

A Mechanistic Digital Twin for Predicting Physiological and Cognitive Performance to Support Operational Decision-Making

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BLUF: An individualized digital twin reproduced physiological responses to controlled physical, cognitive, and dual-task workload, with the strongest results for oxygen uptake, heart rate, and ventilation. Calibrated to each person's own physiology and daily readiness, the model supplies the individualized, explainable prediction layer that AI-enabled planning and monitoring systems require but cannot generate on their own. Cognitive reaction time and accuracy remain limited by mechanisms beyond oxygen availability.

Introduction

Operational readiness is not a fixed property of an individual. Soldiers, operators, and first responders sustain heavy physical loads while making rapid, life-critical decisions, and the resulting workload degrades performance along trajectories that differ markedly from one person to the next. AI-enabled scheduling tools are used to plan around this, but their output is only as good as the predictions they receive. Population-average models cannot say when a particular person will cross an operationally meaningful threshold, and black-box predictors flag a decline without explaining its cause.

Purpose

This study develops and validates an individualized, physiology-based DT model that predicts a person's physiological responses as well as physical and cognitive performance from task demand and daily readiness state, using interpretable parameters, and serves as the prediction layer for AI-enabled planning and decision-making systems.

Materials & Methods

Participants: 12 participants (9M; age 31.3±9.6yr).

Protocol: Each participant completed three 60-minute sessions on separate days, in randomized order:

- Physical — loaded foot march on a treadmill
- Cognitive — friend-vs-foe clicker game shown on a TV, seated
- Dual-task — the march and the game performed together

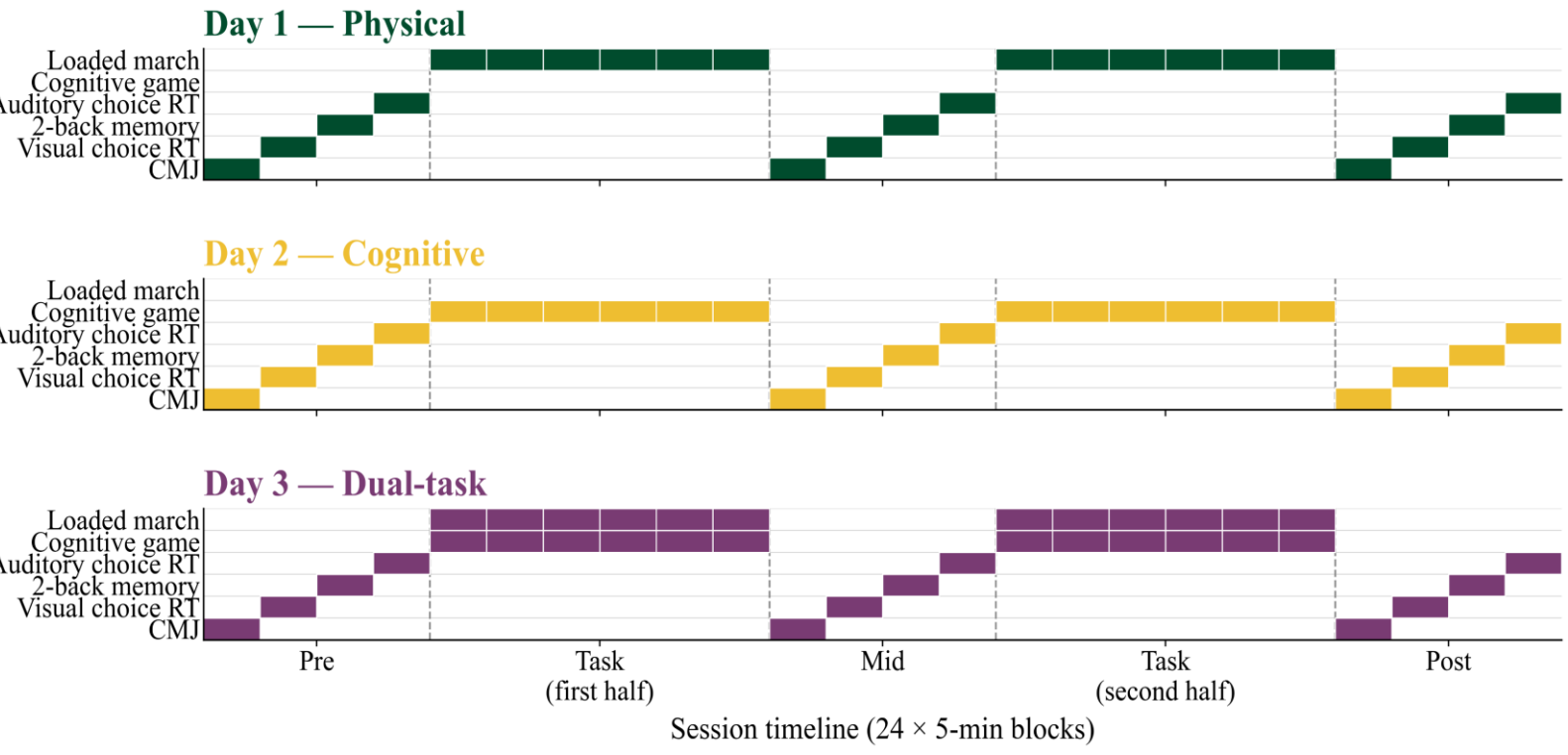
Each day was divided into 24 five-minute blocks — pre-testing, the first half of the task, mid-testing, the second half, and post-testing. Physiological measures were recorded during the final minute of every block. At pre-, mid-, and post-testing, participants completed a countermovement jump (CMJ) and three cognitive tests: a visual choice reaction test, a 2-back memory test, and an auditory choice reaction test.

