿的更大变异性，包括更大幅度的后仰姿态。传统碰撞假人在表征此类坐姿方面能力有限，且其在非标准坐姿下的生物逼真度以及既有损伤判据的适用性仍存在不确定性。上述问题表明，亟需引入更具灵活性的评估方法，以补充传统物理试验的不足[27]。

内部组织响应难以直接测量。碰撞假人主要测量加速度、力、力矩和变形等力学响应。这些测量能够为损伤风险提供有价值的指标，且在工程上相对便于使用和解读，适合常规安全评估与车辆开发。然而，假人无法直接获取脑组织应变、骨骼应力或器官变形等内部组织响应[28]。同时，可用的人体实验数据也限制了对这些响应的认识。志愿者试验只能限于非致伤载荷条件，而遗体捐献者（PMHS）试验数量有限，且受试者往往年龄偏大，难以充分代表更广泛的人群。因此，传统物理试验在评估组织级损伤机理、发展更精细的损伤预测方法方面存在固有局限。

2.1.3 虚拟测评：突破边界的可行路径

基于人体模型的虚拟测评，为突破传统物理试验的局限提供了一条可行路径。计算机辅助工程（CAE）已在车辆安全开发中应用数十年，而虚拟测评在既有仿真能力的基础上，将其应用从设计与优化进一步拓展到正式安全评估。虚拟测评要求在明确的评估流程中使用经过验证与确认的数值模型，并对模型资格、可重复性和可追溯性提出相应要求。由此，仿真结果可作为可信证据用于独立安全评估，对物理试验形成补充，并在适当条件下替代部分物理试验。

上述三类局限对应三项明确的需求。而作为虚拟测评的重要工具，人体模型的能力与之契合：

体征覆盖局限意味着评价对象需可参数化。人体模型可针对不同性别、年龄和体型进行适配，系统探究人群在生物力学响应及损伤风险上的差异，从而实现比传统碰撞假人更具包容性的安全评估，突破其有限的体型覆盖局限[29]。

坐姿与工况覆盖局限意味着评价场景需可扩展。在模型经过充分验证的前提下，依托多方向载荷适应性，同一人体模型原则上可用于正碰、侧碰、后碰、翻滚、行人碰撞及大角度后倾等非标准坐姿工况；不消耗物理样件与试验设施，使海量参数化工况与敏感性分析可在较低成本下开展。

内部响应测量局限意味着评价结论需深入组织与器官层面。人体模型可输出组织应变、器官压力、内部应力动态演化等物理试验难以直接观测的响应，还原碰撞载荷的传递路径与致伤机理，补充物理试验的观测盲区。

因此，虚拟测评及其核心工具人体模型的价值，不在于取代物理试验，而在于把物理试验建立的可重复评价基准，延伸到更广的人群、更多的工况与更深的响应层次。

2.2 测评工具：人体模型与假人的协同

2.2.1 为什么不能相互替代

物理假人作为乘员替代物参与实体试验，通过测量自身的运动与受力响应，反映其与车辆结构、约束系统之间的相互作用，并通过统一的标定和试验程序获得可比较的结果。与任何测量设备相同，碰撞假人需定期进行认证与校准，以确保其响应处于规定容差范围内，保障测量结果的可靠性与可重复性。人体模型的计算则依赖所建立的车辆、约束系统和人体模型，无法独立检验模型中未描述的实际行为。因此，仿真覆盖更多工况，并不等于已经完全证明真实车辆在这些工况下的保护效果；同样，假人的标准化测量也无法完整提供人体模型所描述的内部组织响应。

假人仿真模型与人体模型的验证路径也不能相互替代。假人仿真模型参照对应型号的物理假人，通过部件和整体试验核对运动、变形及测量通道的响应；人体模型则需利用适用的人体生物力学资料，分别评价整体运动、局部组织响应和损伤预测的可信度。志愿者低风险试验、遗体捐献者试验及事故资料在其中承担不同任务。由此，假人仿真模型与实体试验吻合，并不意味着同一仿真环境中的人体模型也已得到验证；整体运动合理，也不能直接证明局部损伤预测可靠。

进一步而言，经过验证的模型响应仍需通过明确的评价规则，才能用于法规或星级评分。假人指标的使用依托相应的试验规程、损伤评价方法和判定规则，假人仿真模型与人体模型的结果也需满足具体规程对模型资格、适用工况、评价指标及结果处理的要求。是否能够替代某项试验或评价环节，应依据该环节所需的证据及规程要求确定。

2.2.2 协同的三阶段推进路径

假人与人体模型的协同应用，按照验证深度和证据积累程度可分为三个阶段：监测与流程验证、运动学与补充损伤评价、评价扩展与推广。

第一阶段是流程验证与数据监测。在此阶段，物理假人继续承担既定评价任务，人体模型主要作为监测项和研究性数据来源参与测评。其目标不是直接改变评分，而是收集人体运动、约束接触、局部组织响应等数据，跑通模型资格、车辆模型验证、人体模型定位、仿真工况设置、结果处理及审核复现等流程，并识别人体模型在目标工况下仍缺少哪些验证证据[30][31]。模型资格评估还需关注不同体型的验证依据、后处理方法的一致性，以及模型变更与计算结果的可追溯性[32]。以正面碰撞中的胸部保护为例，物理假人提供乘员运动和胸部受载等基准结果，假人仿真模型用于核对车辆及约束系统模型；人体模型则补充观察安全带、气囊等约束载荷在胸部组织中的分布[33]。

第二阶段是运动学与补充损伤评价。这一阶段包含人体模型的两类互补用途。

第一，人体模型可用于运动学一致性检查。在假人难以直接提供信息的方面，人体模型更接近人体的运动学响应可以补充依据。例如在VRU CoHerent中，使用的并不是损伤评价，而是类人体运动学响应，用来检查头部接触时刻[34][35]。

第二，当现有验证证据足以支持所需分析深度时，人体模型可以进一步补充评价假人无法直接测量的损伤类型，例如脊柱载荷、肋骨或皮质骨应变、脑组织应变和器官压力[23]。

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对于假人和人体模型都能测量的指标，应持续进行对比，检查两者在乘员运动、约束接触和局部组织响应上是否一致。如果结果出现差异甚至相互矛盾，不能简单用人体模型结果替代假人结果，而应从模型版本、姿态与接触状态、验证范围、损伤风险函数、求解器设置以及假人自身的适用边界等方面追溯差异来源。只有在差异得到解释、预测也获得充分验证之后，人体模型结果才可用于补充性损伤评价或保护方案比较。

第三阶段是评价及场景扩展。当人体模型的损伤指标、风险函数、阈值及目标工况验证达到相应要求，并满足测评规程对模型资格、数据提交和结果处理的明确规定后，人体模型可逐步承担更多正式评价任务，扩展到更多人群、姿态和碰撞场景[30]。这一过程中应明确各项结果的适用范围，记录模型版本、工况设置和结果处理方法，保证评价证据可复核、可追溯。只有在证据充分、规则明确的前提下，人体模型才可在特定环节替代部分既有试验与分析工作。

