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Physical Task and Sensor Considerations for Close Combat Exoskeletons

by Andrew Tweedell, Angela Boynton, and Joon Park

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Andrew Tweedell
Human Research and Engineering Directorate,
DEVCOM Army Research Laboratory

Angela Boynton
DEVCOM Data & Analysis Center

Joon Park
Department of Mechanical & Aerospace Engineering,
University of Central Florida

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ORCID ID: Angela Boynton, 0000-0003-1192-1369

14. ABSTRACT

This report summarizes multiple, parallel efforts performed by the US Army Combat Capabilities Development Command Army Research Laboratory, Human Research and Engineering Directorate to understand the required functionality for close combat exoskeletons and the tools to assess them. The purpose of this effort was 1) to identify opportunities for exoskeleton technologies within close combat operations based on an understanding of the associated physical demands and task constraints, and 2) to identify and assess wearable sensors necessary to quantify performance during these operations. To this end, we reviewed literature related to the physical employment standards and operational fitness requirements of combat arms tasks, observed performance of close combat activities during field experiments, and performed a decomposition of Infantry Battle Drills and Warrior Drills to their component tasks and required functional physical abilities. In addition, laboratory validations and operational feasibility assessments were performed on wearable sensors with potential to quantify these physical abilities.

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1. Introduction and Summary

Exoskeleton technologies show promise as Soldier lethality and survivability enablers during close combat operations. However, a mismatch between the design features and functionality of current systems and the physical requirements of close combat tasks has prevented their adoption for operational use. As a result, there is also a mismatch between the current tools used to quantify exoskeleton performance within close combat operations and the appropriate ones. Understanding the physical requirements and tasks constraints of close combat operations will be critical to developing exoskeleton systems capable of augmenting performance of combat arms Soldiers.

This report summarizes multiple, parallel efforts performed by the US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory, Human Research and Engineering Directorate to understand the required functionality for close combat exoskeletons and the tools to assess them. The purpose of this effort was 1) to identify opportunities for exoskeleton technologies within close combat operations based on an understanding of the associated physical demands and task constraints, and 2) to identify and assess wearable sensors necessary to quantify performance during these operations. To this end, we reviewed literature related to the physical employment standards and operational fitness requirements of combat arms tasks, observed performance of close combat activities during field experiments, and performed a decomposition of Infantry Battle Drills and Warrior Drills to their component tasks and required functional physical abilities. In addition, laboratory validations and operational feasibility assessments were performed on wearable sensors with potential to quantify these physical abilities.

Close combat tasks generally involve prolonged or rapid movement over, through, or around terrain and obstacles while under load, the lifting, carrying, pushing and/or pulling of heavy objects, and employment of individual weapons to engage targets. Beyond the primary physical demands of cardiovascular endurance, muscular strength, and muscular endurance inherent to the majority of these activities, we identified additional requirements for flexibility, gross body coordination, and gross body equilibrium across close combat component tasks. Further, complex interactions exist between these abilities both within and across the component tasks required to execute close combat operations. Wearable technologies like physiological monitoring systems (heart rate monitors), inertial measurement units (IMUs) and insole pressure sensors for foot pressure offer attractive ways to measure different aspects of strength, mobility, and balance in the field.

The findings from our analysis indicate that close combat exoskeleton technologies designed to augment explosive and dynamic strength components of close combat tasks while considering requirements for flexibility, balance, and coordination have the greatest potential to support close combat operations. Additionally, wearable motion capture sensors, like IMU suites, offer potentially feasible ways to quantify mobility in the field. However, additional research is needed to generate detailed design guidance and assessment methodologies for close combat exoskeletons.

2. Background

Military experts anticipate that urban environments—characterized by densely populated, multi-level terrain and close-quarters enemy engagement—will feature heavily in the future battlespace. Achieving overmatch in these complex and highly dynamic environments will depend greatly on the ability of ground units to effectively maneuver and defeat enemy forces. Exoskeletons have been identified as a modernization enabler for Soldier lethality capabilities; increasing human performance by mitigating the effects of physical burden. However, despite nearly two decades of research and development across multiple defense agencies, and demonstrated success of several prototype technologies in reducing the metabolic cost of load carriage (Boynton et al. 2017; Diamond-Ouellette et al. 2020; Ding et al. 2018; Mooney and Herr 2016), a field-ready exoskeleton capability for close combat operations has yet to be produced.

The limited nature of the current state-of-the-art in military exoskeletons can be attributed in part to a lack of focus on close combat activities. The majority of recent development efforts have focused almost exclusively on reduction of metabolic cost and muscular work during prolonged load carriage activities. When applied to more dynamic activities such as those encountered in close combat environments, the physical design and control strategies associated with load carriage exoskeletons can hinder rather than augment performance. For example, added weight, bulk, and stiffness of rigid load-bearing components can limit functional range of motion and create snag hazards during obstacle negotiation and movement through complex terrain. Active hardware components may also lack the ability to apply the forces and torques required to perform certain dynamic motions. Additionally, steady state activity control strategies cannot be readily adapted to sense and respond appropriately to emergent and short duration actions, potentially resulting in a mismatch between exoskeleton behavior and the user’s intended movement. Given these challenges, targeted investment is needed to develop exoskeleton technologies specifically designed for close combat activities.