Daily state: Prior-night sleep duration and morning urine specific gravity were recorded before every session.

Measurements: Oxygen uptake (VO₂), ventilation, heart rate, muscle oxygenation (SmO₂), CMJ peak force, reaction time, and hit rate for each game and the cognitive task.

Modeling: Five coupled physiological modules were fitted to each participant by calibrating 65 subject-specific parameters, minimizing the sum of squared errors between model predictions and observed measurements.

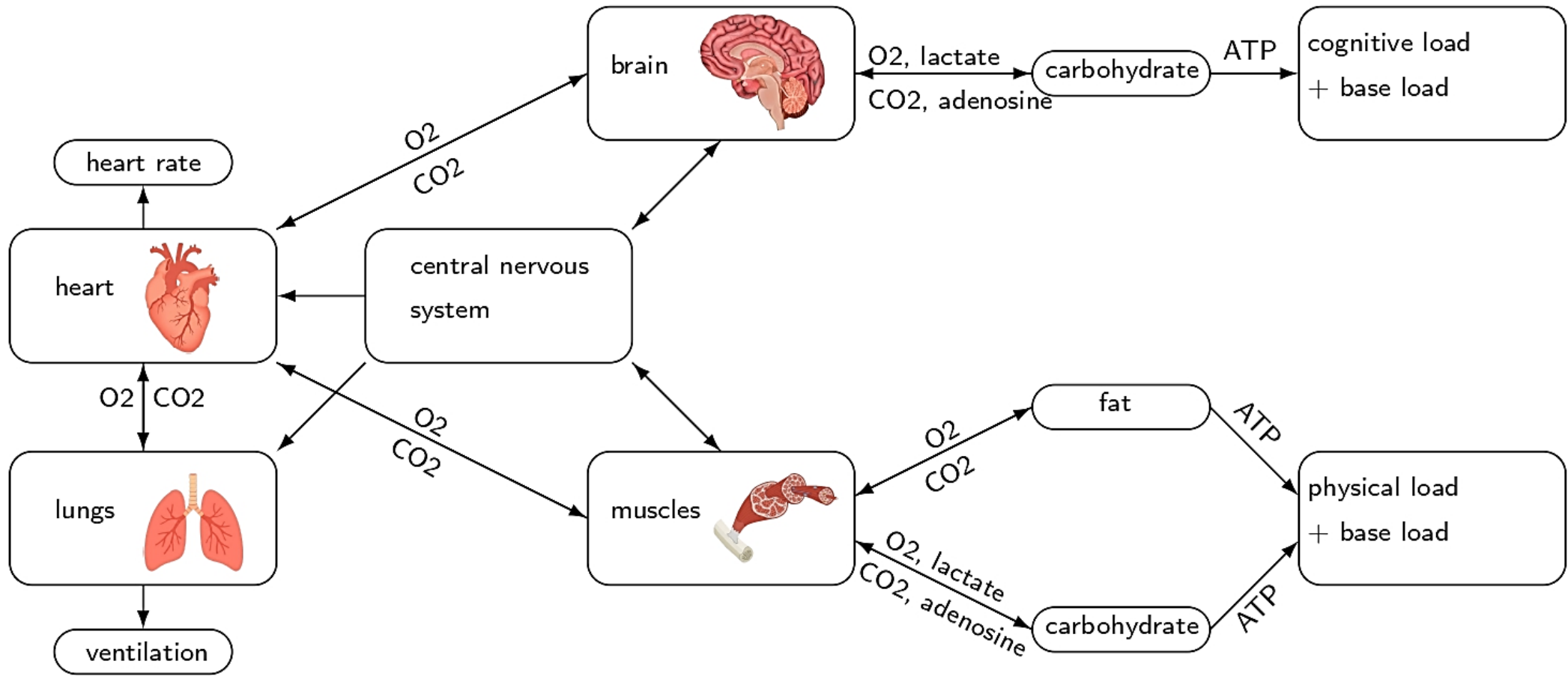
A. Session structure



B. Dual-task session



Physiological Structure



Mathematical Model

Sleep and Hydration Module

$$v_{\text{Sleep}} = \min \left\{ \left(\frac{f_{\text{Sleep}}}{g_{\text{SleepMax}}} \right)^{g^{\text{Sleep}}}, 1 \right\}$$
$$v_{\text{USG}} = \min \left\{ \left(\frac{g_{\text{USGMax}} - f_{\text{USG}}}{g_{\text{USGMax}} - g_{\text{USGMin}}} \right)^{g^{\text{USG}}}, 1 \right\}$$

Oxygen Supply Module

$$v_{\text{HR}} = g_{\text{HRMax}} - (g_{\text{HRMax}} - g_{\text{HRMin}}) [1 - g_{\text{USGHR}} (1 - v_{\text{USG}})] \left[1 - \left(\frac{v_{\text{VO2}} - 1}{g_{\text{VO2Max}}} \right)^{g^{\text{O2Min}}} \right] \forall t$$