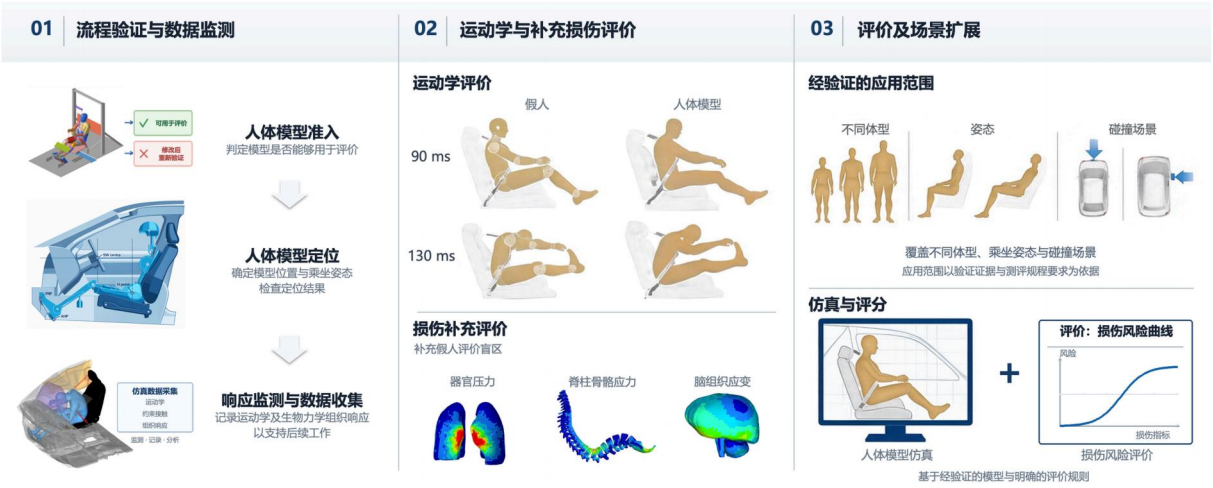

图 9　人体模型与假人协同推进路线

已有应用案例：WorldSID手臂加载。Euro NCAP CP203规定，在满足试验前申报、手臂与第一胸肋加载关系、约束系统工作状态及支持数据等要求时，可对第一胸肋采用替代评价；支持数据包括WorldSID和人体模型仿真[36]。

行人保护中的主动发动机罩应用体现了特定用途下的试验与仿真协同。物理试验与满足认证要求的人体模型仿真，共同用于论证系统对不同体型行人的探测能力、系统展开时机，以及身体加载引起的发动机罩变形[34]。这一应用说明，人体模型的使用必须对应具体保护功能和证据要求，而不能脱离适用范围推广。

总体来看，假人与人体模型的协同不是简单的替代关系，而是“物理试验建立基准—人体模型补充信息—验证充分后扩展应用”的渐进过程。未来需要进一步明确现有验证证据能够支持哪些人群、姿态和碰撞条件，假人指标与人体模型预测不一致时如何判断各自可信程度，以及不同模型、版本和求解设置的结果应依据什么标准判断其可比性与可采信性。

CHAPTER 03

本期总结与展望

03

3.1 本期总结

本期围绕“人体模型与假人：从区别到协同”，对人体模型的基本概念、全球格局、应用场景及其与假人的关系进行了系统梳理。人体模型以人体解剖结构和组织力学特性为建模依据，能够输出整体运动、约束接触、骨骼应力、组织应变和器官响应等多层次信息，为损伤机理研究、防护装置优化和测评体系扩展提供了新的技术工具。但人体模型并不是天然优于假人的“高级答案”，其结果可信度取决于模型构建、验证证据、适用边界和结果处理规则。

本期形成的第一项基本判断是：**物理假人仍然是现有法规与测评体系中可重复、可比对、可追溯的评价基准。**其标准化程度高、规程体系成熟，在车辆安全性能比较中仍具有不可替代性。假人仿真模型延续了物理假人的测量对象和评价逻辑，可用于方案筛选、参数分析和试验解释。人体模型则进一步补充人体内部组织响应、多人群差异和非常规姿态等信息。三类工具各有边界，应围绕评价任务形成互补，而非简单替代。

本期形成的第二项基本判断是：**人体模型进入正式测评应采取渐进路径。**短期内，应以补充监测和研究性数据收集为主，积累流程和基线证据；中期，应在验证充分的人群、姿态和工况下，补充评价假人难以直接测量的损伤类型，并通过同测量项目对比检验结果一致性；长期，则应在损伤指标、风险函数、阈值和模型资格要求完善后，扩大人体模型在正式评价中的应用范围和使用权重。这个过程应以验证证据和规程要求为依据，而不是以技术成熟度或宣传预期为依据。

本期形成的第三项基本判断是：**人体模型的行业价值不仅取决于模型本身，还取决于配套的验证、数据和治理体系。**模型开发者需要提高模型验证的透明度和完整性，整车企业需要在开发中建立规范的模型使用流程，测评机构需要逐步明确模型资格、适用工况、数据提交和结果复核要求。只有形成可复核、可比较、可追溯的应用生态，人体模型才能真正从科研工具转化为可信任的测评工具。

3.2 人体模型的发展展望

3.2.1 模型开发：多体征、多姿态扩展

在体征维度，人体模型将由以标准成年男性为基准，逐步扩展到覆盖不同体型、性别和年龄的人群谱系，为不同道路参与者提供更具代表性的安全评价。已有参数化研究表明，即使性别、身高和体重相同，肋廓、骨盆等解剖几何的个体差异仍可能显著影响碰撞损伤风险[37]。因此，多人群发展不能停留在增加若干体型档位或将基准模型简单缩放，而应通过个性化建模与群体多样化相结合，逐步表征关键解剖结构的个体和群体差异。

在姿态维度，模型将由标准直立坐姿和站立、行走姿态，进一步扩展到斜躺、AEB离位、骑行和避撞等非标准姿态。快速重定位技术的发展，使姿态生成逐步由耗时的外力调整转向参数化、流程化处理[38]。但“能够摆出姿态”并不等于“能够评价损伤”：姿态变化会改变安全带、气囊与人体的作用方式以及内部载荷传递路径，斜躺、离位等姿态下的损伤预测不能直接沿用标准坐姿的验证结论。因此，多体征与多姿态扩展必

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须与相应的验证证据同步推进，避免将几何和姿态上的扩展直接等同于评价能力的扩展。

3.2.2 应用拓展：损伤研究、工程研发与跨领域



图 10 人体模型的应用拓展

交通损伤机理研究方面，人体模型可重建真实道路事故中人体由整体运动到组织损伤的完整响应过程，覆盖弥漫性轴索损伤、肋骨骨折、脏器损伤与韧带撕裂等典型交通伤。通过对组织级响应量的定量分析，建立损伤表征量与实际损伤之间的关系，为损伤风险曲线与耐受阈值的制定提供生物力学依据。

汽车安全防护装置研发方面，人体模型广泛用于评估安全带、安全气囊、方向盘、弹起式发罩、行人安全气囊等装置与人体各部位的相互作用和载荷传递，通过参数化仿真对安全防护装置的设计变量进行寻优，可可在物理试验前规避风险，缩短开发周期，降低试验和样机成本。

跨领域应用方面，在医疗健康领域，人体模型可用于康复植入物、医疗器械设计及个性化手术规划，比如脊柱矫形效果模拟。在航空航天领域，人体模型可用于评估航空器起飞、着陆、应急迫降等工况下乘员的损伤风险，优化座椅吸能结构与约束布局。在作业安全领域，人体模型可用于作业人体工学评估与防护装备研发，比如模拟搬运、前屈等典型作业姿态下的椎间盘内压、椎体应力与肌肉活动，研发外骨骼等新型防护装备。

3.3 白皮书系列展望

后续两期将分别承接本期提出的模型可信性与测评应用问题：第二期系统介绍人体模型的开发与验证技术体系，重点回答“模型如何建立、如何验证、如何判断可信度”；第三期聚焦虚拟测评中的应用与路线图，重点回答“模型如何进入测评、需要满足哪些准入条件、未来如何发展”。

CHAPTER 01

Overview of Human Body Models

01

This chapter provides definitions and terminology for human body models, outlines the major global human body model lineages and development ecosystems, and compares the capability differences among human body models, physical dummies, and dummy models.

1.1 Definition and Characteristics of the Human Body Model

1.1.1 Definitions

A human body model (HBM) carries different meanings across disciplines and engineering contexts: it may refer to a physical human body model or an anatomical specimen, or to a digital human model. The human body model discussed in this book specifically refers to the finite element human body model (FE-HBM) used in automotive crash safety. In the literature, terms such as "digital human model" and "numerical human model" are sometimes used interchangeably with HBM, although their connotations and scope of application may be broader. Unless otherwise stated, "human body model" or "HBM" in this book refers to FE-HBM.