In order to develop exoskeletons for close combat operations, an understanding of the associated physical task requirements must first be established. Extensive efforts to identify the most physically demanding tasks for combat arms Military Occupational Specialties (MOS) have been previously undertaken to establish Physical Employment Standards (PES) for those job series and develop operationally relevant physical performance assessment methodologies (e.g., US Army Occupational Physical Assessment Test [OPAT], Canadian Forces [CF] Fitness for Operational Requirements of CF Employment [FORCE] test). The outcomes from such efforts can additionally provide insight regarding opportunities for exoskeleton technologies to augment Soldier performance. With a primary focus on establishing the minimum physical capabilities an individual requires to successfully perform within a combat arms position, however, they fail to capture the full spectrum of physical activities that an exoskeleton would need to enable beyond those that would benefit from augmentation. Therefore, there remains a need to characterize the physical activities and abilities associated with close combat operations in order to inform the development of exoskeleton technologies.

3. Close Combat Task Demands

3.1 Purpose

The purpose of this effort was to identify potential opportunities for the application of exoskeleton technologies within close combat operations through an understanding of the physical demands associated with close combat tasks.

3.2 Methods

We employed a multi-faceted approach to identify those tasks and activities within close combat operations for which exoskeleton technologies could provide the greatest benefit. This approach consisted of a review of PES literature for combat arms positions, observation of close combat field activities, and task demands analysis of battle drills and Warfighter skills for Infantry Soldiers and Squads. Observations and findings from across each of these activities were compared and consolidated to identify those tasks with the greatest physical demands and the functional abilities required for their execution.

3.2.1 Literature Review

We reviewed a total of nine manuscripts and technical reports identified as relevant to understanding the physical requirements of close combat tasks. The reviewed PES literature primarily consisted of manuscripts and technical reports generated by the US Army Research Institute for Environmental Medicine (USARIEM) to document development of the OPAT for combat arms Soldiers (Foulis et al. 2015), but also included a report on the CF Project FORCE (Reilly et al. 2013). Relevant NATO Research and Technology Organisation (RTO) and US Army Public Health Command (USAPHC) reports on the topic of operational physical fitness (Hauschild et al. 2014; NATO 2009) were also included in the review.

3.2.2 Observation of Close Combat Field Activities

Ongoing dismounted Soldier and Squad field assessments were leveraged as opportunities to observe and evaluate a variety of close combat tasks under operationally relevant conditions. Two key events were used for this purpose. The first was a Soldier touchpoint conducted by DEVCOM Soldier Center to gather user feedback and system performance data for two prototype mobility exoskeletons. During this event, we observed Infantry Soldiers conducting a road march through varied terrain, executing a Squad assault in urban terrain, and performing individual movement techniques with and without the exoskeletons. The second event was the Squad Performance Metrics–Active Measures Evaluation (SPM-AME) conducted by Program Executive Office (PEO) Soldier to establish a baseline of Squad performance through quantitative measures taken during combat activities. During this event, we observed Infantry Squads conducting a road march; performing maximal effort mobility trials through an urban environment, completing a stress shoot lane, and executing day and night iterations of Battle Drill 2A (Conduct a Squad Assault).

3.2.3 Physical Task Demands Analysis

We performed a task demands analysis of Infantry Battle and Warrior Drills to develop an understanding of the physical requirements associated with conduct of close combat operations. The first step of this analysis involved a thorough review of Army Techniques Publications, Soldier Training Publications, and Field Manuals for Infantry Squads and combat arms MOS (Headquarters, Department of the Army 2013, 2016, 2017) to identify those Battle and Warrior Drills incorporating physical behaviors. Next, selected Battle and Warrior Drills (e.g., react to direct fire) were decomposed from Warfighter skills (e.g., engage targets with M4 series carbine) into component tasks and functional activities (e.g., engage the target). Functional activities were then mapped to specific abilities within the categories of Sensory, Cognitive, Psychomotor, and Physical as shown in Fig. 1. Finally, from the mapped human abilities we identified the most common physically demanding Warfighter skills and the frequency with which specific physical abilities are required for their execution.

Specific abilities associated with each of the four categories (Sensory, Cognitive, Psychomotor, Physical) were derived from an established taxonomy of human performance (Fleishman 1967; Furnham et. al. 2009). A recent form of Fleishman's taxonomy, the Manual for Ability Requirements Scales (MARS), includes a total of 52 distinct human abilities, 9 of which fall within the Physical category: Static Strength, Explosive Strength, Dynamic Strength, Trunk Strength, Extent Flexibility, Dynamic Flexibility, Gross Body Coordination, Gross Body Equilibrium, and Stamina (Fleishman et al. 1984). For the purposes of our analysis, the categories of Static, Explosive, and Dynamic Strength, and Extent and Dynamic Flexibility were further separated into upper and lower body. Using the definitions associated with each of these physical abilities, an understanding of task requirements derived from military publications and observations of Soldier and Squad close combat activities, and our subject matter expertise in human performance, we identified those specific abilities required for the performance of each component task. We also computed the frequency with which each specific ability occurred across all component tasks and noted those tasks requiring the greatest number of physical abilities.