$$v_{\text{Vent}} = g_{\text{VentMax}} - (g_{\text{VentMax}} - g_{\text{VentMin}}) [1 - g_{\text{USGVent}} (1 - v_{\text{USG}})] \left[1 - \left(\frac{v_{\text{VO2}} - 1}{g_{\text{VO2Max}}} \right)^{g^{\text{O2Min}}} \right] \forall t$$

Oxygen Uptake Module

$$v_{\text{CMJ}02} = g_{\text{CMJ}02} \cdot \max \left\{ \frac{v_{\text{SuO2}}}{v_{\text{t}} - 1} - \frac{g_{\text{BaseO2}}}{g_{\text{HemoHR}} \cdot [1 - g_{\text{USG}02} (1 - v_{\text{USG}})] \cdot v_{\text{HR}}}, 0 \right\}^{g^{\text{O2}}} \forall t$$

$$v_{\text{Game}02} = g_{\text{Game}02} \cdot \max \left\{ \frac{v_{\text{SuO2}}}{v_{\text{t}} - 1} - \frac{g_{\text{BaseO2}}}{g_{\text{HemoHR}} \cdot [1 - g_{\text{USG}02} (1 - v_{\text{USG}})] \cdot v_{\text{HR}}}, 0 \right\}^{g^{\text{O2}}} \forall t, i$$

$$v_{\text{t}}^{\text{CO2}} = g_{\text{CO2}} \cdot \max \left\{ \frac{v_{\text{SuO2}}}{v_{\text{t}} - 1} - \frac{g_{\text{BaseO2}} + E_{\text{March}} \cdot g_{\text{March}02}}{g_{\text{HemoHR}} \cdot [1 - g_{\text{USG}02} (1 - v_{\text{USG}})] \cdot v_{\text{HR}}}, 0 \right\}^{g^{\text{O2}}} \forall t$$