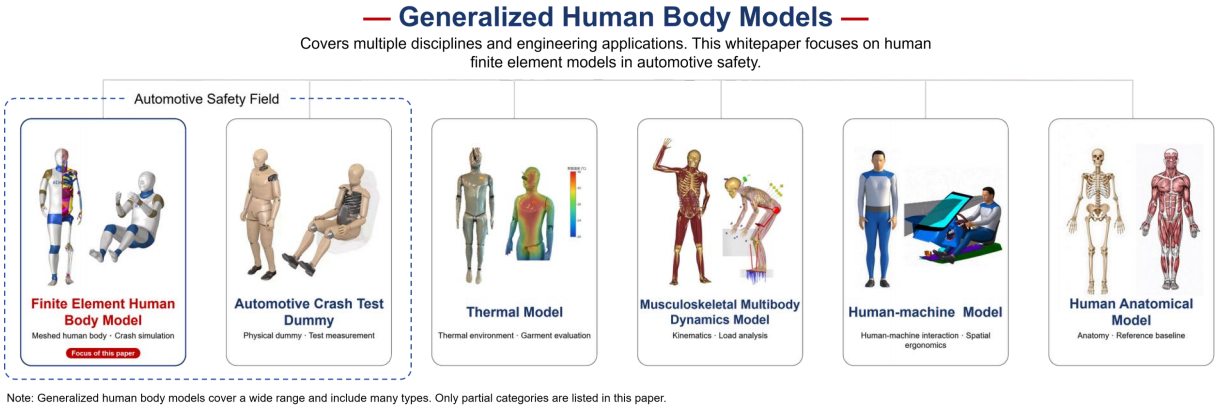

Figure 1. Human Body Models

An FE-HBM is a digital human surrogate constructed primarily with the finite element method to simulate tissue deformation and biomechanical response under external loads such as vehicle crashes. Such models typically include major anatomical components—bones, muscles, internal organs, and brain tissue—simplified to varying degrees depending on the research purpose, with appropriate material constitutive parameters assigned to each structure. The basic principle is to discretize the continuous human body into finite elements, describe tissue deformation, damage, and failure using continuum mechanics, and solve the dynamic equations to obtain kinematic responses and tissue stress and strain fields under loading. Compared with physical anthropometric test devices (ATDs), FE-HBMs can provide tissue-level responses that ATDs cannot directly measure, such as brain tissue strain, bone stress, and organ deformation, thereby providing a basis for injury mechanism research and injury risk assessment.

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1.1.2 Characteristics of the Human Body Model

1) High biofidelity. Human body models are based on anatomical knowledge and medical imaging data of real human subjects. Bones, muscles, skin, internal organs, brain tissue, and ligaments are modeled separately and assigned tissue-specific constitutive material properties including elastoplastic and viscoelastic behaviour. Systematic validation is performed at component, body-region, and whole-body levels using post-mortem human subject (PMHS) test data, ensuring biofidelity from whole-body kinematics to structural-level biomechanical responses in bones, organs, and soft tissues. This enables the simulation of load transfer and injury mechanisms under frontal, side, and rear impacts.

2) Detailed tissue-level response data. Human body models allow extraction of displacement, velocity, acceleration, force, pressure, stress, strain, and energy at arbitrary specified locations. They can therefore obtain tissue-level responses that physical dummies cannot measure because of sensor placement limitations, such as brain tissue strain, bone stress, and organ deformation. This provides rich data support for injury mechanism analysis and the development of injury criteria.

3) Adaptability to different body types and postures. Human body models can be adapted from a baseline model to represent different body sizes and characteristics, including variations in stature, weight, age and sex. This allows researchers to investigate differences in injury response across the population and supports the development of more inclusive vehicle safety systems. The same model framework can also be extended to walking, cycling, seated, and reclined postures, supporting research on non-standard postures such as reclined occupants in automated driving and cyclist impacts.

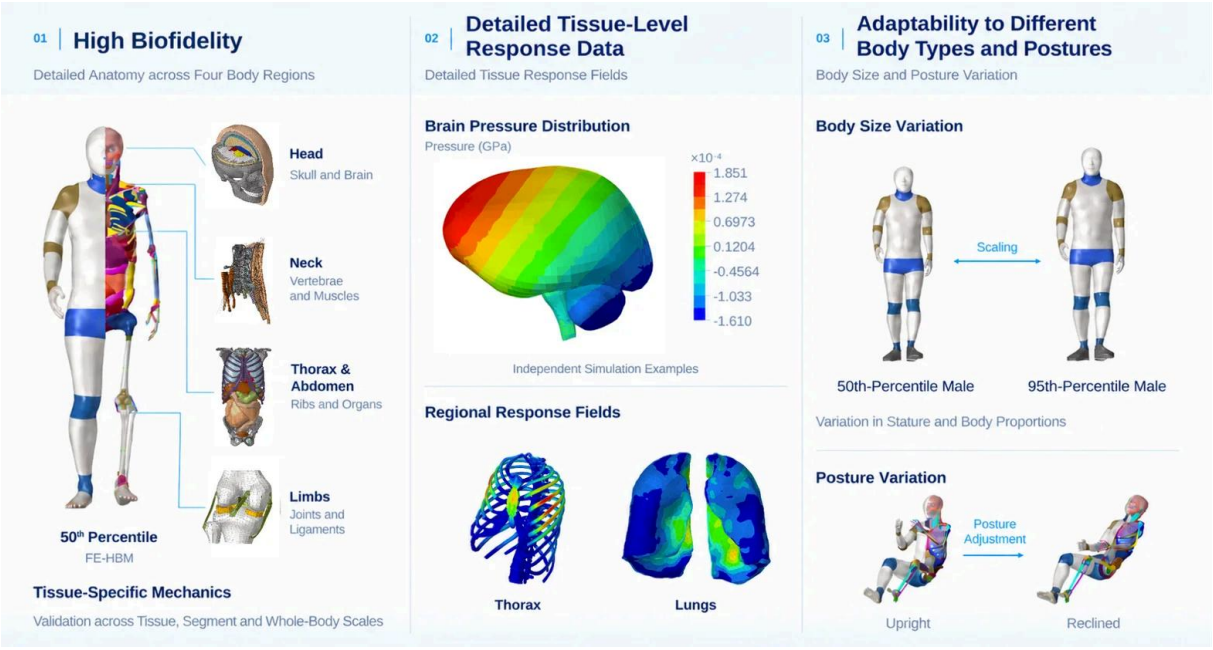

Figure 2. Characteristics of Human Body Models

However, the predictive capability of HBMs depends on the accuracy of their geometry, material properties, modelling assumptions and numerical methods, as well as the extent of their validation. Geometric scaling alone does not ensure that a model accurately represents the biomechanical response of a different population group. Simulation results should therefore be interpreted within the validated scope of the model and should not be regarded as direct measurements of human injury response. At present, HBMs primarily

complement physical testing rather than replace it.

1.2 Overview of Major Human Body Models Worldwide

Finite element human body models have been developed for several decades.

Toyota's Total Human Model for Safety (THUMS) has been a forerunner in this field, playing an important role in advancing the development and application of HBMs for automotive safety research. While early models typically represented a single body size, advances in biomechanics and modelling techniques have led to model families covering different sexes, ages, body sizes and postures, better reflecting the diversity of road users. In recent years, with China's growing independent research capability, Chinese anthropometric human body models have emerged, addressing the limited applicability of foreign models in Chinese road traffic injury research.

To systematically review the technical level and applicability of current mainstream models, several representative models are selected for comparison. The selection follows two principles: first, the model should have complete anatomical structures and comprehensive experimental validation; second, it should have significant influence in automotive safety and biomechanics and be widely cited or applied in engineering practice.

The selection is not intended to be exhaustive. Several other representative human body models exist, including the PIPER Child Human Body Model, Ansys Hans originating from DYNAmore development, HBM Connect developed by Humanetics, and SAFER HBM developed collaboratively by Chalmers University of Technology, Autoliv and Volvo Cars. Their exclusion from this comparison should not be interpreted as a judgement on their technical capabilities or suitability for specific applications.

