On-the-Move Monitoring of Human Health and Performance

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LINCOLN LABORATORY
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Many Wearable Sensors Available for the General Population (and their Pets) …

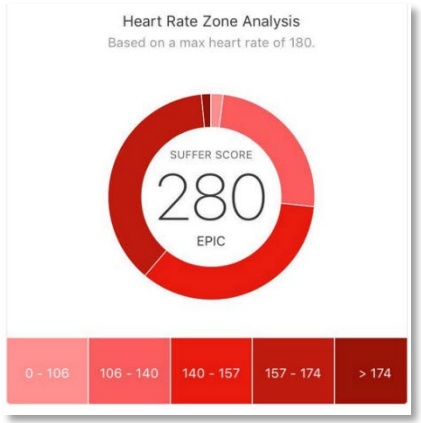
But How About for People Operating in Austere Conditions?

High consequence for poor performance

Examples of Commercial Monitoring Shortcomings for the Military

Proprietary algorithms…

https://news.nike.com/news/what-is-nikefuel

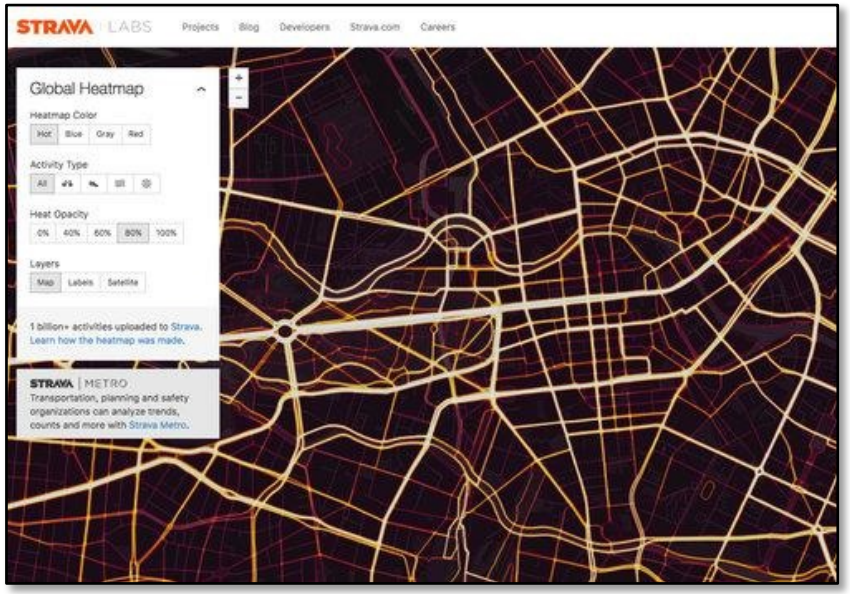


https://twitter.com/strava/status/886144571419246592

… Not trained against military activities

Examples of Commercial Monitoring Shortcomings for the Military

Not secure…



"Strava Fitness App Can Reveal Military Sites, Analysts Say," New York Times, Jan 29 2018

