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Implementers Advancing Digital Health and Care Transformation

Virtual human digital twin and AI agentic integration: Will it change the health prevention paradigm?

虚拟人体数字孪生与智能体AI融合：会改变健康预防范式吗？

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Digital Twins in Healthcare

医疗健康数字孪生

From prediction to personalised simulation and decision-making: not simply predicting the future, but helping us **explore alternative futures**

从预测走向个性化模拟与决策：不只是预测未来，而是帮助我们探索不同的未来

Healthcare is becoming increasingly data-rich — and increasingly complex.

医疗正变得数据更丰富，也更复杂

EHR
电子病历

Imaging
影像

Wearables
可穿戴设备

Genomics
基因组学

Environment
环境

Lifestyle
生活方式

Digital twins are evolving from models of machines, organs or processes towards increasingly comprehensive representations of individual people.

DYNAMIC DIGITAL
REPRESENTATION
动态数字表征

数字孪生正从机器、器官**或流程模型**，发展为对个**体人的更全面表征**

More data • more chronic conditions • more personalised decisions

更多数据 • 更多慢病 • 更个性化的决策

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What exactly is a Healthcare Digital Twin?
什么是医疗数字孪生？

DIGITAL RECORD
数字记录

What happened?
发生了什么

AI MODEL
AI模型

What is likely to happen?
可能发生什么

DIGITAL TWIN
数字孪生

What happens if we do something differently?
如果换一种做法，会发生什么？

Representation • Continuous updating • Prediction • Simulation • Feedback
表征 • 持续更新 • 预测 • 模拟 • 反馈

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Where are we today? 我们现在处于什么阶段？

Maturity is very uneven across healthcare 医疗领域的成熟度很不均衡

RELATIVELY MORE MATURE **相对成熟**	• Cardiovascular • Orthopaedics / musculoskeletal • Selected oncology applications	• 心血管 • 骨科/肌骨系统 • 部分肿瘤应用
EMERGING **正在兴起**	• Brain / neurodegeneration • Frailty / ageing • Chronic disease	• 脑/神经退行性疾病 • 衰弱/老龄化 • 慢性病
RESEARCH FRONTIER **研究前沿**	• Whole-person Digital Twins • Virtual Human Twins	• 全人数字孪生 • 虚拟人体孪生

Whole-person representation remains much less mature than organ- or disease-specific twins.
全人表征仍远不如器官或疾病特异性孪生成熟

Where is the State of the Art? 目前最前沿进展在哪里？

Domain 领域		Current maturity 当前成熟度		Examples of DT use 应用示例	
Cardiovascular	心血管	Relatively advanced	相对先进	electrophysiology, intervention planning	电生理、介入规划
Orthopaedics	骨科	Relatively advanced	相对先进	joint/spine modelling	关节/脊柱建模
Oncology	肿瘤学	Emerging/advanced in specific areas	部分领域兴起/较先进	tumour growth, treatment response	肿瘤生长、治疗反应
Brain/neurodegeneration	脑/神经退行性疾病	Emerging	正在兴起	disease progression, stimulation, diagnosis	疾病进展、刺激治疗、诊断
Frailty/ageing	衰弱/老龄化	Emerging	正在兴起	mobility, falls, functional decline	活动能力、跌倒、功能下降
Whole-person VHT	全人VHT	Research frontier	研究前沿	multimorbidity, personalised trajectories	多病共存、个性化轨迹

While truly promising **we should not oversell the maturity of Virtual Human Twins**.