Table 1. Classification matrix of major global finite element human body models

Model	Developer	Year	Availability	Model-family coverage	Key features
THUMS	Toyota Motor Corporation; Toyota Central R&D Labs	1997	Free to use; license terms subject to official agreement	AM50, AM95, AF05, AF50, 3-, 6-, and 10-year-old children, elderly, pedestrian, occupant, and reclined-posture models	Detailed anatomical structures; active muscle control in V5–V7; supports reclined-posture studies
GHBMC	Global Human Body Models Consortium	2006	Academic licences available to eligible institutions, subject to agreement; commercial license required	AM50, AM95, AF05, AF50, 6-year-old child, elderly, pedestrian, occupant	Detailed and simplified versions; detailed whole-body muscle modeling; supports tissue-level injury prediction
VIVA+	Chalmers University of Technology	2022	Open access / open science	AM50, AF50, pedestrian, occupant	Emphasizes sex differences and open virtual safety assessment; active neck muscles
AC-HUMs	China Automotive Engineering Research Institute	2022	Free for academic use; commercial license required	Chinese AM50, AM95, AF05, AF50, pedestrian, occupant, reclined-posture models	Based on Chinese anthropometric data; active neck muscles; detailed and simplified versions; validated against Chinese traffic accidents

The following sections describe the development positioning, technical characteristics, and applications of

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each model.

1) Total Human Model for Safety (THUMS): jointly initiated in 1997 by Toyota Motor Corporation and Toyota Central R&D Laboratories, THUMS aims to reproduce whole-body injury responses in vehicle crashes. Version 1, released in 2000, focused on skeletal modeling. Over more than two decades, the model was progressively refined in facial bones (V2, 2005), brain tissue (V3, 2008), internal organs (V4, 2010), whole-body muscles (V5, 2015), and organ–muscle coupling (V6, 2019) [1][2]. Version 7, released in 2023, further improved geometric accuracy and added reclined occupant posture modeling for automated driving scenarios [3]. Since January 2021, Toyota has made THUMS freely available worldwide [4], promoting its industrial application.

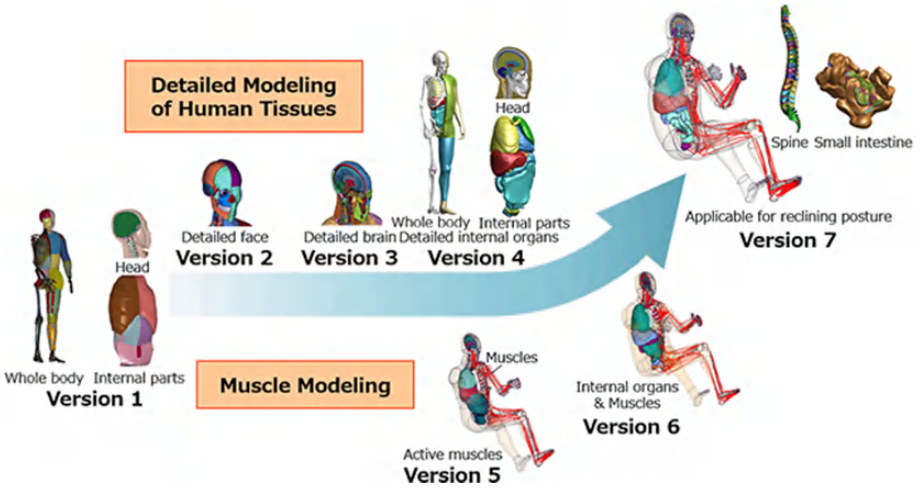

Figure 3. Development history of THUMS

2) Global Human Body Models Consortium (GHBMC): established in 2006 by vehicle manufacturers and suppliers, GHBMC aims to integrate dispersed human body modeling resources and build an industry-shared, comprehensively validated model system [5]. Model development is jointly undertaken by five universities, with detailed and simplified versions. The detailed version fully reconstructs bones, internal organs, and whole-body muscles, offering high biofidelity [6][7], while the simplified version substantially reduces element count and improves computational efficiency [8], making it more suitable for parametric research and engineering application.



Figure 4. GHBMC model family

3) VIVA+: released under an open science model together with validation data. The 2022 model family is based on average female and male body sizes, uses consistent element definitions and mesh topology, and adopts a hexahedral-dominated mesh design to balance computational efficiency and numerical stability. It is intended to support research on sex differences in crash protection[9].

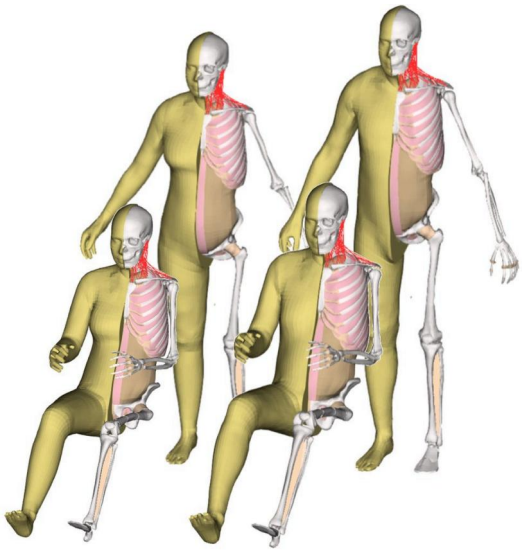

Figure 5. VIVA+ model family

4) AC-HUMs (Advanced Chinese Human Body Models): Led by the China Automotive Engineering Research Institute Co., Ltd., in collaboration with ten universities, the development of AC-HUMs was initiated in 2022, aiming to establish a human body model system representing Chinese anthropometric characteristics for automotive safety assessments. Development began with a model representing the anthropometry of a 50th-percentile Chinese adult male. The geometry is built on Chinese population measurement data[10], while material data are obtained through biomechanical testing of Chinese human skeletons and parameter identification[11]. The modeling of each body part reproduces key anatomical features and has been validated for biofidelity[12][13]. The full-body model has been further validated through reconstructions of real road traffic accidents in China[14]. Both the data foundation and validation scenarios are based on local conditions. Meanwhile, AC-HUMs are not limited to Chinese anthropometric characteristics; models representing Western male characteristics have also been developed. AC-HUMs OS US-M50 (LS-Dyna) is listed among the HBMs qualified under Euro NCAP CP550[15]. Future work will extend the models to diverse human characteristics, building a model system covering a broader population spectrum.

Overall, domestic and international human body models have evolved into families covering multiple sexes, ages, body sizes, and postures, with support for active muscle response. Different development needs have produced detailed models, simplified models, and models suitable for full pre-crash-to-crash simulation. Their biofidelity is validated against PMHS and volunteer tests.

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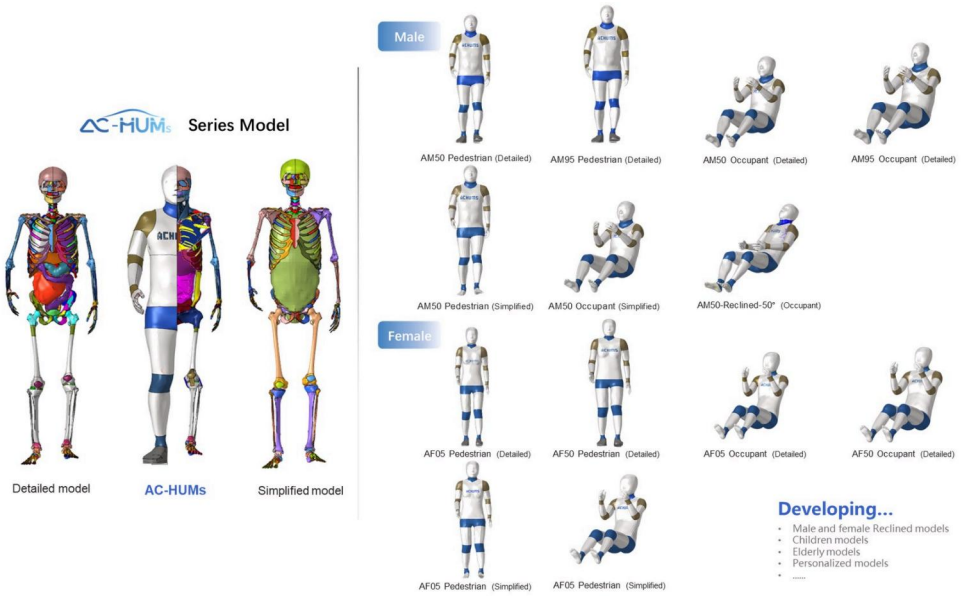

Figure 6. AC-HUMs model family

1.3 Differences Between Human Body Models and Dummies

Assessment tools must not only be capable of evaluating a wider range of scenarios but also provide evaluation evidence that is clearly scoped, validated, and reproducible. This is essential in both physical testing and virtual testing. Physical dummies, dummy simulation models, and human body models should play complementary roles within a common assessment framework: physical tests provide the benchmark for real vehicle and restraint system responses; dummy simulation models support analysis and scenario extension of corresponding tests; and human body models supplement validated human motion and tissue injury information. Results from different tools should be linked only when crash conditions, indicator definitions, and validation bases are clear, and their use should follow specific assessment procedures.