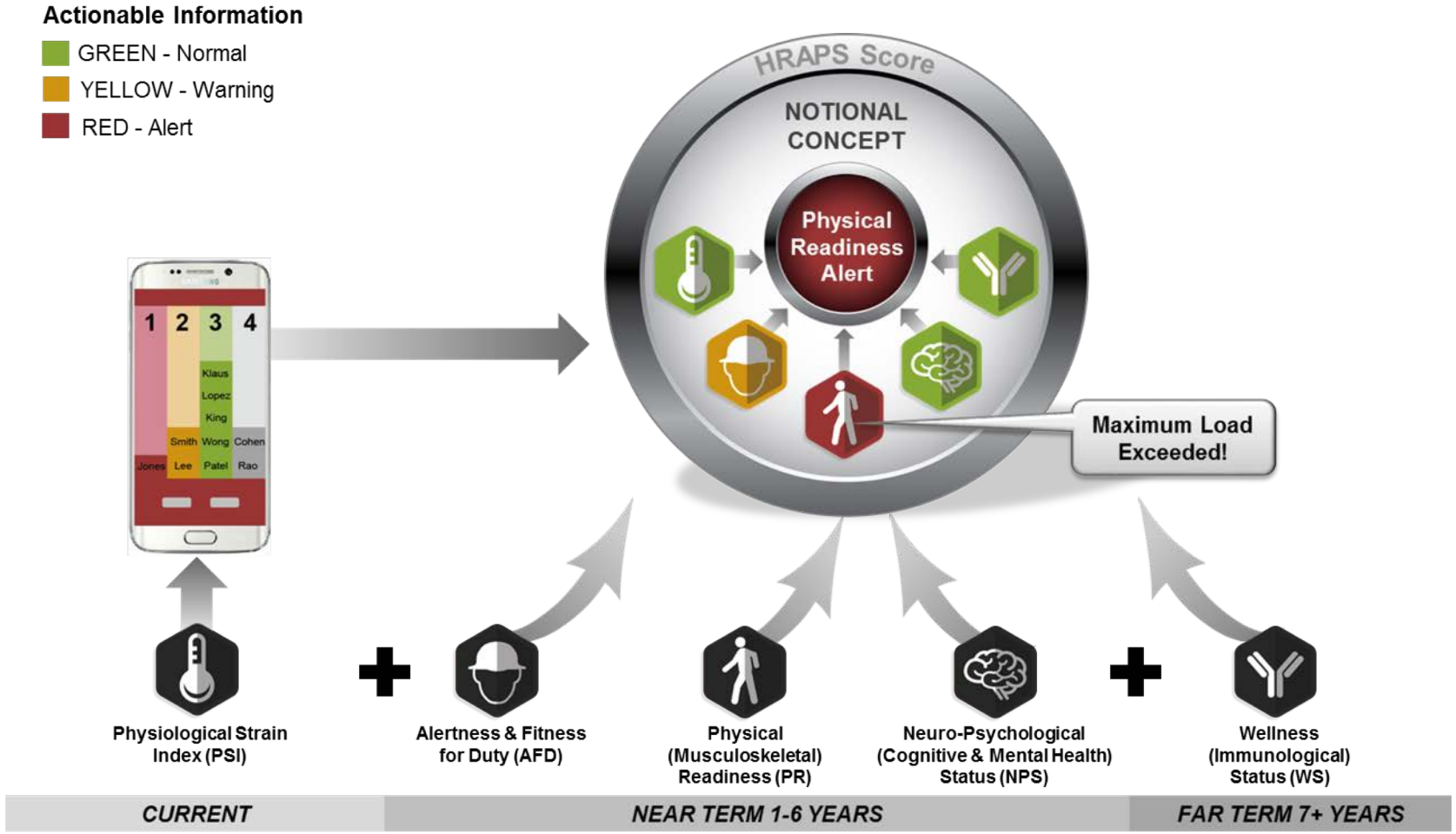
… For integration into military systems

General Requirements for Military Wearables

- **Actionable**
  - Scientifically validated, individualized models
  - Understandable mapping of alerts to actions
- **Acceptable**
  - Comfortable
  - Compatible with military tactical equipment
  - Long battery life
  - Vanishingly small
- **Secure**
  - Cybersecure
  - Low detectability
  - Protected data (PHI / PII concerns)
- **Integratable, Upgradable**
  - Open system architecture
  - Integrated across team
  - Integrated with comms and downstream data management
- **Affordable**
  - Procurement costs
  - Utilization burden

PHI: Protected Health Information
PII: Personally Identifiable Information

Health Readiness and Performance System (HRAPS) Concept



U.S. Army advanced development underway for acquisition-ready fieldable system

Outline

- Introduction
- Gap Identification
- Development
- Integration
- Summary

Health Readiness and Performance System: Lincoln Gap Analysis

Actionable Alerts	Sense	Model	Decide	Limitations
Stopped activity				Simple ‘Are you OK?’ based on location / movement
Heat stress				Needs compensable/uncompensable modeling
Cold stress				Confounded core temperature sensing
Musculoskeletal injury				Limited predictive models
Agility				Limited predictive models
Hypoxia				Challenges in collecting data
Dehydration				Lacking sensing modality; limited predictive models
Exhaustion / metabolic				Metabolic cost models limited
Training recovery				Proprietary commercial products not validated
Diminished cognition				Alert states not well defined
Alertness				Current metrics require intervention; limited models
Emotional instability				Lacking sensing modalities, alert states not defined
Infection / bioagent				Primate model data only
Chemical exposure				Rodent model data only

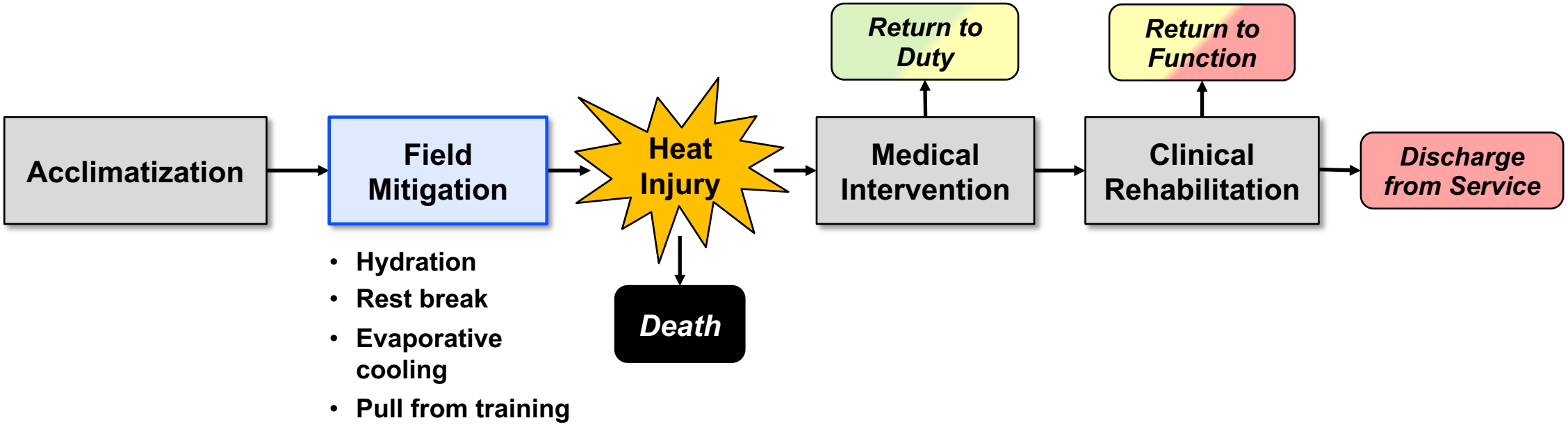
Sufficiently validated for routine use

Further development needed

Further research needed

Preventing Heat Casualties During Military Training

- High prevalence from heavy loads combined with encapsulating protective gear
- Results in incoordination, impaired cognition, unconsciousness, and in severe cases, organ damage and death