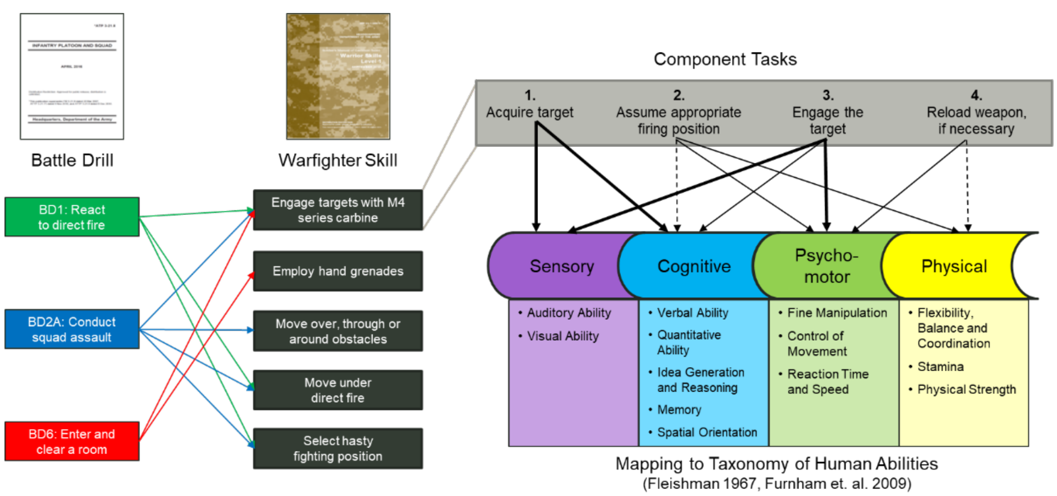


Fig. 1 Decomposition of close combat tasks into physical performance requirements

3.3 Results

3.3.1 Literature Review Results

In developing the US Army OPAT, under the guidance of the Training and Doctrine Command (TRADOC), USARIEM scientists compiled the physical requirements of Army tasks (Sharp et al. 1998), and conducted focus groups (Boye et al. 2016a, 2016b, 2016c) with Army personnel from each of the seven combat arms MOS (11B Infantryman, 11C Infantryman–Indirect Fire, 12B Combat Engineer, 13B Cannon Crewmember, 13F Fire Support, 19D Cavalry Scout, and 19K Armor Crewman) to identify those tasks with the greatest physical demands. Across all MOS, a total of 32 tasks were identified as physically demanding and the characteristics (e.g., frequency, distance, and load) of these tasks and their physiological requirements were studied (Foulis et al. 2015). Of the 10 physically demanding tasks associated with two or more of the analyzed MOS, four were specific to weapon operation or maintenance on the Bradley Fighting Vehicle (Foulis et al. 2015). The remaining six tasks included: Conducting a Tactical Movement/Foot March, Employing Hand Grenades, Preparing a Fighting Position (Fill and Emplace Sandbags), Transporting a Casualty (Drag to Safety, Extract from Vehicle), Moving Under Direct Fire, and Moving Over, Through, or Around Obstacles. With the exception of the last task, which applied only to Infantry MOS (11B and 11C), each of these tasks were common across the majority of combat arms positions. Several of these tasks were further linked to primary physical domains of load carriage, repeated lift and carry, heavy drag, heavy lift, and agility (Table 1).

Table 1 Physically demanding combat arms tasks and their primary physical domains

Task	Physical Domain
Conducting a Tactical Movement/Foot March	Load carriage
Preparing a Fighting Position	Repeated lift and carry
Drag a Casualty to Safety	Heavy drag
Extract a Casualty from a Wheeled Vehicle	Heavy lift
Moving Under Direct Fire	Agility

Notes: Adapted from "Development of the Occupational Physical Assessment Test (OPAT) for Combat Arms Soldiers", by Foulis et al. 2015, USARIEM Technical Report (T16-2), Tables 1 and 2.

Through similar processes, Project FORCE scientists identified 13 essential physical tasks for Canadian Forces (Reilly et al. 2013). Following evaluation of their associated biomechanical and aerobic demands, these 13 tasks were further consolidated to 6 critical tasks: Escape to Cover, Pickets and Wire Carry, Sandbag Fortification, Picking and Digging, Stretcher Carry, and Vehicle Extrication. While several of these bear similarity to the physically demanding tasks identified by the US Army, the CF tasks included several unique activities such as thumping in pickets to erect a fence, and picking and shoveling soil for ablution facilities, both of which were noted to require overhead repetitive lifting.

Common physically demanding tasks across NATO countries were documented by a NATO RTO Panel for Optimizing Operational Physical Fitness (NATO 2009). Identified tasks were consolidated into categories of Manual Materials Handling, Marching, and Digging, and physical capacities found to predict performance within each category were reviewed. Measures of isometric and isokinetic trunk strength, knee extension strength, ankle plantarflexion strength, and aerobic fitness were identified as strong predictors of Marching performance. For Digging tasks, aerobic capacity and isometric arm strength and endurance were identified as predictors of performance, with the shoulders, upper arms, hands, and lower back noted as body areas experiencing the greatest physical strain. Manual Materials Handling, which encompassed a wide range of tasks requiring lifting, carrying, pushing, and/or pulling objects, was noted to require a combination of muscular strength, aerobic and anaerobic endurance depending on tasks constraints (e.g., weight, height, distance, frequency, duration), with whole body muscular strength (as measured by one repetition maximum lift) commonly used as a predictor of performance.