虚拟人体孪生确实前景可期，但不应夸大其成熟度

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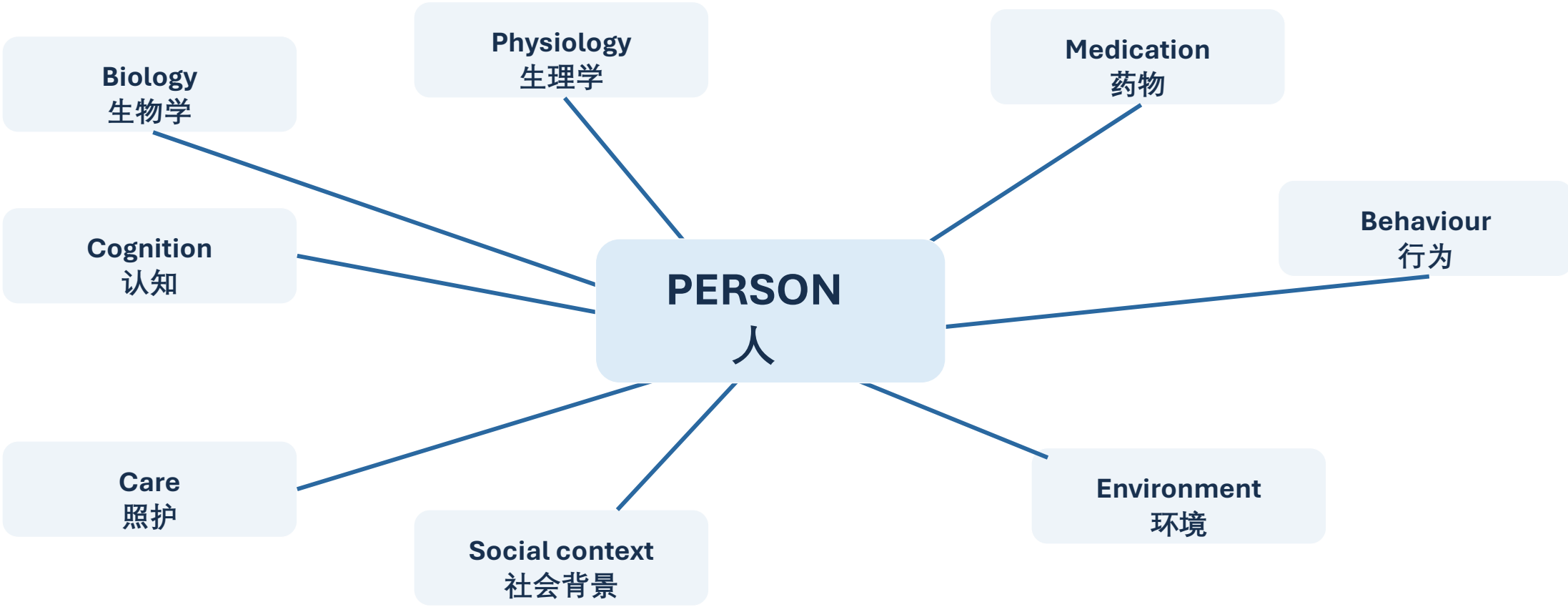
Why is the human being the hardest Digital Twin?
为什么人是最难构建的数字孪生？



Multiple interacting systems • multiple data sources • multiple timescales:
The challenge is not simply having more data. It is understanding how these different dimensions interact over time

多个相互作用系统 • 多种数据来源 • 多个时间尺度：
挑战不只是拥有更多数据，**而是理解**这些不同维度如何随时间相互作用

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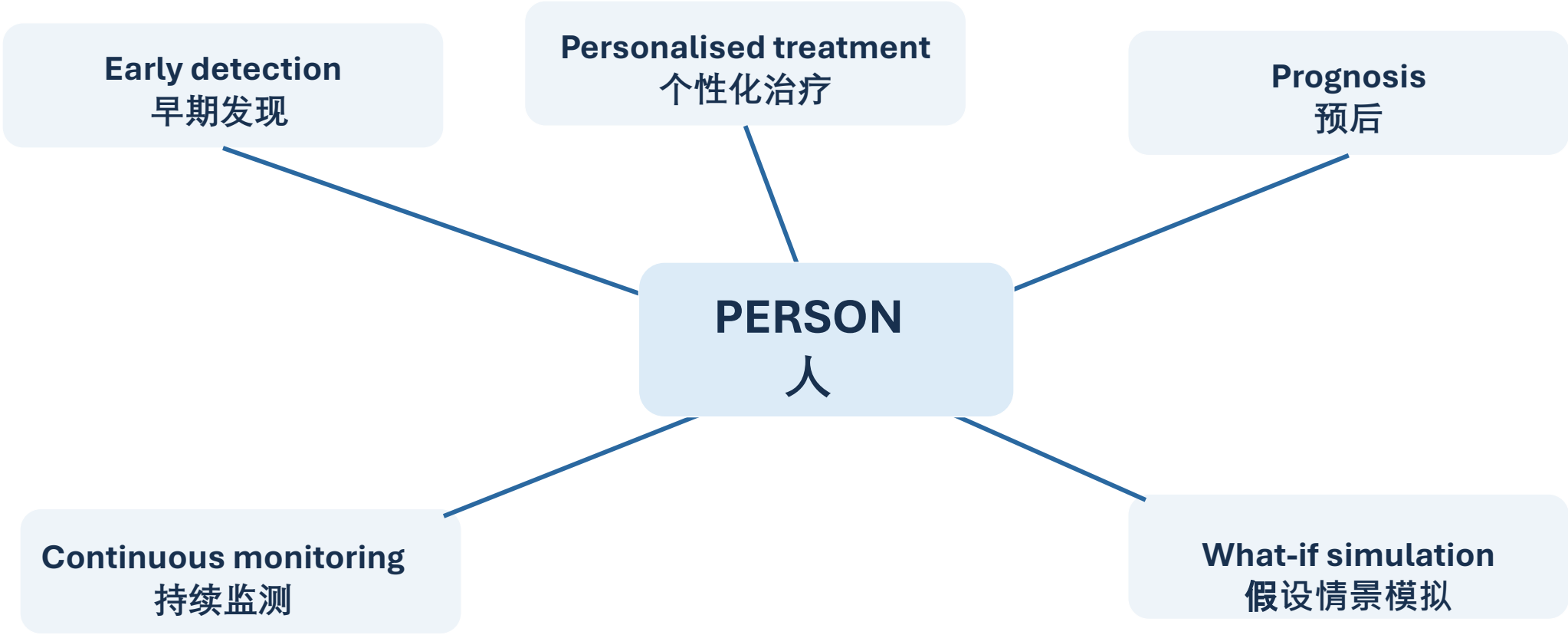
Where could Digital Twins create the greatest value? 数字孪生能在哪些方面创造最大价值？