Real-time monitoring needed to 'cue' mitigation action to prevent heat injury

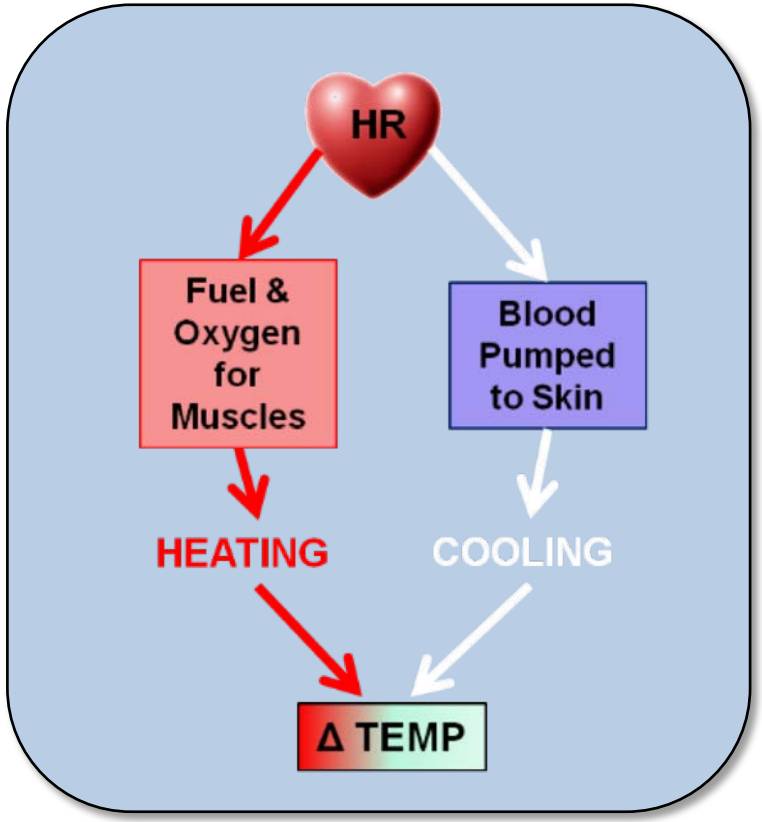
Options for Measuring Core Temperature

	Option	Comments
Truth Sensors	Pulmonary arterial blood temperature	Medical use only
	Rectal or esophageal	Operationally unacceptable
	Ingestible capsule	Expensive (~$50/use), logistics issue
Potentially Fieldable Measures	Axillary or tympanic thermometer	Acceptability, accuracy issues
	Zero-flux sensor	Long response time, reliability issues
	Estimation algorithm	Based on heart rate data from wearable sensors

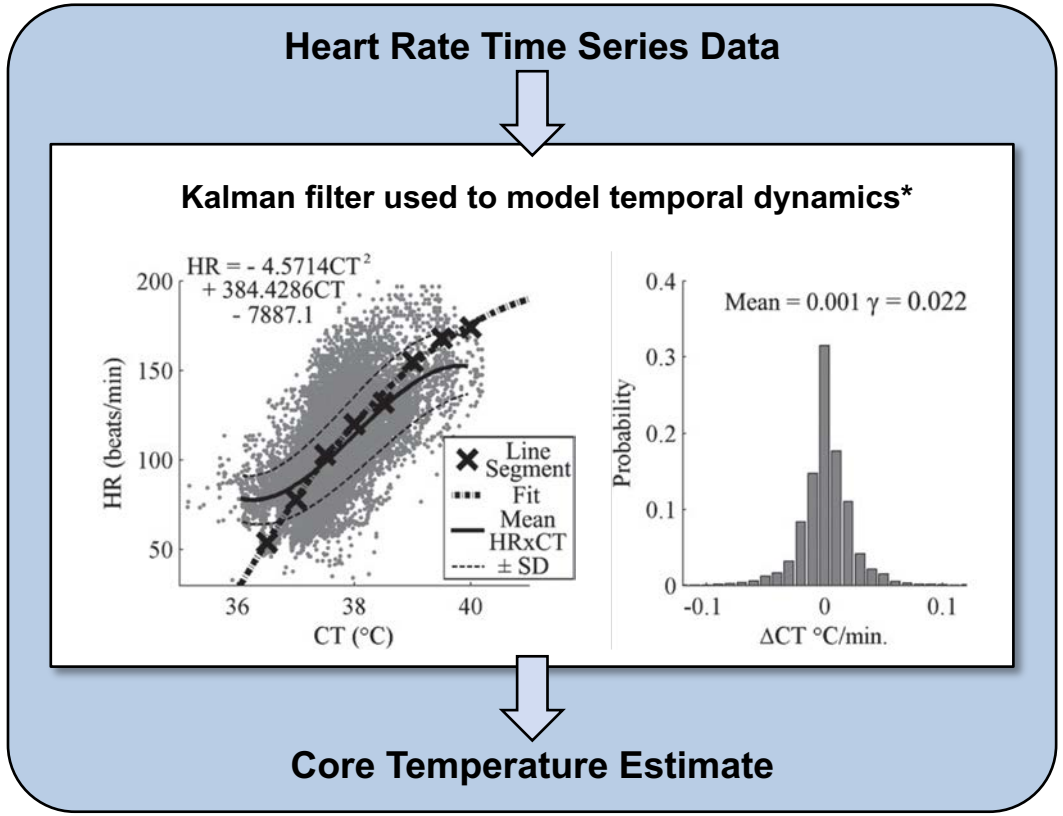
Heart-rate-based estimation algorithm is most promising option for field-expedient monitoring

Core Temperature Estimation Algorithm

Physiological Rationale



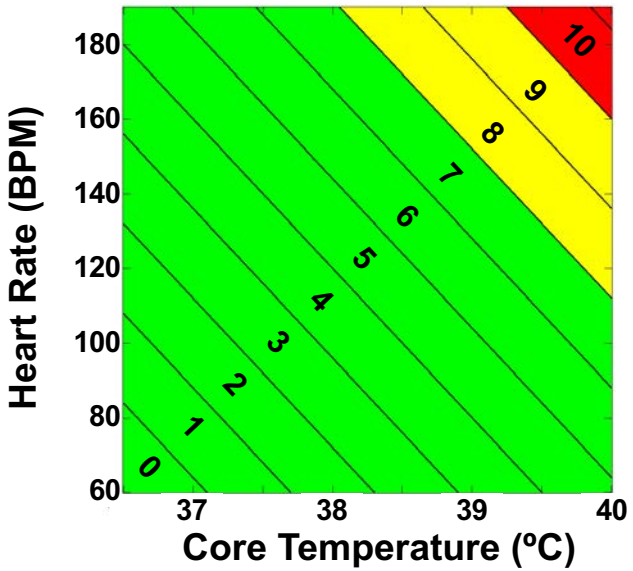
Empirical Modeling Approach



**M. Buller et al., "Estimation of human core temperature from sequential heart rate observations," Physiol Meas, 34, 781-798, 2013*