A 2014 report by the US Public Health Command (Hauschild et al. 2014) examined the relationships between physical fitness tests and physical performance demands of military tasks. Their review included a meta-analysis of Army tasks identified across NATO countries as physically demanding and their physical performance requirements corresponding to fitness components of cardiorespiratory endurance, muscular endurance, muscular strength, and flexibility. Tasks identified as requiring cardiorespiratory endurance tasks included those involving continuous movement under load (e.g., foot march) and high-intensity activities with minimal breaks (e.g., repetitive lift and carry, prolonged drag). Muscular endurance was noted as a requirement for tasks involving lifting and carrying (e.g., movement of equipment and supplies, preparing a fighting position) as well as those involving high rates of movement (e.g., movement under direct fire, react to contact). Muscular strength was divided into requirements of static strength (e.g., pushing/pulling heavy objects, throwing grenade, extricating a casualty) and explosive power (e.g., climbing or jumping over obstacles, moving under fire, reacting to contact, shooting). Tasks involving changes in direction (movement under fire), reacting to enemy contact, and climbing or jumping over obstacles (e.g., walls, fences) were categorized as requiring flexibility. Tasks were additionally classified as "Manual Movement" of equipment, supplies or people, and "Body

Movement" with or without load. Manual Movement tasks included those involving single or repetitive lifting and lowering, lifting and carrying, pushing and pulling, dragging, and digging, while those tasks involving marching or walking, moving fast, climbing, and crawling were categorized as Body Movement.

3.3.2 Observation of Close Combat Field Activities Results

Through our participation in several close combat data collection events, we were able to observe a multitude of Soldier and Squad activities (Fig. 2) requiring a variety of physical attributes, including agility, dexterity, coordination, balance, movement speed, strength, flexibility and endurance. The extent to which each of these attributes contributed to execution of a particular activity, however, depended largely on the task objectives and constraints.

Fig. 2 Examples of observed close combat tasks. Top (left to right): members of a fire team close on enemy during BD2A, a SAW gunner provides suppressive fire during BD2A, climbing over a railing and down a ladder, climbing out of a tunnel hatch and through a window, climbing over a wall. Bottom (left to right): engaging moving targets during the stress shoot, low crawl, climbing through a basement window, casualty carry.

Overall, ability to move efficiently through complex terrain under load, ability to negotiate obstacles under load, and ability to effectively engage targets under dynamic conditions appeared to be critical to successful execution of the majority of observed activities. Efficient movement under load during activities such as prolonged road marching, movement to contact, and flanking, required muscular strength and endurance to support and sustain motion under the weight of carried equipment, as well as balance and coordination to avoid hazards and prevent tripping or falling in complex terrain. Negotiating obstacles such as those found in urban environments (e.g., windows, doorways, tunnels, stairs, ladders, walls, etc.) required muscular strength, muscular endurance, balance, and coordination as well, but additionally required speed, agility, and flexibility to move quickly through constrained spaces and perform tasks requiring large ranges of motion. Finally, effectively engaging targets during activities such as the stress shoot and Squad assaults, required speed, agility, and coordination to move quickly and efficiently between firing positions and postures, as well as muscular strength, balance, and dexterity to stabilize and manipulate the weapon quickly and accurately.

3.3.3 Physical Task Demands Analysis Results

An initial review of ATP 3-21.8 (Infantry Platoon and Squad) and STP 21-1-SMCT (Soldier's Manual of Common Tasks – Warrior Skills Level 1) (Headquarters, Department of the Army 2016, 2017) identified a total of nine Battle and Warrior Drills that incorporated physical task performance at the Squad, small team, or individual Soldier level (Table 2).

Table 2 Physical task performance actions derived from ATP 3-21.8 and STP 21-1-SMCT

Battle drills	Warrior drills
BD1: React to Direct Fire Contact BD2A: Conduct a Squad Assault BD4: React to Ambush BD6: Enter and Clear a Room	React to Contact Establish Security at the Halt Perform Tactical Combat Casualty Care React to Ambush – Near React to Ambush – Far

Using information contained in the reference documents, those 9 Battle/Warrior Drills were decomposed into 10 independent Warrior Skills involving physical task performance. Based on their commonality across multiple Battle/Warrior Drills, criticality to mission outcome, and/or being primarily physical in nature, 6 of the 10 Warrior Skills from the Battle/Warrior Drill decomposition, and one additional Warrior Skill (Conduct a foot march) were selected for further decomposition:

- Engage targets with rifle or carbine
- Employ hand grenades
- Move over, through, or around obstacles
- Move under direct fire
- Select a hasty fighting position
- Transport a casualty
- Conduct a foot march

A total of 44 component tasks were decomposed from the seven Warrior Skills and mapped to specific physical abilities. Gross Body Coordination, Gross Body Equilibrium, Dynamic Flexibility, Upper Body Dynamic Strength, and Trunk Strength were found to be the most frequently required physical abilities, each being associated with at least 25% of the evaluated component tasks (Fig. 3). Twelve of the 44 component tasks were also found to require 6 or more physical abilities to perform (Table 3).