$$v_{\text{t}}^{\text{VO2}} = g_{\text{BaseO2}} + E_{\text{CMJ}} \cdot v_{\text{CMJ}02} + \sum_i E_{\text{Game}} \cdot v_{\text{Game}02} + E_{\text{March}} \cdot g_{\text{March}02} + E_{\text{t}}^{\text{CO2}} \cdot v_{\text{t}}^{\text{CO2}} \forall t$$

$$v_{\text{t}}^{\text{SuO2}} = v_{\text{t}}^{\text{SuO2}} - \frac{v_{\text{VO2}}}{g_{\text{HemoHR}} \cdot [1 - g_{\text{USGSuO2}} (1 - v_{\text{USG}})] \cdot v_{\text{HR}}} \forall t$$

CMJ Module

$$v_{\text{t}}^{\text{CMJ}} = g_{\text{CMJMax}} \cdot [1 - g_{\text{SleepCMJ}} \cdot (1 - v_{\text{Sleep}})] \cdot [1 - g_{\text{USGCMJ}} \cdot (1 - v_{\text{USG}})] \cdot \left(\frac{v_{\text{CMJ}02}}{g_{\text{CMJ}02}} \right)^{g^{\text{O2}}} \forall t$$

Cognitive Module

$$v_{\text{t}}^{\text{RTGame}} = g_{\text{RTGameMin}} \cdot [1 + g_{\text{SleepRTGame}} \cdot (1 - v_{\text{Sleep}})] \cdot [1 + g_{\text{USGRTGame}} \cdot (1 - v_{\text{USG}})] \times \left[1 + g_{\text{O2RTGame}} \cdot \log \left(\frac{g_{\text{GameO2}}}{v_{\text{t}}^{\text{GameO2}}} \right) \right] \forall t, i$$

$$v_{\text{t}}^{\text{RTCog}} = g_{\text{RTCogMin}} \cdot [1 + g_{\text{SleepRTCog}} \cdot (1 - v_{\text{Sleep}})] \cdot [1 + g_{\text{USGRTCog}} \cdot (1 - v_{\text{USG}})] \times \left[1 + g_{\text{O2RTCog}} \cdot \log \left(\frac{g_{\text{CogO2}}}{v_{\text{t}}^{\text{CogO2}}} \right) \right] \forall t$$