Physiological Strain Index (PSI) for Predicting of Heat Injuries

Current Algorithm



- Validated U.S. Army algorithm
- Requires heart rate only when used with core temperature estimation

Improvements under Research

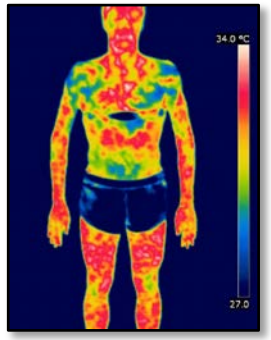
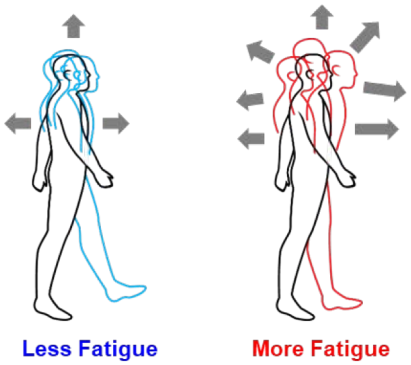


*Image: G Tanda 2015 J. Phys.: Conf. Ser. **655** 012062*



- Thermoregulatory compensation via skin temperature measurement
- Neuromotor incoordination via accelerometry measurement features

Measurements required: heart rate, skin temperature, and accelerometry

D. Moran, A. Shitzer, K. Pandolf, "A physiological strain index to evaluate heat stress," Am J Physiol, 275: R129-134, 1998.

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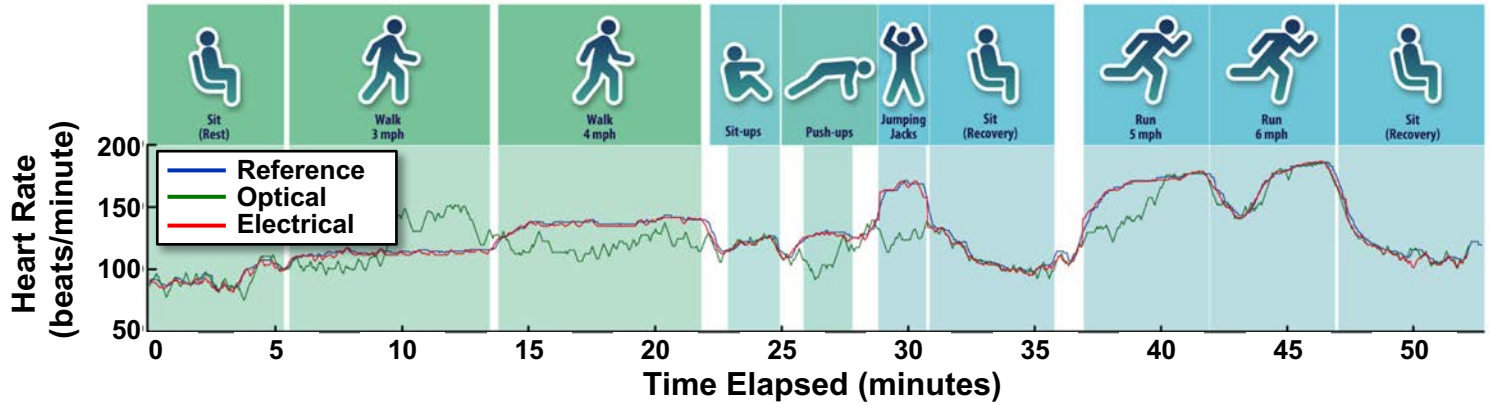
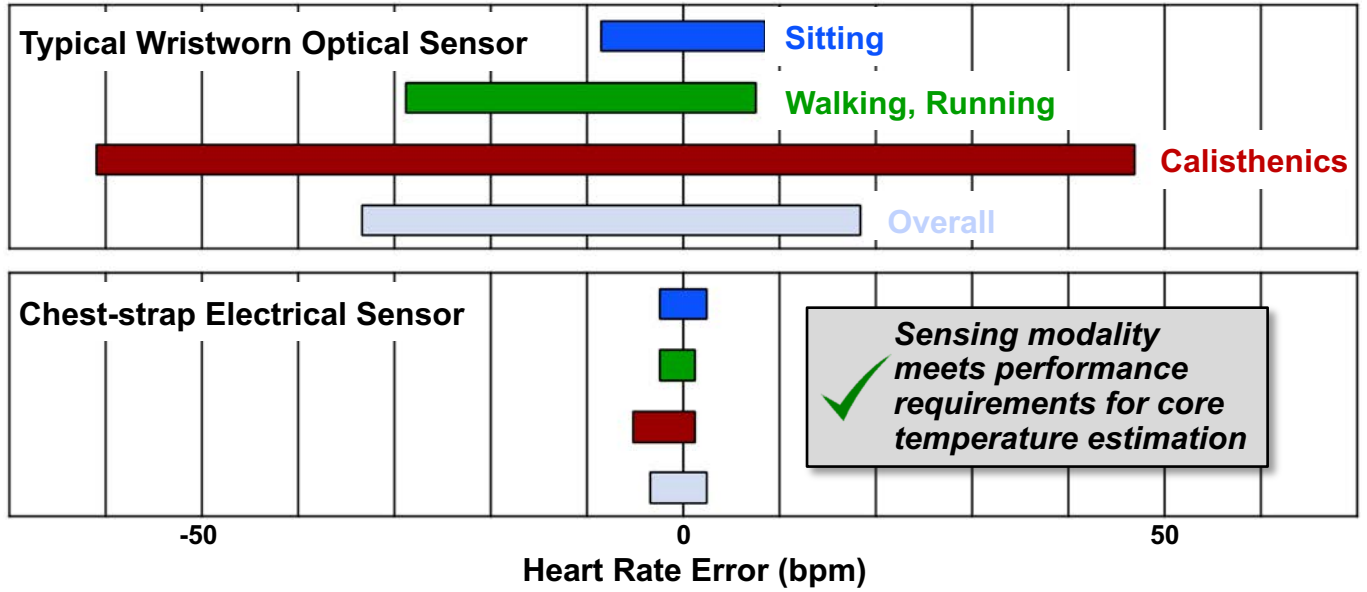
Assessing Heart Rate Accuracy