1.3.1 Roles and Uses of Dummies and Human Body Models

A physical crash test dummy is a human surrogate manufactured with specified body size and structure. During testing, it is placed in the occupant position of a real vehicle and records motion and force responses through sensors in the head, chest, pelvis, and other regions. Its standardized measurements rely on clear model specifications, calibration requirements, and test procedures. By controlling dummy condition, installation posture, and measurement channels, real vehicle crash and sled tests can obtain objective and comparable response data for evaluating different protection solutions. Based on a specific dummy model, a dummy simulation model can be established to describe its geometry, materials, joints, and measurement components, thereby predicting the motion and measurement response of the corresponding physical dummy. Such models must be compared with component and whole-body tests of the same dummy type to confirm their applicability in target scenarios, after which they can support design screening, parameter analysis, and interpretation of test results.

A human body model, by contrast, is based on human anatomical structure and tissue mechanical properties. Through bones, joints, muscles, soft tissues, and organs, it calculates human motion and deformation under crash loads. Unlike a dummy simulation model, which reproduces a specific mechanical device, a human body model describes load transfer between body regions and the response of different

tissues. Within the structures and functions represented by the model, it can output not only overall motion and contact forces but also local tissue stress and strain, providing a basis for analyzing internal loading and potential injury mechanisms.

Physical dummies, dummy simulation models, and human body models should therefore be distinguished as three types of tools: the first two obtain dummy responses through physical measurement and simulation prediction, respectively, while the human body model calculates human responses based on anatomy and tissue mechanics. A dummy simulation model does not become a human body model merely because it uses a finer modeling approach; the difference lies in the object being modeled and its mechanical representation.

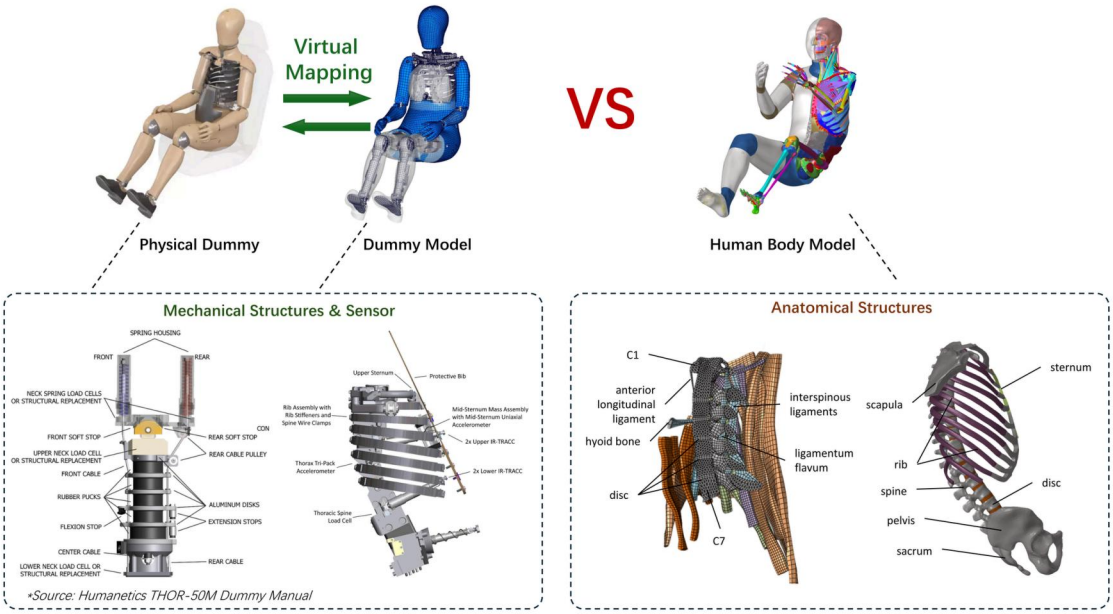

Figure 7. ATD, ATD model, and HBM

1.3.2 Capability comparison between human body models and dummies

Capability differences should be understood in the context of specific evaluation tasks. Physical dummies and their simulation models mainly support comparison of vehicle protection performance under specified conditions and established measurement indicators. Human body models supplement information on tissue injury, population differences, and responses in non-standard postures through anatomical and tissue-level mechanical description. The key question is whether a tool can effectively answer the corresponding evaluation problem.

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Table 2. Capability comparison of dummies and human body models

Dimension	Physical dummy	Dummy model	Human body model
Main role	Provides standardized measurements in physical tests	Predicts the motion and measurement response of the corresponding dummy	Studies human motion and the tissue responses represented by the model
Main validation basis	Specified calibration, certification, and relevant biomechanical evidence	Component and whole-body tests of the corresponding dummy model	Applicable human biomechanical test data
Main outputs	Acceleration, deformation, and load at specified measurement points	Predicted values of corresponding dummy measurement channels	Kinematics, tissue stress and strain, and related responses
Population and posture extension	Limited by model type and design scope	Limited by the corresponding dummy and model validation scope	Can be extended parametrically, but extension basis and validation scope must be stated
Repeatability and reproducibility	Affected by calibration, assembly, and test control	Requires control of version, solver settings, and boundary conditions	Also requires control of posture generation, materials, and injury post-processing
Cost structure	Hardware, maintenance, facilities, and testing	Model, correlation validation, and computation	Model preparation, validation, computation, and injury analysis
Biofidelity basis	Evaluated through applicable biomechanical test responses; performance varies by body region and loading condition	Mainly validated against the response of the corresponding physical dummy; agreement with a dummy does not imply agreement with a human	Validated against applicable PMHS, volunteer, and other data; injury prediction also requires corresponding injury data
Regulatory acceptance and use conditions	Uses specified dummy models according to procedures and must meet calibration and test requirements	Whether and how it can be used is determined by specific procedures; model qualification and test comparison are usually required	Whether and how it can be used is determined by specific procedures; model qualification, applicability, and evaluation criteria must be clear; validation does not automatically mean scoring eligibility

In injury assessment, crash test dummies rely on measurements at predefined locations, using indicators such as acceleration, chest deflection and applied loads to assess occupant protection and estimate injury risk. Human body models can provide additional local tissue responses, helping to analyze injury location and mechanical causes. For example, dummy chest indicators can compare different restraint solutions, while a human body model can combine applicable injury risk functions to assess rib fracture risk[16][17].

In population coverage, dummies and their simulation models mainly represent different occupant groups through established body-size models. Human body models can adjust human geometry and tissue material parameters and combine corresponding injury tolerance data to study broader population differences. Age-related rib tolerance can be incorporated into such analysis[18].

In crash direction and posture adaptability, dummies and their simulation models are constrained by mechanical structure, joint characteristics, and design purpose. Frontal, side, and rear impact dummies are not generally interchangeable. Human body models can describe multi-directional loads, reclined postures, and out-of-position conditions through the interaction of body structures and tissues. In side and far-side impacts, both overall motion and local responses of the chest and pelvis should be considered because similar motion trajectories do not necessarily imply identical local loading[19][20]. For out-of-position conditions caused by AEB, active muscle models can further study the effect of muscle action on pre-crash posture[21]. For reclined seating, both dummy models and human body models can analyze occupant motion and submarining, but differences in pelvic structure and seatbelt interaction may affect predictions and should be compared with relevant human tests[22].

CHAPTER 02

From Differences to Synergy: Why Human Body Models Are Needed

02

This chapter reviews the achievements and boundaries of physical testing, explains the need for and feasibility of virtual testing, and sets out the preconditions and three-stage pathway for collaboration between HBMs and dummies.