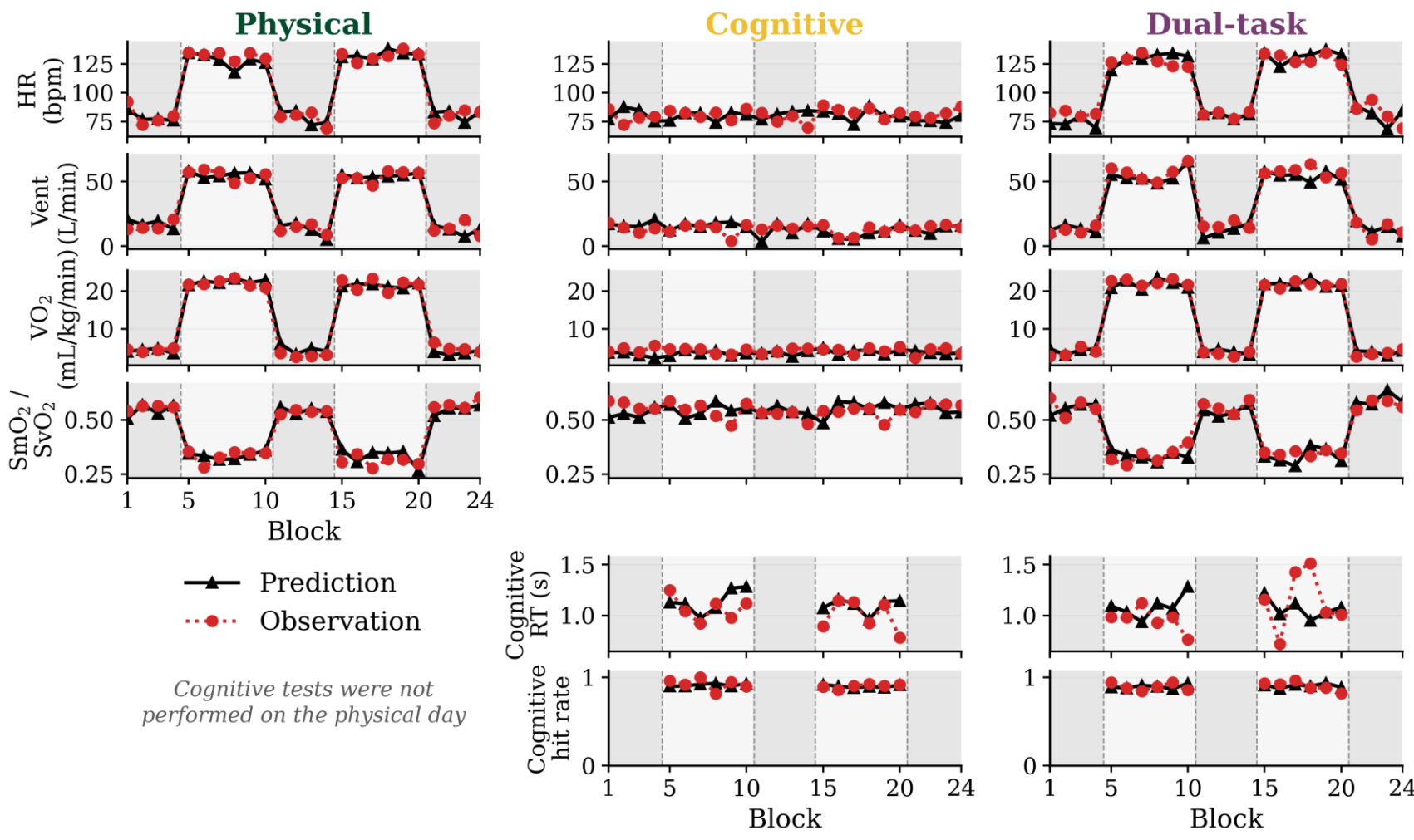
$$v_{\text{t}}^{\text{HitGame}} = g_{\text{HitGameMax}} \cdot [1 - g_{\text{SleepHitGame}} \cdot (1 - v_{\text{Sleep}})] \cdot [1 - g_{\text{USGHitGame}} \cdot (1 - v_{\text{USG}})] \times \left(\frac{v_{\text{t}}^{\text{GameO2}}}{g_{\text{GameO2}}} \right)^{g^{\text{O2}}} \forall t, i$$

$$v_{\text{t}}^{\text{HitCog}} = g_{\text{HitCogMax}} \cdot [1 - g_{\text{SleepHitCog}} \cdot (1 - v_{\text{Sleep}})] \cdot [1 - g_{\text{USGHitCog}} \cdot (1 - v_{\text{USG}})] \times \left(\frac{v_{\text{t}}^{\text{CogO2}}}{g_{\text{CogO2}}} \right)^{g^{\text{O2}}} \forall t$$