From reactive care → proactive, personalised care

从被动医疗 → 主动、个性化照护

The real breakthrough: “What if?”
真正的突破：“如果……会怎样？”

CURRENT PATIENT
TRAJECTORY
当前患者 轨迹

PATIENT
DIGITAL TWIN
患者 数字孪生

Treatment A → trajectory A
治疗A → 轨迹A

Treatment B → trajectory B
治疗A → 轨迹A

No intervention → trajectory C
无干预 → 轨迹A

What if:
- medication is changed?
- physical activity increases?
- rehabilitation starts?
- nutrition improves?
- home environment changes?
- treatment is delayed?

如果：
- **改**变用药？
- **增加身体活**动？
- **开始康复？**
- **改善**营养？
- **改**变居家环境？
- **延**迟治疗？

Prediction tells us what may happen. Simulation asks what could happen.
Decision support helps us choose.

预测告诉我们可能发生什么，模拟追问还可能怎样发生
决策支持帮助我们作出选择

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A Digital Twin is an ecosystem — not an AI model

数字孪生是一个生态系统，而不只是AI模型

REAL WORLD
真实世界

Patient • EHR • Imaging • Sensors • Omics • Environment
患者 • 电子病历 • **影像** • 传感器 • 组学 • 环境

INTEGRATION
整合

Interoperability • semantic harmonisation • trusted access
互操作性 • 语义统一 • **可信**访问

MODEL
模型

Patient-specific representation
患者特异性表征

SIMULATION + AI
刺激+AI

Prediction • risk • scenarios
预测 • 风险 • **情景**

DECISION
决策

Clinician • patient • care team
临床医生 • **患者** • **照**护团队

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The missing ingredient: integration
缺失的关键：整合

EHR
电子病历

Lab
检验

Imaging
影像

Wearable
可穿戴设备

Genomics
基因组学

Home
家庭

Patient-reported
患者报告

INTEROPERABILITY + SEMANTICS + GOVERNANCE
互操作性 + 语义 + 治理

COHERENT, LONGITUDINAL
PATIENT MODEL
连贯、纵向的患者模型

Data quality determines twin quality.

数据质量决定孪生质量

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AI alone will not be enough 仅靠AI还不够

AI / MACHINE LEARNING
AI/机器学习
Pattern recognition 模式识别
Prediction 预测
Personalisation 个性化

MECHANISTIC / KNOWLEDGE MODELS
机制/知识模型
Physiology 生理学
Disease mechanisms 疾病机制
Causal relationships 因果关系

HYBRID DIGITAL TWIN
混合型数字孪生

Data-driven + knowledge-driven
数据驱动 + 知识驱动

What does a clinician actually need?
临床医生真正需要什么？

RELEVANT
相关

Answers a real clinical question
回答真实临床问题

RELIABLE
可靠

Validated against real outcomes
经真实结局验证

UNDERSTANDABLE
可理解

Clinicians can interpret the output
临床医生能解释输出

ACTIONABLE
可行动

Supports a possible intervention
支持可实施的干预

INTEGRATED
可整合

Fits the clinical workflow
融入临床工作流

The best Digital Twin is not the most sophisticated one. It is the one that improves a decision.
最好的数字孪生不是最复杂的，而是能改善决策的