2.1 Testing Methods: From Physical Testing to Virtual Testing

2.1.1 Achievements of Physical Testing

Over the past several decades, vehicle safety regulations, including GB, FMVSS and UN Regulations, together with consumer assessment programmes such as Euro NCAP, IIHS and C-IASI, have established a framework for repeatable, objective and comparable crash safety assessments. Standardised crash test dummies remain central to these assessments, supported by clearly defined test conditions, dummy positioning procedures and performance criteria. This approach allows vehicle safety performance to be compared across manufacturers and models, while providing a basis for regulatory compliance and consumer information. It has been instrumental in driving continuous improvements in vehicle structures, restraint systems and occupant protection technologies.

These efforts have contributed to significant improvements in vehicle safety, although overall road casualty trends are also influenced by factors such as road infrastructure, traffic conditions, driver behaviour and changes in the vehicle fleet. In China, road traffic fatalities have declined from a peak of about 110,000 around 2002 to approximately 60,000 since 2019, entering a plateau period[23]. Total fatalities remain above 50,000 per year, and deaths among non-motorized vehicle users have increased in recent years[24]. In 2024, China recorded 59,280 road traffic deaths[23]. Globally, the trend is similar. According to the World Health Organization, annual road traffic deaths decreased from about 1.25 million in 2010 to about 1.19 million in 2021, a reduction of about 5%, indicating limited overall progress[25].

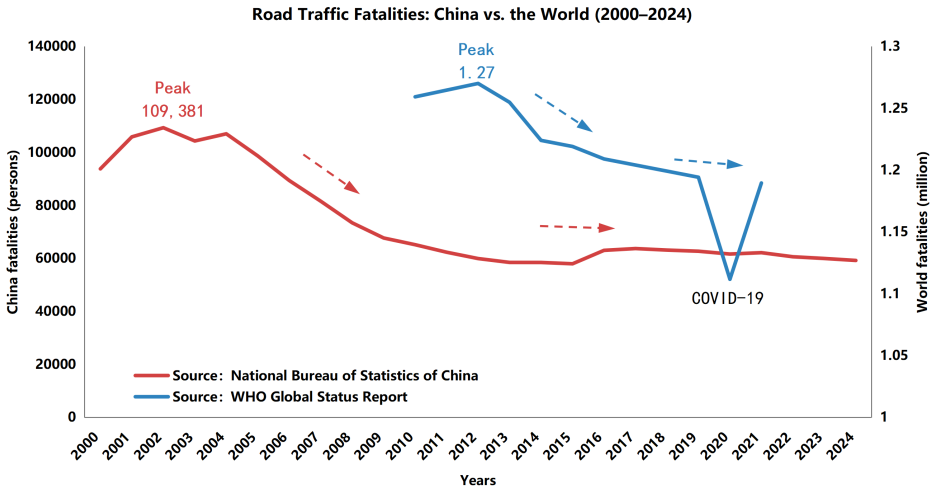

Figure 8. Trends in road traffic fatality data in China and globally

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2.1.2 Boundaries of Physical Testing

While progress in reducing road casualties is influenced by many factors, further improvements in vehicle safety will require assessment methods that go beyond the capabilities of conventional physical testing. Despite its proven value, current physical testing has inherent limitations in representing the diversity of road users, covering a wider range of crash scenarios and assessing injury responses at tissue level. These limitations provide a strong rationale for complementing physical tests with virtual assessment methods.

First, coverage of evaluated body sizes is limited. Current regulations and assessment procedures use dummy families including Hybrid III, THOR, WorldSID, SID-IIs, and Q-series child dummies, with the 50th-percentile adult male still the core benchmark. Many of these dummies were originally developed using biomechanical knowledge and experimental data from the 1970s through to the 1990s. Although some have undergone significant improvements since their introduction, their design and biomechanical response characteristics do not necessarily reflect the latest understanding of human anatomy, injury mechanisms and population diversity.

Some small-stature models, such as the Hybrid III 5th-percentile female dummy, are mainly constructed by geometric scaling. These dummies are generally not systematically calibrated for the physiological structures, tissue mechanical properties, and injury tolerance thresholds of women, elderly people, obese occupants, and children. Assessment based on a single standard body size may underestimate or misjudge the injury risk of vulnerable occupants.

Second, coverage of postures and crash conditions is limited. Regulatory and consumer assessment procedures rely on standardised test conditions to ensure repeatability and comparability. However, these necessarily represent only a limited selection of real-world crash configurations. Chinese in-depth accident data confirm that many crashes occur under conditions not fully covered by existing test procedures [26]. At the same time, developments in automated driving may introduce greater variation in occupant seating positions, including more reclined postures. Conventional crash test dummies have limited capability to represent these configurations, while their biofidelity and the applicability of established injury criteria outside standard seating positions remain uncertain [27]. These challenges highlight the need for more flexible assessment methods that can complement conventional physical testing.

Third, internal tissue responses cannot be directly measured. Crash test dummies primarily measure mechanical responses such as acceleration, force, moment and deformation. These measurements provide valuable indicators of injury risk and are relatively straightforward for engineers to use and interpret, making them well suited to routine safety assessment and vehicle development. However, they cannot directly capture internal tissue responses, such as brain strain, bone stress or organ deformation [28]. Our understanding of these responses is further limited by the availability of experimental human data. Volunteer testing is necessarily restricted to non-injurious loading conditions, while post-mortem human subject (PMHS) testing is limited in availability and often involves older subjects who may not adequately represent the wider population. As a result, conventional physical testing has inherent limitations in assessing tissue-level injury mechanisms and developing more detailed injury prediction methods.

2.1.3 Virtual Testing: A Viable Path to Overcoming These Limitations

Virtual testing using HBMs offers a promising approach to addressing some of the limitations of conventional physical testing. While computer-aided engineering (CAE) has been widely used in vehicle safety

development for decades, virtual testing builds on these established simulation capabilities by extending their use beyond design and optimisation to formal safety assessment. It involves the application of verified and validated numerical models within defined assessment procedures, with appropriate requirements for model qualification, reproducibility and traceability. This allows simulation results to be used as credible evidence in independent safety assessments, complementing or, where appropriate, replacing physical tests.

The three boundaries of physical testing correspond to three clear requirements, and the capabilities of human body models match them one by one.

1. Extending the range of body sizes. Human body models can be adapted to represent different sexes, ages and body sizes, enabling systematic investigation of population differences in biomechanical response and injury risk. This supports more inclusive safety assessments beyond the limited range of anthropometries represented by conventional crash test dummies[29].

2. Extending the range of postures and crash scenarios. Human body models offer greater flexibility to investigate different loading conditions and occupant postures, including frontal, side, rear and rollover crashes, as well as pedestrian impacts and reclined seating positions. Subject to appropriate model validation, virtual testing also enables large-scale parametric studies and sensitivity analyses without the need for additional physical prototypes or crash tests, potentially reducing testing costs and expanding assessment coverage**.**

3.Extending assessment to tissue-level responses. Human body models can provide detailed information on internal responses, including tissue strain, organ deformation and stress distribution, which cannot be directly measured using conventional crash test dummies. These predictions offer valuable insights into load transfer and injury mechanisms, complementing the measurements obtained from physical testing.

The main value of virtual testing, and human body models in particular, is therefore not to replace physical testing, but to build on its established foundation of repeatable and comparable safety assessments. Virtual testing offers opportunities to extend assessment to a wider range of body types, crash conditions and injury responses, while maintaining the essential role of physical testing in model validation and safety evaluation.

2.2 Assessment Tools: Collaboration Between Human Body Models and Dummies

2.2.1 Why They Cannot Replace Each Other

Physical dummies participate in physical tests as occupant surrogates. By measuring their own motion and force responses, they reflect the interaction between the dummy, vehicle structure, and restraint system, and produce comparable results through unified calibration and test procedures. Like any measurement device, crash test dummies require regular certification and calibration to ensure that their responses remain within specified tolerances and their measurements are reliable and reproducible. Human body model calculations depend on the established vehicle, restraint, and human models and cannot independently verify actual behaviors not represented in the model. Therefore, simulation of more scenarios does not by itself prove the real vehicle's protection performance in those scenarios. Similarly, standardized dummy measurements cannot provide the internal tissue responses described by human body models.