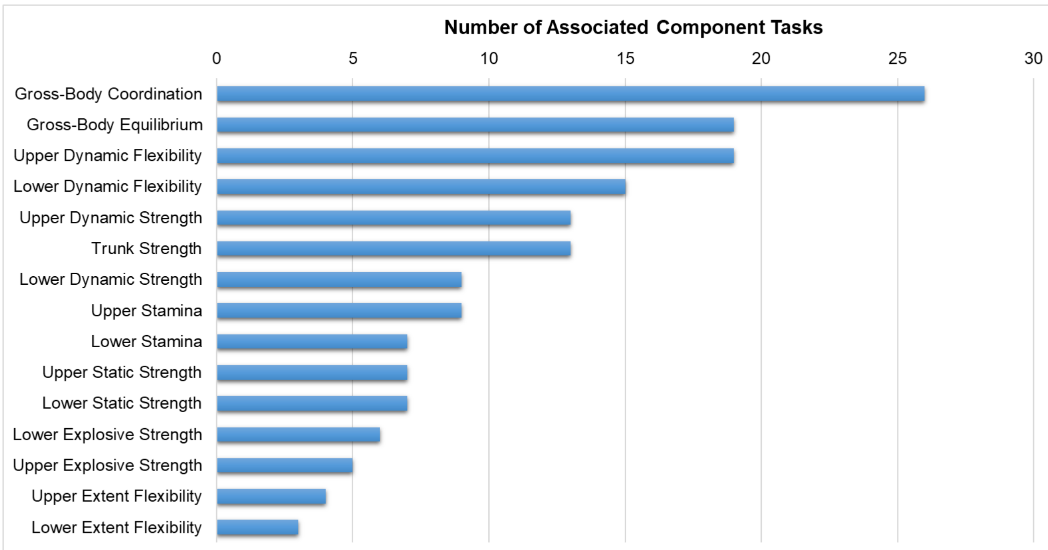


Fig. 3 Instances of physical ability required across 44 close combat component tasks

Table 3 Physically demanding close combat tasks and their required abilities

Component Task	Static Strength	Explosive Strength	Dynamic Strength	Trunk Strength	Stamina	Extent Flexibility	Dynamic Flexibility	Gross Body Coordination	Gross Body Equilibrium
3–5 second rush		U, L	U, L	X	U, L		U, L	X	X
Accurate sustained fire	U, L			X	U, L	U, L	U, L	X	X
Cross wall	L	U, L	U, L	X			U, L	X	X
Carry casualty	U	L	U, L	X	U, L		U, L	X	X
Fill/carry sandbag	U		U, L	X	U, L		U, L	X	X
High crawl			U, L	X	U, L		U, L	X	X
Cross wire obstacle		U, L	U, L	X			U, L	X	X
Cross ditch		U, L	U, L	X			U, L	X	X
Foot march			U, L	X	U, L		U, L	X	X
Low crawl			U, L	X	U, L		U, L	X	
Seek cover		L		X		U, L	U, L	X	
Throw grenade		U	U	X			U	X	X

Notes: U = upper body, L = lower body.

3.4 Discussion

The primary purpose of this analysis was to identify opportunities for exoskeleton technologies to provide the greatest benefit to Soldiers operating in close combat environments. A multi-faceted analysis of physical tasks demands associated with close combat operations was conducted to better understand the specific abilities required to perform component tasks and identify those tasks with the greatest physical demands. Despite the difference in approaches employed, several common findings regarding tasks with the greatest physical demands emerged across the PES literature review, close combat activities observation, and task decomposition. In addition, the findings from our task decomposition analysis provide a more comprehensive understanding of the functional requirements for the performance of close combat tasks.

The most physically demanding tasks for Soldiers and Squads conducting close combat operations appear to be those involving prolonged or rapid movement under load (e.g., foot march, moving under direct fire) and those requiring the manipulation of external loads (e.g., lifting and placing sandbags or ammo cans, extricating or dragging a casualty, picking and shoveling). Further, aerobic capacity, muscular strength, and muscular endurance are generally found to be the best predictors of an individual's ability to perform these highly demanding tasks. Looking more in depth at the physical abilities required to perform close combat tasks, however, we find that these same physically demanding tasks also require flexibility, balance, and coordination. In fact, these three attributes appear to be inherent to nearly all physical tasks performed by combat arms Soldiers. Further, each of the tasks included in the decomposition analysis were found to require at least half of the physical abilities derived from Fleishman's taxonomy.

This complex and interrelated need for multiple physical abilities likely explains why attempts to field exoskeleton technologies for close combat operations have thus far been unsuccessful. Despite the demonstration of several exoskeleton technologies to effectively mitigate the physical demands of prolonged load carriage, adoption of these systems for military use has been limited by their inability to support the broader range of close combat tasks. In order for exoskeleton technologies to be suitable for the close combat environment they must not only provide tangible performance benefits for the most demanding and/or most critical tasks, but also enable the unhindered performance of all other close combat tasks. Specifically, in addition to augmenting strength and endurance components of a particular task, close combat exoskeletons must be designed in such a way as to support or maintain the dynamic flexibility required for tasks such as bounding rush, crossing obstacles, and crawling, as well as the gross body coordination and equilibrium required for dynamic task execution.

Based on our review of the PES and operational fitness literature, observation of close combat task performance, and physical demands decomposition of Soldier tasks, as well as taking into consideration those tasks that are most critical to Soldier lethality and survivability, we can identify several key opportunities for the application of exoskeleton technologies within close combat operations. Explosive and dynamic strength were found to be required for the majority of evaluated tasks, therefore exoskeletons that augment those human abilities could be particularly advantageous in close combat operations. Augmentation of upper body explosive and dynamic strength could offer performance advantages for tasks such as pushing up from the ground during bounding rushes, climbing walls, crawling, lifting or dragging a casualty, and throwing a grenade. For the lower extremities, augmentation of explosive or dynamic strength could be expected to enhance a Soldier's ability to carry loads over distance, jump when crossing obstacles, and move quickly during a bounding rush or when seeking cover. However, care would be needed to ensure that the design of such exoskeletons also provides the flexibility required to achieve the large ranges of motion associated with those tasks, does not disrupt the individual's gross body equilibrium and coordination, and does not hinder the dexterity required by an individual to effectively engage targets or to carry or manipulate objects.