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And what does the patient need?
患者又需要什么？

CLINICIAN
临床医生

DIGITAL TWIN
数字孪生

PATIENT
患者

“Which intervention is most appropriate?”
“哪种干预最合适？”

“What does this mean for me?”
“这对我意味着什么？”

Personalised information • shared decision-making • prevention • self-management • feedback
个性化信息 • 共同决策 • 预防 • 自我管理 • 反馈

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Trust is the real gateway to adoption
信任才是采用的真正入口

No trust → no adoption

没有信任 → 就没有采用

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The “valley of death”: from prototype to healthcare
“死亡之谷”：从原型走向医疗实践

Research
研究

Prototype
原型

Technical
validation
技术验证

Clinical
validation
临床验证

Real-world
implementation
真实世界实施

Health-economic
evidence
卫生经济学证据

Routine care
常规医疗

THE GAP
断层

The hardest step is not building the twin.

It is proving its value in the real world.

最难的一步不是构建孪生，
而是在真实世界证明其价值。

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Five priorities for Europe 欧洲的五项优先任务

01 **DATA**

数据

Interoperable longitudinal health data

可互操作的纵向健康数据

02 **MODELS**

模型

Independent clinical & real-world evidence

独立的临床与真实世界证据

03 **VALIDATION**

验证

Open, robust, reusable approaches

开放、稳健、可复用的方法

04 **TRUST**

信任

Infrastructure, interoperability & sustainability

基础设施、互操作性与可持续性

05 **SCALE**

规模化

Privacy, ethics, transparency & accountability

隐私、伦理、透明度与问责

Europe's opportunity is to build a trusted ecosystem in which Digital Twins can work across healthcare systems.

欧洲的机会在于构建一个可信生态系统，使数字孪生能够跨医疗体系发挥作用

VHTnet

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PDT Architecture & Data Integration
PDT架构与数据整合

COMFORTage

Data Collection
数据采集

Wearables, Clinical Assessments, Genomics

可穿戴、临床评估、基因组学

Data Integration
数据整合

FHIR/HL7, ETL Pipelines, Quality

FHIR/HL7、ETL **流程**、质量

AI Engine
AI 引擎

ML Models, Deep Learning, NLP

机器学习模型、深度**学**习、NLP

Digital Twin
数字孪生

Patient Model, Simulation, Prediction

患者模型、**模**拟、预测

Key Standards & Technologies 关键标准与技术

FHIR R4 | HL7 v2 | OMOP CDM | SNOMED CT | LOINC | REST APIs

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Continuous Monitoring Data

连续监测数据

24/7 data streams from wearable devices and smart home sensors

来自可穿戴设备和智能家居传感器的7×24小时数据流

COMFORTage

Sleep Patterns 睡眠模式

- Sleep duration & quality
  - 睡眠时长与质量
- Sleep stage distribution
  - 睡眠分期分布
- Night-time awakenings
  - 夜间觉醒
- Circadian rhythm changes
  - 昼夜节律变化

Physical Activity 身体活动

- Step count & distance
  - 步数与距离
- Activity intensity levels
  - 活动强度水平
- Sedentary time tracking
  - 久坐时间追踪
- Gait speed & stability
  - 步速与稳定性

Vital Signs 生命体征

- Heart rate variability
  - 心率变异性
- Blood pressure trends
  - 血压趋势
- SpO_2 monitoring
  - SpO_2监测
- Body temperature
  - 体温

Data is collected passively and non-intrusively, ensuring patient comfort and compliance