Human Subject Research Protocol and Example Test Data



Heart Rate Accuracy of Example Devices (5 and 95 percentiles)



Lincoln OBAN PSM Phase 1 Prototype

Open Body Area Network - Physiological Status Monitoring

Squad Members

Strap-Mounted Hub

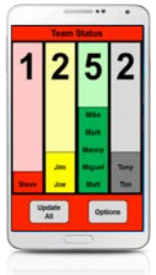
- 3+ day battery life
- Heart rate
- Skin temperature
- Accelerometer
- Data logging

OBAN TNB Link

Tactically acceptable comms* (2 – 3 m)

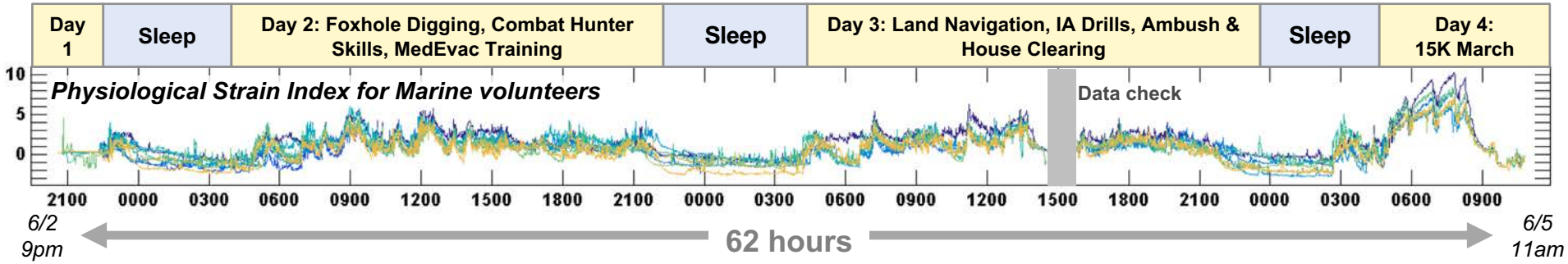
Squad Leader / Medic

End User Display



- Vital sign monitoring of squad members
- Physiological Strain Index and core temperature estimation *(USARIEM algorithms)*

Prototype Demonstration – *USMC School of Infantry East, June 2015*



Thirty prototypes produced and validated for military field use

TNB: Tunable Narrow Band (270 – 320 MHz) USARIEM: U.S. Army Research Institute of Environmental Medicine
** Approved DoD Equipment Frequency Allocation (NTIA DD 1494)*

OBAN PSM Industry Transition

- **Prototype matured through competitive-bid contract to Odic Inc.**
  - **Smaller, more rugged, longer mission profile**
- **Device functionality:**
  - **7-day battery life**
  - **Heart rate, skin temperature, and accelerometry**
  - **Core temperature estimation and PSI**
  - **BLE and TNB wireless body area network**
  - **Inexpensive commercial chest strap**
- **Odic awarded Small Business Association Subcontractor of the Year for the New England Region**

Wearable Device

Moto-Z Phone* with TNB Antenna

300 wearable devices delivered between Fall 2017 and Spring 2018

PSI: Physiological Strain Index
BLE: Bluetooth Low Energy
TNB: Tunable Narrowband (DD-1494 approved)

****Shown with customized Moto Mod backplate for TNB***

2018 OBAN PSM Testing

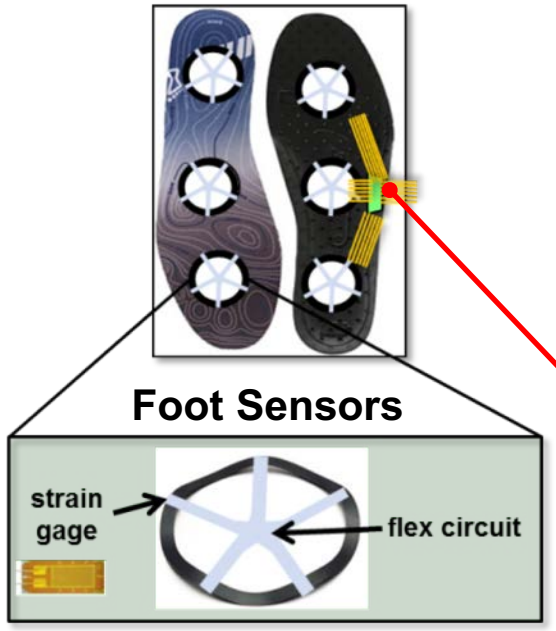
Users / Event	Location	Date	# Devices
NATO Working Group*	United Kingdom	May	2
UK Jungle Warfare Division	Brunei	May	15
U.S. Army infantry training	Fort Benning GA	Jun-Aug	270
U.S. Coast Guard National Strike Force Joint Exercise	Anniston AL	Aug	15
DTRA CBOA Exercise	Joint Base Lewis-McCord WA	Sep	15

OBAN PSM has allowed testing to scale up by an order of magnitude

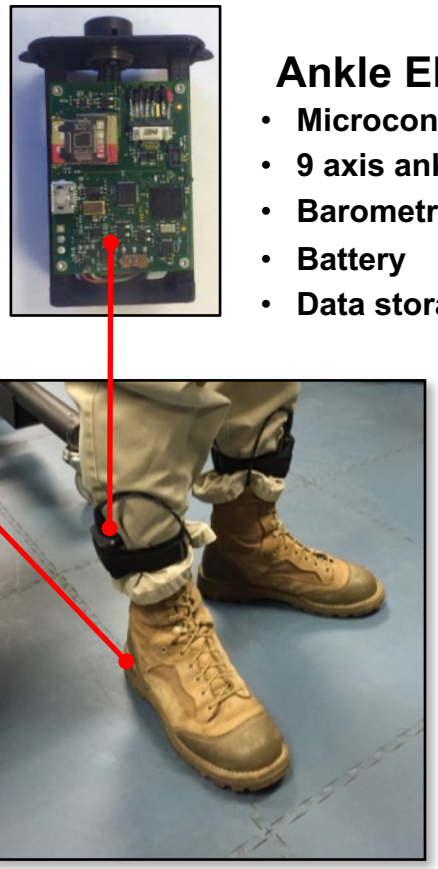
** HFM-260 Enhancing Warfighter Effectiveness with Wearable Biosensors and Physiological Models*
CBRN: Chemical, Biological, Radiological, Nuclear
DTRA CBOA: Defense Threat Reduction Agency Chemical Biological Operational Analysis