We have identified several opportunities and constraints for close combat exoskeletons; however, additional work is needed to fully understand the specific biomechanical and physiological requirements for the physical abilities associated with each of the component tasks. Such information will provide system developers with the detailed parameters required to guide the design of exoskeleton hardware and controls optimized for close combat operations. The component tasks and functional capabilities identified here can additionally be used to inform assessment methodologies against which the performance of any developed systems can be evaluated.

4. Sensor Validation and Feasibility for Close Combat Tasks

4.1 Purpose

The purpose of this effort was to investigate the validity and feasibility of various wearable sensors for use in operational environments, specifically for body movement, muscle activation, and foot pressure of Soldiers during various operational movements. These wearable sensors represent systems that may be used by future exoskeletons for the estimation of performance parameters or control of actuation. Three different studies were designed and executed, separately, to evaluate the accuracy and usability of the sensors while a group of Soldiers performed various operationally relevant movements in indoor or outdoor environments. The types of studies performed ranged from high-fidelity laboratory validations to quality assessments in operational environments. This was done to capture a full view of the potential for these sensor systems to be used accurately in relevant environments.

4.2 Wearable Motion Capture Validation

The first study consisted of comparing wearable motion capture using IMUs (Noraxon Myomotion) to the gold standard for biomechanical evaluation, IR optical motion capture (Motion Analysis). Three healthy adult subjects (labeled N1, N2, and N3) performed 10 activities; range of motion (ROM), walking, jogging, step up/down, squat, lateral stepping, zig-zag run, broad jump, changing between firing positions, and loaded walking. ROM tasks consisted of a series of flexion and extension of individual joints of upper and lower limbs, independently. The error in the body segment orientation measurement between wearable motion capture and optical motion capture was calculated. Each activity consists of a pre- and post-static trial (Fig. 4), a motion trial consisting of either three repetitions of a single motion task (ROM, step, squat, zig zag, broad jump) or 1-min long recording of treadmill walking (walking, jogging, loaded walking, lateral stepping; Fig. 5). Optical and wearable motion capture data were collected simultaneously and synchronized during post processing the data using the trigger signal (digital “ON”; 5V logic) sent from the optical motion capture system to the wearable motion capture system.

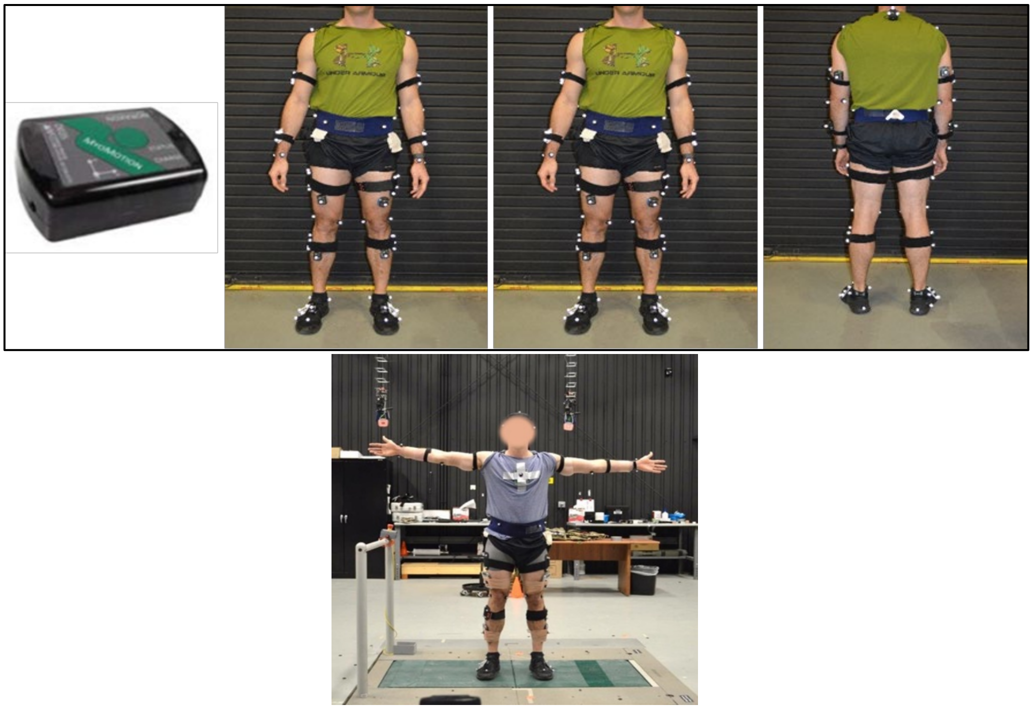


Fig. 4 (Top left) Noraxon IMU sensor; (top right) reflective marker and IMU placement on subject landmarks. Markers were placed on the body joints and IMU boxes to track the body segment orientations simultaneously from optical motion capture system and the Noraxon system. (Bottom) Static T-pose measurement taken before and after each session to compare the static error.