数据以被动、非侵入方式采集，确保患者舒适性与依从性

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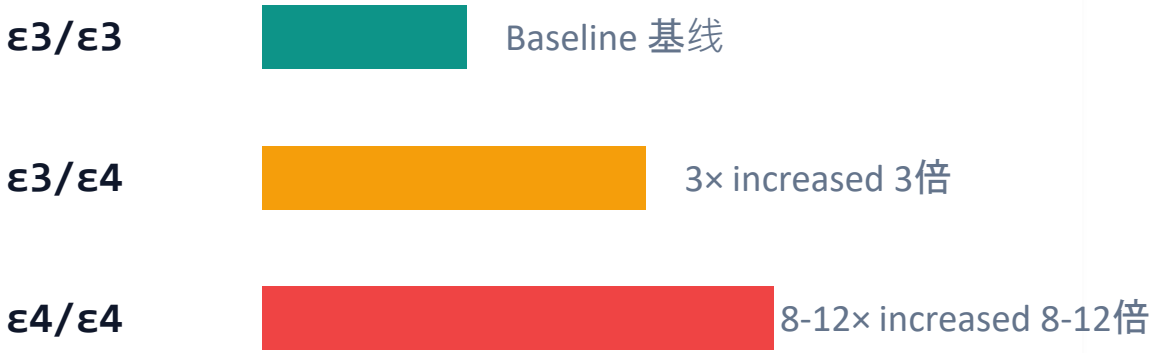
Genetic Markers Integration
遗传标志物整合

COMFORTage

APOE-ε4: The Key Genetic Risk Factor 关键遗传风险因素

The APOE-ε4 allele is the strongest known genetic risk factor for late-onset Alzheimer's disease. Its integration into the PDT enables personalized risk stratification. APOE-ε4等位基因是晚发型阿尔茨海默病已知最强遗传风险因素。纳入PDT可实现个体化风险分层



How Genetics Enhance the PDT
遗传信息如何增强PDT

- Personalized risk scoring calibrated to genetic profile
  基于遗传特征校准个体化风险评分
- Refined trajectory predictions combining genetics + lifestyle
  结合遗传+生活方式优化轨迹预测
- Earlier intervention triggers for high-risk genotypes
  为高风险基因型提前触发干预
- Tailored monitoring frequency based on genetic susceptibility
  根据遗传易感性调整监测频率
- Pharmacogenomic considerations for treatment planning
  将药物基因组学纳入治疗规划

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Multimodal AI for Trajectory Prediction
用于轨迹预测的多模态AI

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AI Pipeline

Data Fusion 数据融合

Merge clinical, sensor, and genomic streams

融合临床、传感器和基因组数据流

Feature Engineering 特征工程

Extract temporal patterns & biomarkers

提取时间模式与生物标志物

Deep Learning Models 深度学习模型

LSTM, Transformer, GNN architectures

LSTM、Transformer、GNN架构

Trajectory Forecasting 轨迹预测

6-24 month progression predictions

6–24个月进展预测

Prediction Capabilities 预测能力

Cognitive Decline 认知下降

MMSE/MoCA score trajectory over time

MMSE/MoCA评分随时间的轨迹

Frailty Progression 衰弱进展

CFS score evolution with confidence intervals

CFS评分变化及置信区间

Fall Risk 跌倒风险

Probability estimation using gait & balance data

基于步态和平衡数据估计概率

Intervention Impact 干预影响

Simulated outcomes of treatment modifications

模拟治疗调整后的结局

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Clinical Validation: Parallel Examination

临床验证：平行评估

Comparing traditional clinical assessment with PDT predictions on synthetic patient cases

在合成患者案例中比较传统临床评估与PDT预测

Clinical Assessment 临床评估

- Standardized battery tests (MMSE, MoCA, CDR)
  - 标准化量表测试（MMSE、MoCA、CDR）
- Physical examination & frailty screening
  - 体格检查与衰弱筛查
- Medical history & medication review
  - 病史与用药审查
- Functional assessment (ADL/IADL)
  - 功能评估（ADL/IADL）
- Care planning based on clinical judgment
  - 基于临床判断制定照护计划