Biomechanics Sensing for Neuromotor Incoordination Monitoring

Mobility and Biomechanics Insert for Load Evaluation (MoBILE)

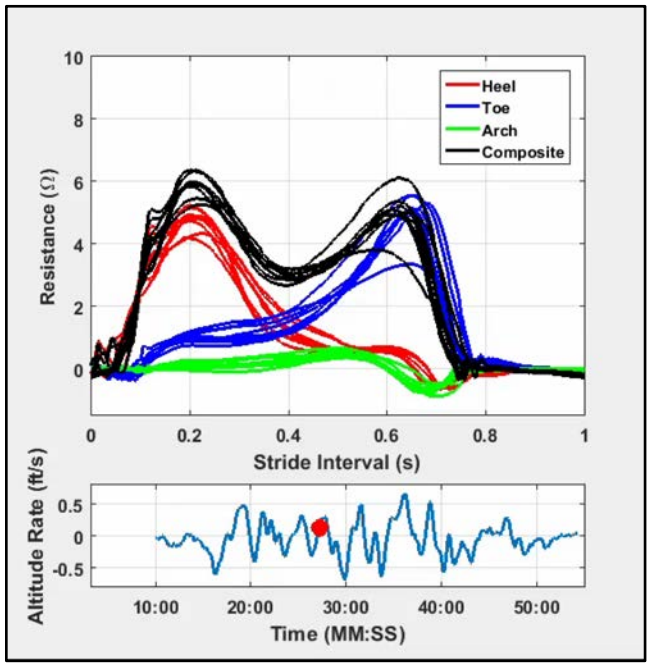


- 3-point foot load sensors
- 9-axis foot IMU



Ankle Electronics

- Microcontroller
- 9 axis ankle IMU
- Barometric pressure
- Battery
- Data storage



Venue: Washboard Road
Quantico, VA, 24 May 2017
Male, 188 lbs with 40 lb pack, size 9 boots

Lincoln "biomechanics lab in an insert" prototype will undergo industry transition in 2019

IMU: Inertial Measurement Unit
MERS: USMC Marine Expeditionary Rifle Squad
MSI: Musculoskeletal Injury

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Wearable Device Suitability Evaluation

- **Goal: assess suitability of commercial devices for potential integration into HRAPS architecture**

- **Assessment criteria based on:**
  1. **Human movement impact on device performance**
  2. **Device impact on human performance**

- **Performance evaluated as a function of:**
  - **Gait (stand, walk, run)**
  - **Upper-body movement (torso, arm, & head rotations)**
  - **Equipment use (e.g., simulated rifle, body armor)**

Immersive Virtual Environment testing prior to advanced development for fielding

MIT Lincoln Laboratory: High-End CAREN System

STRIVE center

Sensorimotor Technology Realization in Immersive Virtual Environments

Research Uses

- Wearables T&E
- Physiological modeling
- TBI assessment
- Exoskeleton development
- Data visualization
- Telepresence