Fig. 5 One-min long treadmill walking tasks; (from left) walking, jogging, loaded walking, and lateral stepping

For post processing, both IMU and optical motion capture data was filtered using a zero-phase digital low pass filter (fourth order Butterworth, f_c = 10 Hz for the motion trials, f_c = 2 Hz for the static trials). Then the local coordinate frame of each IMU was reoriented to match the coordinate frame of the corresponding segment from the optical motion capture system. This adjustment was done using the pre-static T-pose (Fig. 4) and was used for subsequent error calculations from post-static T-pose trials. Because of the variability in time to complete each task, each trial was time normalized such that comparisons could be made at percentages of a cycle. For instance, one gait cycle refers to the time interval between a heel strike and the next heel strike from the same foot. A schematic of this process is shown in Fig. 6. Validity of the IMU wearable motion capture was assessed with two different error variables.

Static (T-pose) error was measured as the difference in the body segment orientations before and after motion trials were performed and represents long-term accuracy. The sensor drift, the mean, and the peak errors in the static pose trials were 0.065 ± 0.032 degree/s, 0.864 ± 0.490 degree and 2.223 ± 1.286 degree, respectively. Figure 6 and Table 4 depict the results in graphical and tabular form.

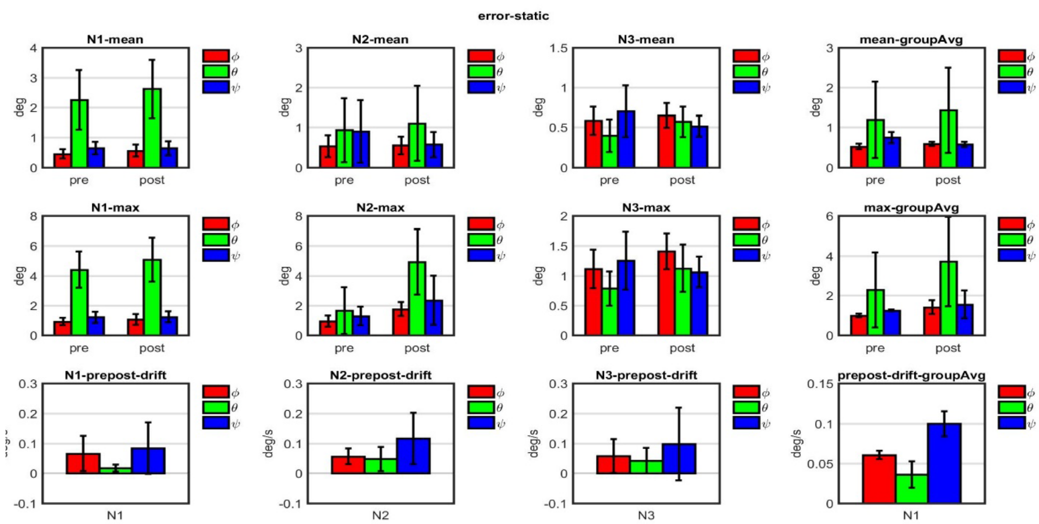


Fig. 6 **Static error during T-pose measured from pre- and post-motion trials; mean error (top row), peak error (middle row), and drift (bottom row) for each orientation for N1, N2, N3, and the group average**

Table 4 Static error (mean ± standard deviation)

Static error (mean ± sd)		N1	N2	N3	Group average
Drift (deg/s)	φ	0.066 ± 0.059	0.057 ± 0.026	0.058 ± 0.057	0.060 ± 0.005
	θ	0.017 ± 0.012	0.048 ± 0.040	0.042 ± 0.043	0.036 ± 0.016
	ψ	0.085 ± 0.086	0.116 ± 0.086	0.098 ± 0.121	0.099 ± 0.157
All 3 angles		**0.056 ± 0.035**	**0.074 ± 0.037**	**0.066 ± 0.029**	**0.065 ± 0.032**
Mean post (deg)	φ	0.559 ± 0.203	0.549 ± 0.218	0.651 ± 0.158	0.587 ± 0.057
	θ	2.617 ± 0.977	1.102 ± 0.939	0.569 ± 0.193	1.429 ± 1.063
	ψ	0.637 ± 0.236	0.571 ± 0.312	0.516 ± 0.133	0.575 ± 0.061
All 3 angles		**1.271 ± 1.166**	**0.741 ± 0.313**	**0.578 ± 0.068**	**0.864 ± 0.490**
Max post (deg)	φ	1.071 ± 0.346	1.757 ± 0.467	1.410 ± 0.299	1.413 ± 0.343
	θ	5.081 ± 1.471	4.913 ± 2.199	1.124 ± 0.395	2.706 ± 2.237
	ψ	1.234 ± 0.371	2.355 ± 1.658	1.062 ± 0.253	1.550 ± 0.703
All 3 angles		**2.462 ± 2.270**	**3.008 ± 1.677**	**1.199 ± 0.186**	**2.223 ± 1.286**

To compute errors during cyclic motions, drift during motion was first calculated for each angle as the change in the sum of the error of each cycle over time. The drift fit well to a linear model, which was confirmed by the coefficient of determination. Then, the drift was compensated for each cycle such that the mean and the peak errors are independent of the drift. Error was then calculated for each cycle as a difference in the orientation angles (φ, θ, ψ) between the IMU and optical motion capture systems (difference can be observed from example gait data during walking in Fig. 7), and then rectified. This linear envelope of the error was obtained and averaged over the cycles (Fig. 8). Root Square Error (RSE) on each orientation is averaged over three cycles (or gait cycles for the walking, jogging, loaded walking, lateral stepping sessions). This represents the short-term accuracy. The entire process is depicted graphically in Figs. 9 and 10.