The validation paths of dummy simulation models and human body models are also not interchangeable. Dummy simulation models are benchmarked against the corresponding physical dummy through component

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and whole-body tests to verify motion, deformation, and measurement channels. Human body models require applicable human biomechanical data to evaluate the credibility of overall motion, local tissue response, and injury prediction. Low-risk volunteer tests, PMHS tests, and accident data serve different purposes. Agreement between a dummy simulation model and a physical test does not mean that a human body model in the same simulation environment has also been validated; reasonable overall motion does not necessarily prove reliable local injury prediction.

Furthermore, validated model responses still require explicit evaluation rules before they can be used in regulations or star ratings. Dummy indicators rely on corresponding test procedures, injury assessment methods, and decision rules. Results from dummy simulation models and human body models must also satisfy procedure requirements for model qualification, applicable scenarios, evaluation indicators, and result processing. Whether a test or evaluation step can be replaced should be determined by the evidence required and the procedure, not merely by similar responses or better predictions.

2.2.2 A Three-Phase Roadmap for Collaboration

Collaboration between dummies and human body models can be divided into three stages according to validation depth and evidence accumulation: supplementary monitoring and process validation; supplementary injury evaluation and consistency checking; and formal evaluation expansion and application promotion.

The first stage is monitoring and process validation. In this stage, physical dummies continue to perform established evaluation tasks, while human body models mainly participate as monitoring items and research data sources. The objective is not to directly change scores, but to collect data on human motion, restraint contact, and local tissue responses; to complete processes including model qualification, vehicle model validation, human body model positioning, simulation setup, result processing, and review; and to identify missing validation evidence in target scenarios [30][31]. Model qualification assessment should also address the basis for validation across different body types, the consistency of post-processing methods, and the traceability of model changes and computational results [32]. Taking chest protection in frontal impact as an example, the physical dummy provides benchmark occupant motion and chest loading; the dummy simulation model verifies the vehicle and restraint system model; and the human body model supplements observation of seatbelt and airbag load distribution in chest tissues [33].

The second stage is supplementary injury evaluation and consistency checking. This stage covers two complementary uses of human body models. First, HBM can be used for kinematic consistency checking where its more human-like representation provides information that dummies cannot readily offer. The CoHerent project (Methodology for Comparison of Human Body Models for pedestrian simulations) at Graz University of Technology developed a kinematic comparison method adopted in the Euro NCAP pedestrian HBM certification procedure. Body trajectories and head impact time (HIT) are compared to check model consistency[34][35]. Second, where existing validation evidence supports the required analysis depth, HBM can supplement the evaluation of injury-related responses that dummies cannot directly measure, such as spinal load, rib or cortical bone strain, brain tissue strain, and organ pressure [33]. For indicators with corresponding definitions and measurement locations, occupant motion and restraint contact responses should be compared between dummies and HBMs. Local tissue responses from HBMs should be compared with relevant human biomechanical test data. If results diverge or even contradict each other, the HBM result should not simply replace the dummy result. Instead, differences should be traced to model version, posture

and contact state, validation scope, injury risk functions, solver settings, and the applicability boundaries of the dummy itself. Only after these differences are explained and the predictions are sufficiently validated should HBM results be used for supplementary injury evaluation or protection comparison.

The third stage is formal evaluation expansion and application promotion. When injury indicators, risk functions, thresholds, and target-scenario validation of human body models meet the relevant requirements and satisfy explicit procedure rules for model qualification, data submission, and result processing, human body models can gradually undertake more formal evaluation tasks, extend to more populations, postures, and crash scenarios, and increase the weight of their results in clearly defined evaluation steps [30]. Applicability should be stated explicitly, and model version, scenario setup, and result processing should be recorded to ensure that evidence is auditable and traceable.

Existing application: WorldSID arm loading. Euro NCAP CP203 permits an alternative assessment of thorax rib 1 when its requirements for advance declaration, arm-to-rib loading, restraint-system operation and supporting data are met. The supporting data include WorldSID and HBM simulations[36].

The active hood application in pedestrian protection illustrates task-specific collaboration between testing and simulation. Physical tests and certified human body model simulations are jointly used to demonstrate the system's ability to detect pedestrians of different body sizes, the deployment timing, and hood deformation caused by body loading[34]. This example shows that human body model use must correspond to a specific protection function and evidence requirement and should not be generalized beyond its applicable scope.

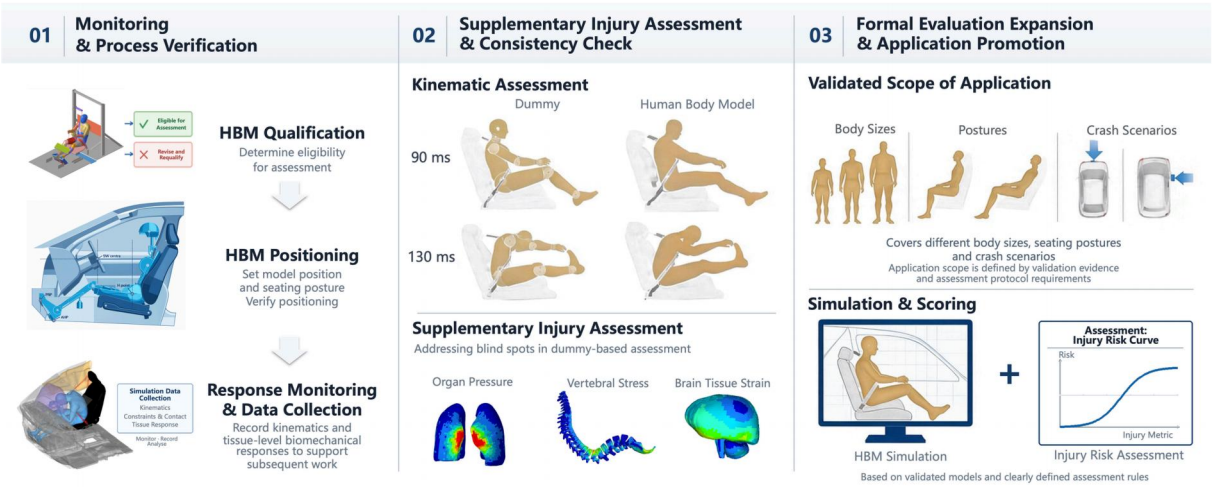

Figure 9. Roadmap for collaboration between human body models and dummies

Overall, the collaboration between dummies and human body models is not simple replacement, but a gradual process of "physical testing establishes the benchmark—human body models supplement information—validated applications are expanded." Further work is needed to clarify which populations, postures, and crash conditions existing validation evidence can support; how to judge the credibility of dummy indicators and human body model predictions when they disagree; and what standards should be used to determine the comparability and admissibility of results from different models, versions, and solver settings.

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CHAPTER 03

Summary and Outlook

03

3.1 Summary

This part systematically reviews the basic concepts, global landscape, application scenarios, and relationship with dummies of human body models under the theme "Human Body Models and Crash Test Dummies: From Differences to Synergy". Human body models are based on human anatomical structure and tissue mechanics and can output multi-level information including whole-body motion, restraint contact, bone stress, tissue strain, and organ response. They provide a new technical tool for injury mechanism research, protection system optimization, and assessment system expansion. However, human body models are not automatically superior to dummies; the credibility of their results depends on model construction, validation evidence, applicability boundaries, and result-processing rules.

The first basic conclusion of this part is that **physical dummies remain the repeatable, comparable, and traceable evaluation benchmark in current regulations and assessment systems.** Their high degree of standardization and mature procedural system make them irreplaceable in comparing vehicle safety performance. Dummy simulation models inherit the measurement object and evaluation logic of physical dummies and can support design screening, parameter analysis, and interpretation of test results. Human body models further supplement internal tissue response, multi-population differences, and non-standard posture information. The three tools have different boundaries and should complement one another around specific evaluation tasks rather than simply replace one another.