VS

PDT Analysis PDT分析

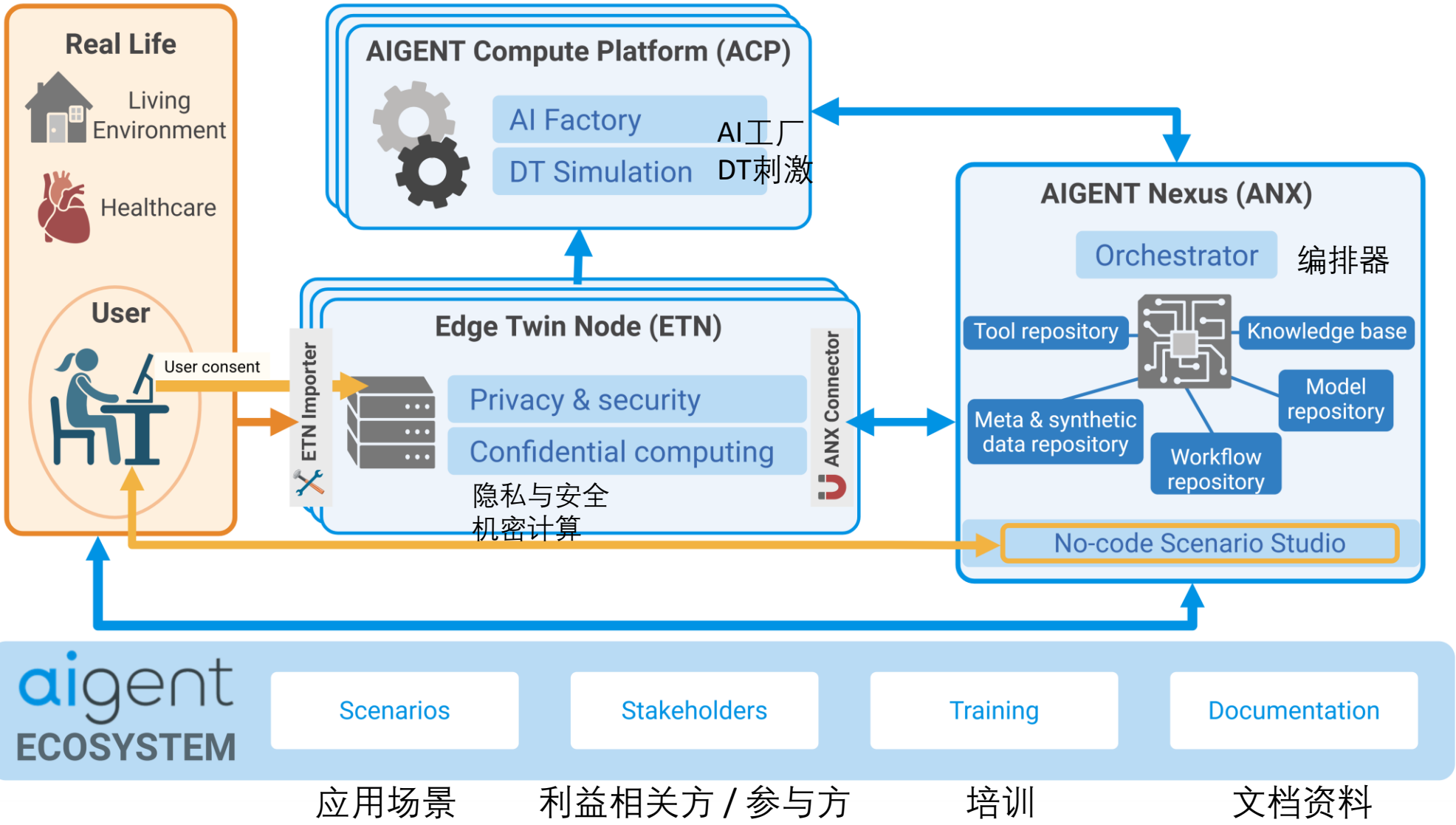
- Continuous monitoring data aggregation
  - 连续监测数据汇聚
- AI-driven trajectory prediction (6-24 mo)
  - AI驱动的轨迹预测（6–24个月）
- Genetic risk factor integration (APOE-ε4)
  - 遗传风险因素整合（APOE-ε4）
- Anomaly detection & early warning alerts
  - 异常检测与早期预警
- Intervention simulation & optimization
  - 干预模拟与优化

现实世界

生活环境

医疗健康

用户



The destination: Virtual Human Twins
目标：虚拟人体孪生

TODAY
DIGITAL HEALTH DATA
今天

NEXT
PATIENT DIGITAL TWIN
Prediction • Personalisation • Simulation
下一步

FUTURE
VIRTUAL HUMAN TWIN
Continuous • Multimodal • Predictive • Simulative • Trusted
未来

数字健康数据

患者数字孪生
预测 • **个性化** • **模拟**

虚拟人体孪生
连续 • **多模态** • 预测性 • **可模拟** • **可信**

BETTER DECISIONS • BETTER PREVENTION • BETTER OUTCOMES
更好决策 • 更好预防 • 更好结局

The goal is not a perfect digital copy of a human being — but a sufficiently trustworthy model to make better decisions for that person.

目标不是创造一个完美的人类数字复制体，而是建立一个足够可信的模型，为这个人做出更好的决策。

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Thank you !

谢谢 !

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