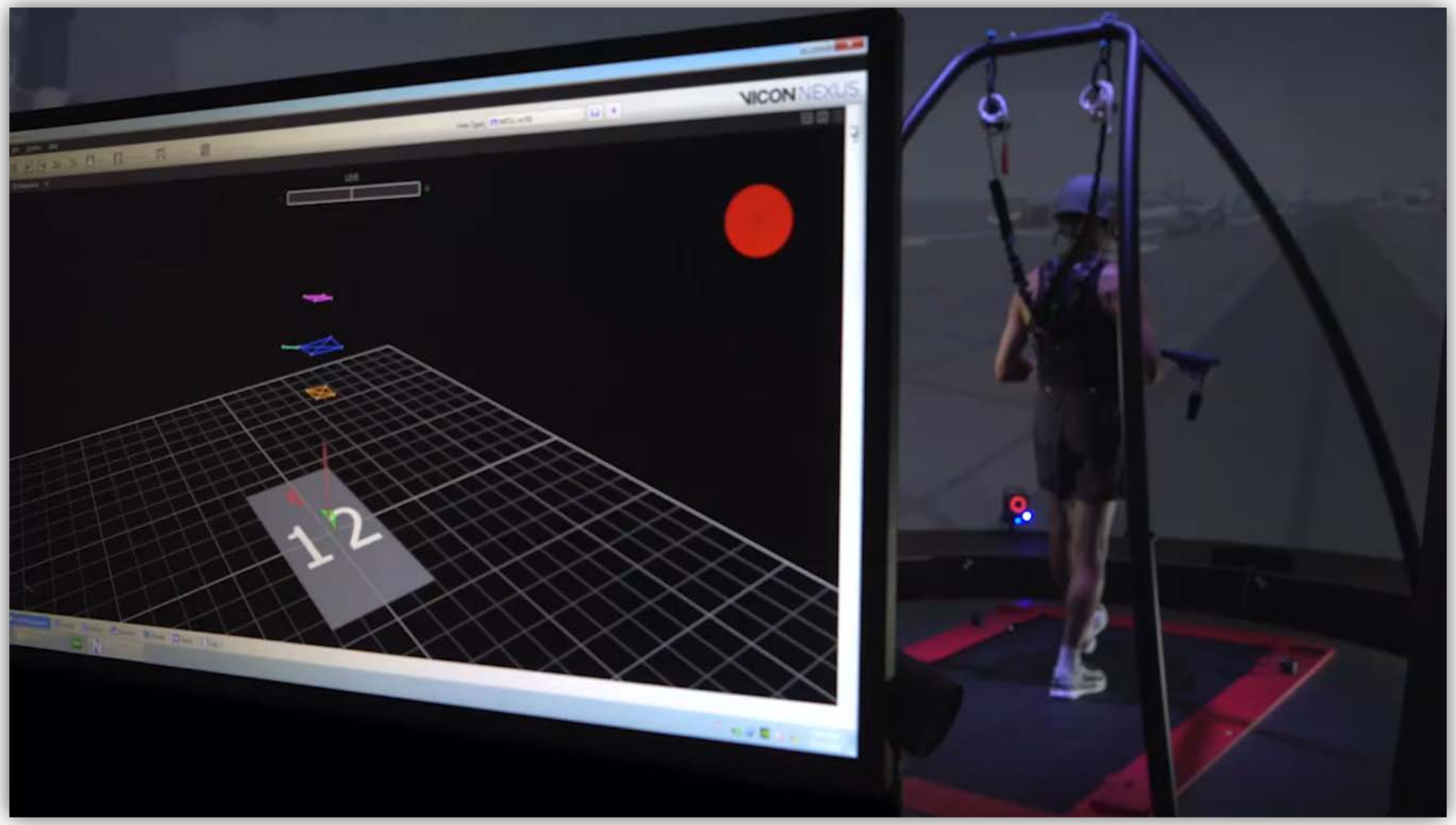
Built-in Instrumentation

- 24-foot dome screen
- Motion capture
- Split belt treadmill
- Load sensors
- 6 Degree of Freedom platform

Instrumented testbed with capability for seamless integration of new devices

CAREN: Computer-Assisted Rehabilitation Environment

MIT Lincoln Laboratory: High-End CAREN System



Instrumented testbed with capability for seamless integration of new devices

CAREN: Computer-Assisted Rehabilitation Environment
USAMMDA: U.S. Army Medical Materiel Development Activity

CAREN Data Streams (Subset)