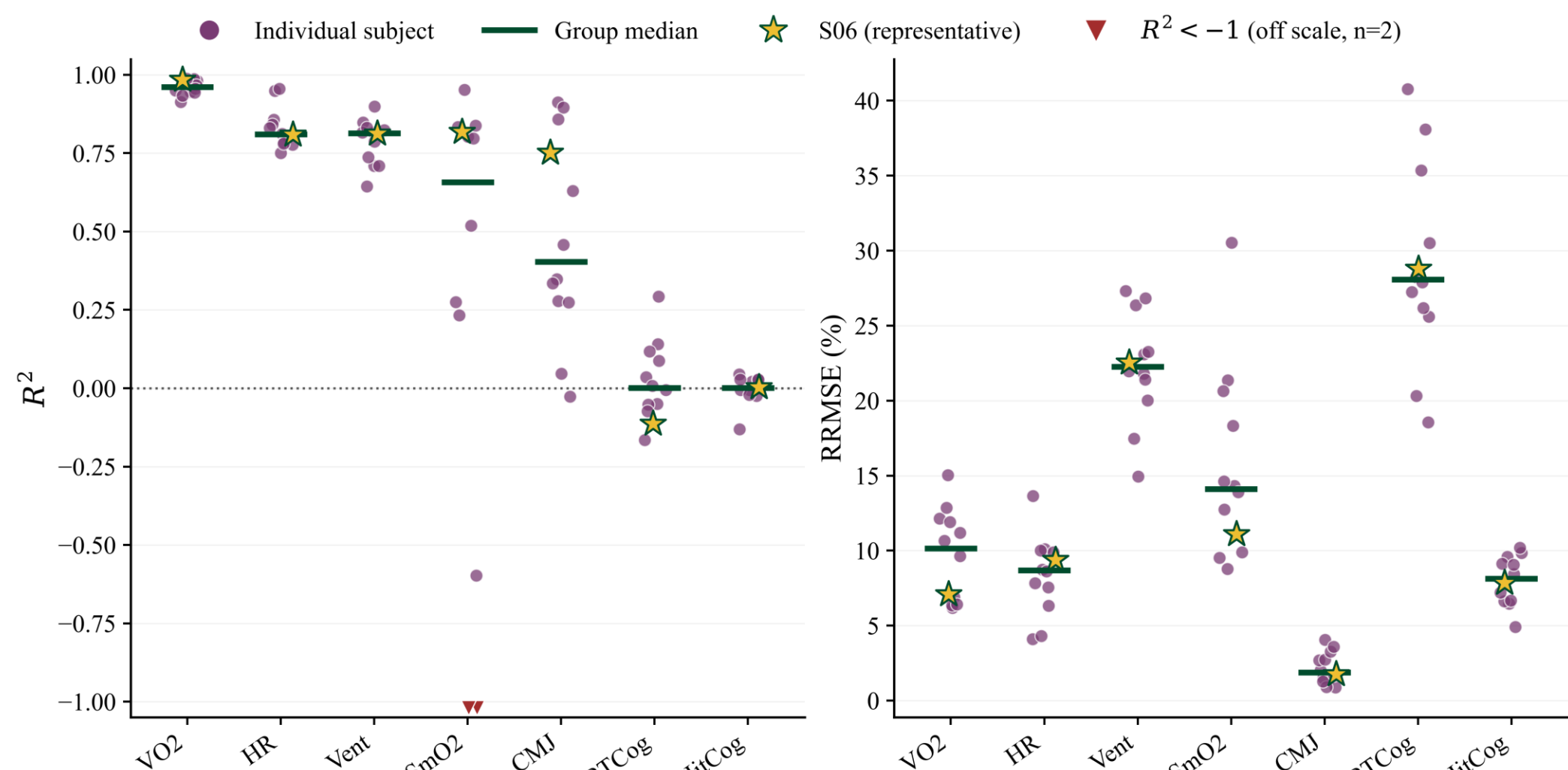
Results

- The physiological response was well captured for the three core measures: oxygen uptake (R²=0.96, RMSE=1.58 mL/kg/min, RRMSE=9.8%), heart rate (R²=0.83, RMSE=9.58 bpm, RRMSE=8.4%), and ventilation (R²=0.79, RMSE=8.33 L/min, RRMSE=22.3%).
- CMJ peak force was predicted with moderate accuracy (R²=0.47, RMSE=42.6 N), with sleep and hydration state accounting for much of the variation between sessions.
- Cognitive reaction time and hit rate were the weakest outputs, isolating a mechanism beyond oxygen availability.

Representative Participant



Model Fit Across Participants



Conclusion & Operational Implementation

- A small set of physiological relationships explains strain and cognitive demand under load, and because the same structure carries both, they fit in one framework. Sleep and hydration as daily inputs let the model tell whether a drop comes from the day's state or the person's own limits, and every prediction traces to a pathway, so a decline comes with its cause. Validation on new sessions and cognitive-specific mechanisms are still needed.
- By simulating how each individual responds to combined physical and cognitive load, the DT shifts readiness monitoring from reacting to failure toward preventing it. It is the prediction layer an AI planner runs on: the planner decides what to assign, and the DT predicts how each person will respond.

- Individual capacity during training:** Because every parameter is fitted to the individual, the model quantifies a soldier's own physiological limits rather than a population average, identifying who is near capacity before performance breaks down.
- Scenario prediction:** Once extended and validated, the model can answer what-if questions the field asks: under a heavier load or a longer march, when does physical and cognitive performance begin to decline, and by how much?

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