The second basic conclusion is that **the introduction of human body models into formal assessment should follow a gradual path.** In the short term, they should mainly provide supplementary monitoring and research data to accumulate process and baseline evidence. In the medium term, they should supplement the evaluation of injury types that dummies cannot directly measure in sufficiently validated populations, postures, and scenarios, and use comparison of commonly measurable indicators to examine result consistency. In the long term, once injury indicators, risk functions, thresholds, and model qualification requirements are established, the scope and weight of human body models in formal evaluation can be expanded. This process should be based on validation evidence and procedural requirements, not on technical maturity alone or promotional expectations.

The third basic conclusion is that **the industrial value of human body models depends not only on the models themselves but also on the supporting validation, data, and governance systems.** Model developers need to improve the transparency and completeness of validation; vehicle manufacturers need to establish standardized model-use processes in development; and assessment organizations need to progressively clarify model qualification, applicable scenarios, data submission, and result-review requirements. Only by forming an auditable, comparable, and traceable application ecosystem can human body models truly evolve from research tools into trusted assessment tools.

3.2 Outlook for the Development of HBM

3.2.1 Model Development: Expansion of Multi-Population and Multi-Posture Coverage

In terms of population characteristics, human body models are expected to evolve from a single benchmark standard adult male toward a population family covering different body sizes, sexes, and ages, thereby providing more representative safety assessments for different road users. Previous parametric studies have shown that even among individuals of the same sex, stature, and weight, differences in anatomical geometry—such as the ribcage and pelvis—can still significantly affect crash injury risk [37]. Therefore, progress toward population diversity should not stop at adding several body-size categories or simply scaling a baseline model. Instead, it should combine personalized modeling with population diversity to progressively represent individual and population differences in key anatomical structures.

In terms of posture, models are expected to extend from standard upright seated, standing, and walking postures to non-standard postures such as reclined seating, out-of-position conditions caused by AEB, cycling, and evasive maneuvers. The development of rapid repositioning techniques is gradually shifting posture generation from time-consuming external-force-based adjustment toward parametric and streamlined processing [38]. However, being able to position a model does not mean being able to evaluate injury: postural changes alter the interaction between seatbelts, airbags, and the human body, as well as internal load-transfer paths. Injury prediction in reclined, out-of-position, and other postures cannot directly inherit validation findings established for standard seating. Therefore, multi-population and multi-posture extension must advance in parallel with corresponding validation evidence, so as to avoid equating extension in geometry and posture with expanded assessment capability.

3.2.2 Applications: Injury Research, Engineering Development and Others

1) Traffic injury mechanism research. Human body models can reconstruct the complete response process from whole-body motion to tissue injury in real road accidents, covering typical traffic injuries such as diffuse axonal injury, rib fracture, organ injury, and ligament rupture. By quantitatively analyzing tissue-level responses, they help establish relationships between injury indicators and actual injuries, providing a biomechanical basis for injury risk curves and tolerance thresholds.

2) Automotive safety device development. Human body models are widely used to evaluate the interaction and load transfer between devices such as seatbelts, airbags, steering wheels, pop-up hoods, and pedestrian airbags and different human body regions. Parametric simulation supports optimization of design variables, helps identify risks before physical testing, shortens development cycles, and reduces test and prototype costs.

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3) Cross-domain applications. In medical health, they can support rehabilitation implants, medical device design, and personalized surgical planning, such as spinal correction simulation. In aerospace, they can assess occupant injury risk during takeoff, landing, and emergency landing, and help optimize seat energy absorption and restraint layout. In occupational safety, they can be used for ergonomic assessment and protective equipment development, such as simulating intervertebral disc pressure, vertebral stress, and muscle activity in lifting and bending postures, and supporting the design of exoskeletons and other protective equipment.

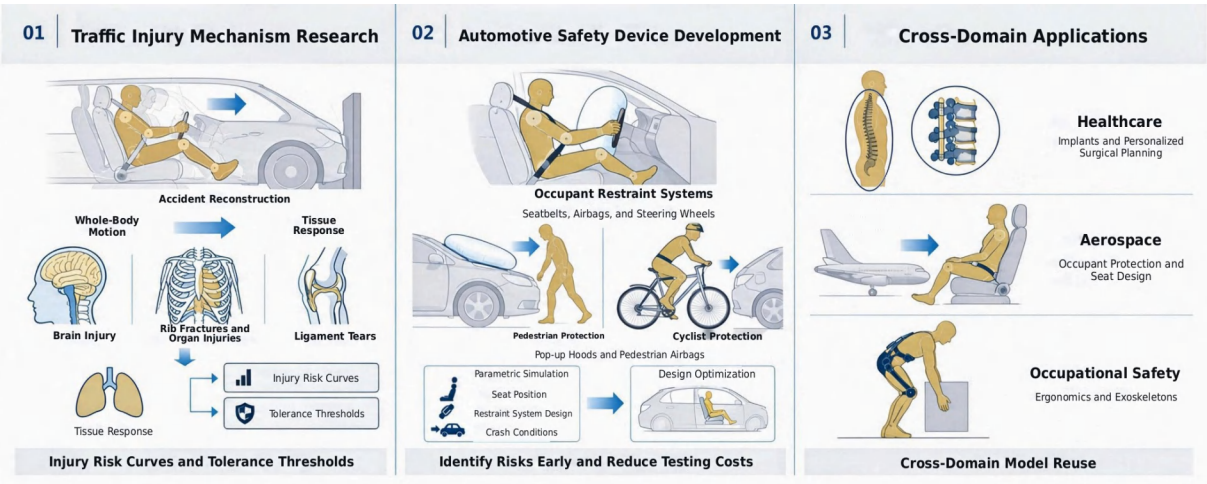

Figure 10. Application expansion of human body models

3.3 Outlook for the White Paper Series

The next two parts will build on this foundation. Part 2 will systematically introduce the development and validation system of human body models, focusing on how models are constructed, validated, and judged for credibility. Part 3 will focus on applications and roadmaps in virtual testing, addressing how models enter assessment, what qualification conditions they must satisfy, and how they should develop in the future.

APPENDIX A · GLOSSARY

附录A　本期术语表

A

本期白皮书涉及的主要缩写与术语，供跨语种阅读与技术沟通参考。

This appendix lists the main abbreviations and terms used in this white paper for cross-language reading and technical communication.

缩写/术语 Abbreviation/Term	英文全称Full term	释义Definition
HBM	Human Body Model	人体模型。本文在无特别说明时默认指人体有限元模型。A human body model; unless otherwise stated, this paper refers to finite element human body models.
FE-HBM	Finite Element Human Body Model	有限元人体模型，用于计算组织变形、应力应变与损伤响应。A human body model constructed with the finite element method to compute tissue deformation, stress, strain, and injury response.
ATD	Anthropomorphic Test Device	物理碰撞试验假人，用于实体试验中提供标准化测量。A physical crash test dummy used to provide standardized measurements in physical tests.
PMHS	Post-Mortem Human Subject	遗体捐献者试验样本，用于获取生物力学响应数据并支持模型验证。A deceased human donor specimen used to obtain biomechanical response data and support model validation.
AIS	Abbreviated Injury Scale	简明损伤定级标准，用于描述损伤严重程度。A standardized injury scale used to describe injury severity.
CORA	Correlation and Analysis	信号相关性评价方法，常用于比较仿真曲线与试验曲线的一致性。A signal-correlation method commonly used to compare simulation and test curves.
Star Rating	Star Rating	星级评价，用于综合反映车辆在测评规程中的安全表现。A rating system used to summarize vehicle safety performance in assessment procedures.
CP 550	Euro NCAP Qualification Procedure for Human Body Models	Euro NCAP 人体模型资格认证程序。Euro NCAP procedure for qualifying human body models.
CP 551	Euro NCAP Human Body Model Simulation for Frontal Impacts	Euro NCAP 正面碰撞 HBM 仿真、数据提交与使用范围要求。Euro NCAP requirements for frontal-impact HBM simulation, data submission, and scope of use.
VT	Virtual Testing	以经过验证的模型和仿真补充或替代部分实体试验的评价方式。An evaluation method that uses validated models and simulation to supplement or replace some physical tests.

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APPENDIX B · REFERENCES

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