Integrated Collection of Biosignals, Biomechanics, and Behavioral Context

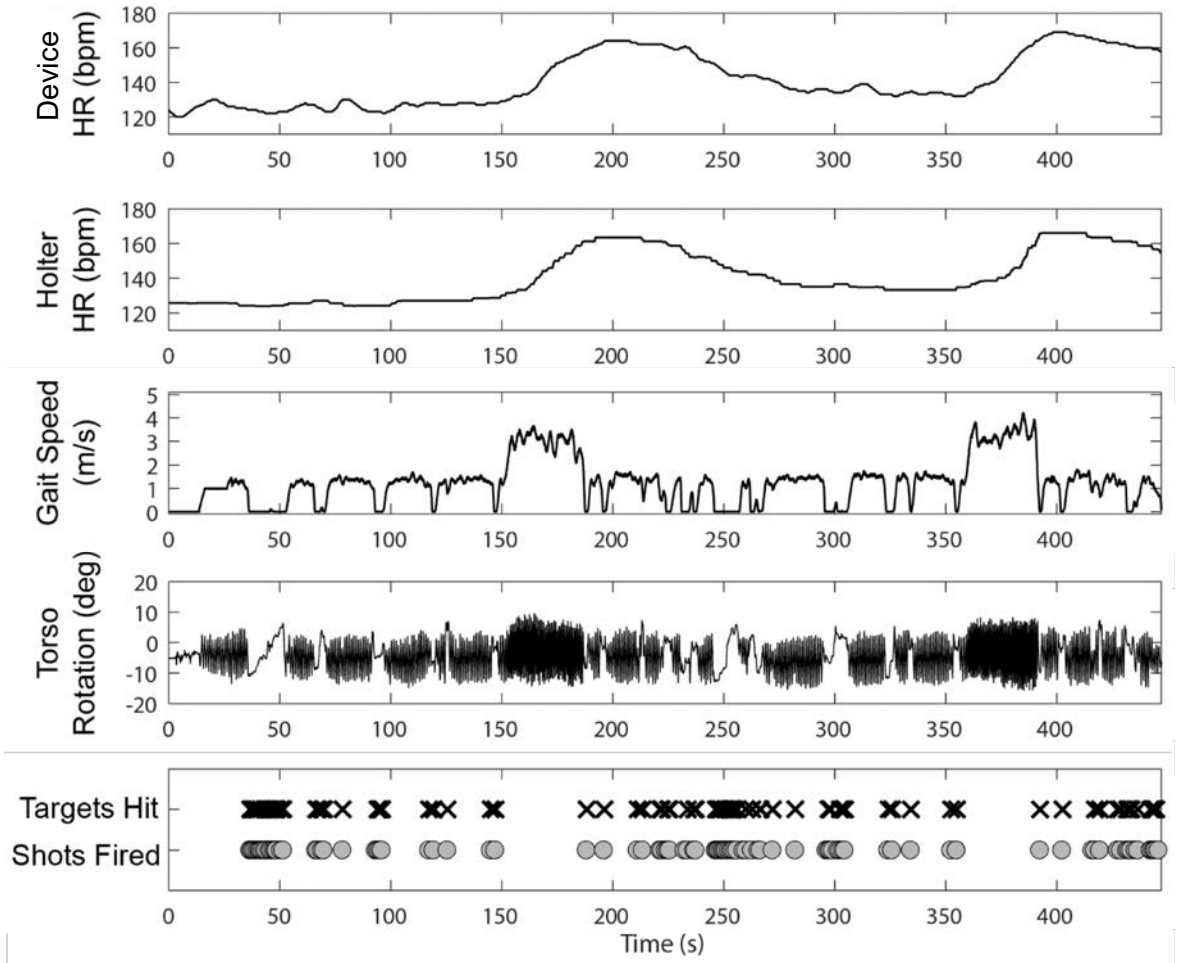
Device Under Test

Independent Reference

Movement Behavior

Biomechanics

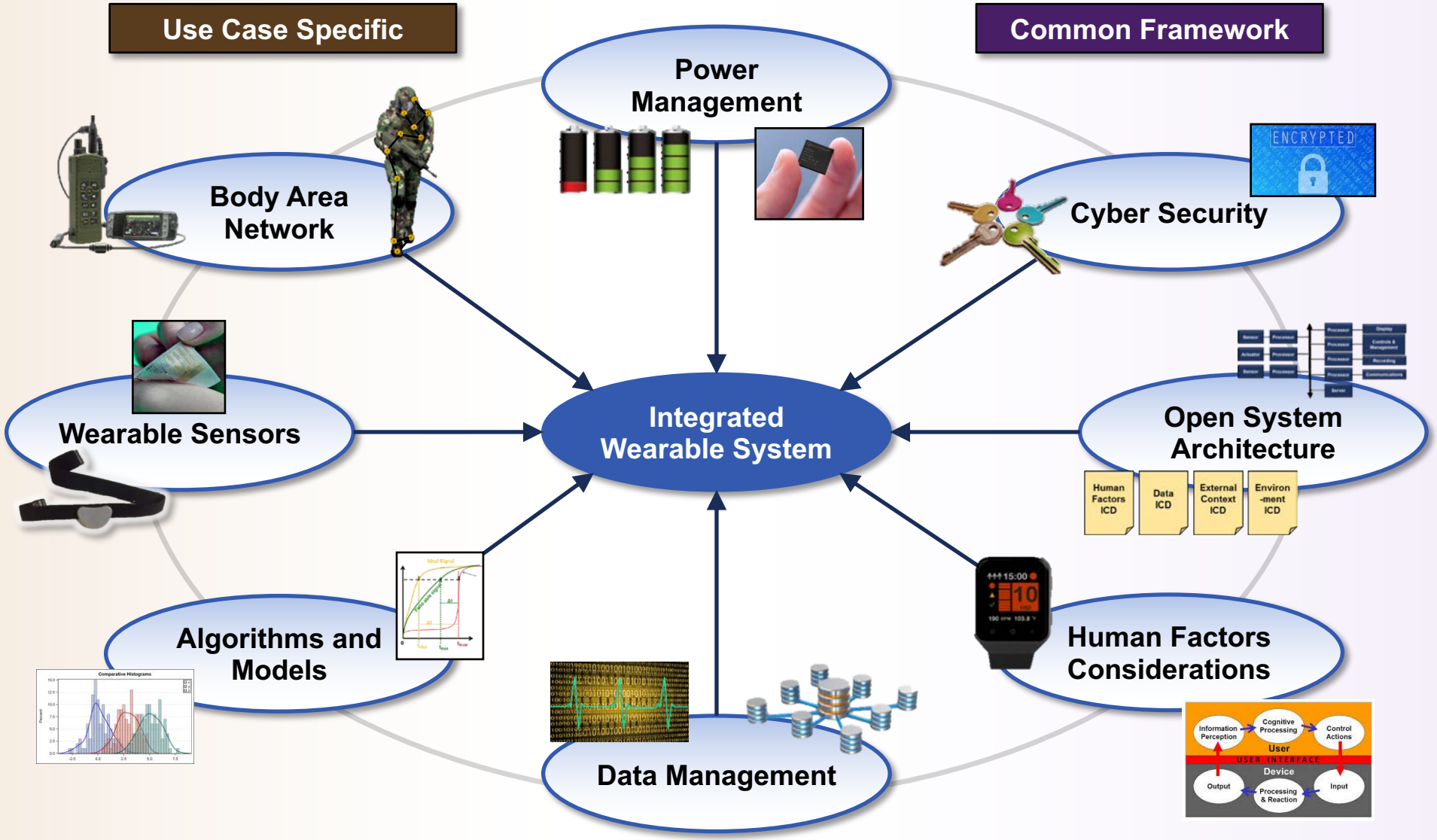
Operational Performance



Unique resource for R&D collaborations

HR: Heart Rate
R&D: Research & Development

Elements of an Integrated Physiological Status Monitoring System



Need for DoD Wearables Coordination

DoD Organizations Conducting Wearables R&D (Partial List)

U.S. Army Medical Materiel Development Activity

U.S. Army Research Institute of Environmental Medicine

Office of Naval Research

National Guard Bureau

DoD Integration Lead

Military Operational Medicine Research Program

U.S. Army Program Executive Office - Soldier

U.S. Marine Expeditionary Rifle Squad

Defense Threat Reduction Agency

U.S. Army Research Laboratory

U.S. Army Natick Soldier Research, Development and Engineering Center

U.S. Air Force Research Laboratory

U.S. Special Operations Command

On-the-Move Monitoring Vision for Austere Military Environments

Low SWaP Sensors

Cognitive
- Voice / stress / emotion

Physiological
- Heart rate
- Oximetry
- Metabolic / temperature
- Fluid intake

Environmental
- Noise
- Toxins

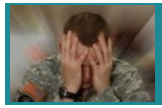
Biomechanics
- Force
- Acceleration

Individualized, Predictive Analytics

Actionable Information for Early Mitigation

Heat Injuries / Degraded Performance

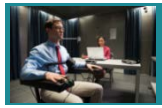
Musculoskeletal Overuse Injuries



Cognitive Fatigue & Overload

Infectious Disease

Chem/Bio Agent Exposure



Anomalous Behavior / Psychology

Toxic Environmental Exposure

Performance Enhancement

Technology-agnostic open architecture integrating sensing that fits operational needs

SWaP: Size, Weight and Power

Summary

- Integrating biosensing systems with open architectures for on-the-move monitoring enabling training and real-time tactical overmatch
- Developing predictive performance and health monitoring through individualized sensing, analysis, and intervention
- Leveraging, extending, and collaborating with commercial technology base
- Transferring solutions to DoD labs, Warfighters, and industry

Acknowledgements

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U.S. Marine Expeditionary Rifle Squad

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Military Operational Medicine Research Program

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LCDR Chris Steele
Roy Vigneulle, PhD

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Matthew Hickcox
Steve Grillo

PsiKick, Inc.

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Hrishikesh Rao, PhD
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Al Swiston, PhD
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Konrad Vesey
Christine Weston
Jim Williamson, PhD
Whitney Young