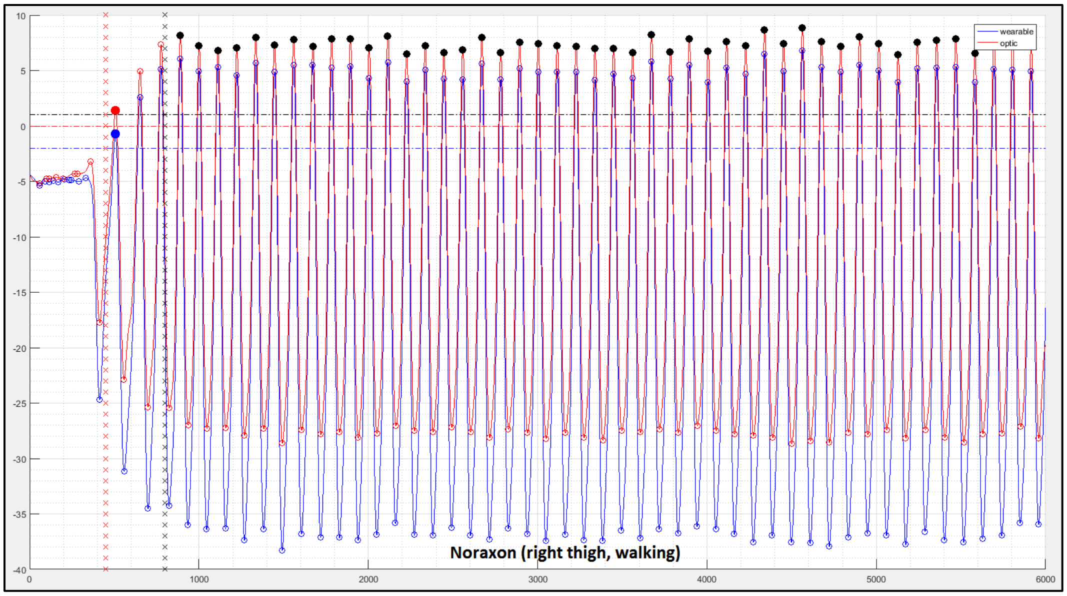


Fig. 7 Comparison on the right thigh sagittal angle measured during treadmill walking compared between IMU wearable motion capture (blue) and optical motion capture (red). The error in the orientation angle includes both overestimation and offset of the IMU wearable motion capture system. There was no noticeable phase difference (i.e., latency) between the two data sets.

The sensor drift, the mean, and the peak errors during the motion trials were 0.037 ± 0.015 degree/s, 8.632 ± 3.273 degree, and 16.630 ± 5.775 degree, respectively (mean of the errors in three orientations averaged across four motion types: walking, jogging, loaded walking, and lateral stepping). Figure 8 and Table 5 depict the results in graphical and tabular form.

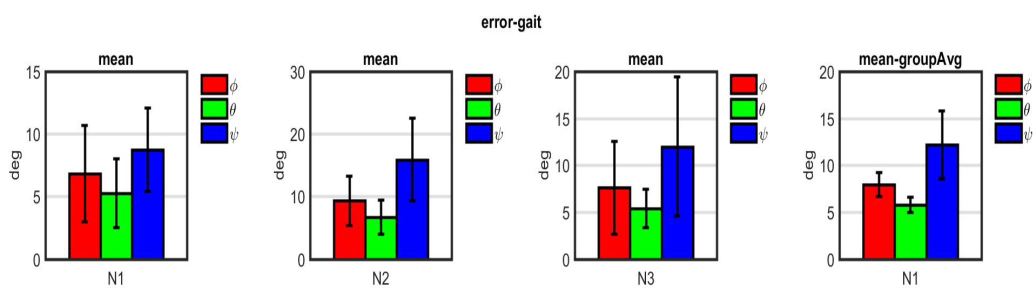


Fig. 8 Mean of the errors in each orientation angle averaged across four dynamic cyclic motions

Table 5 Errors during cyclic motion trials (mean ± standard deviation)

Error during gait cycles (mean ± STD)		N1	N2	N3	Group Average
Drift (deg/s)	φ	0.031 ± 0.012	0.034 ± 0.029	0.022 ± 0.023	0.029 ± 0.006
	θ	0.028 ± 0.033	0.025 ± 0.023	0.033 ± 0.045	0.028 ± 0.004
	ψ	0.050 ± 0.039	0.052 ± 0.044	0.063 ± 0.082	0.056 ± 0.007
All 3 angles		**0.036 ± 0.012**	**0.037 ± 0.014**	**0.039 ± 0.021**	**0.037 ± 0.015**
Mean (deg)	φ	6.821 ± 3.862	9.302 ± 3.912	7.609 ± 4.955	7.911 ± 1.268
	θ	5.279 ± 2.754	6.686 ± 2.758	5.375 ± 2.063	5.780 ± 0.786
	ψ	8.745 ± 3.347	15.889 ± 6.634	11.981 ± 7.413	12.205 ± 3.577
All 3 angles		**6.948 ± 1.737**	**10.626 ± 4.742**	**8.322 ± 3.360**	**8.632 ± 3.273**
Max (deg)	φ	13.695 ± 6.656	19.044 ± 6.082	16.686 ± 3.559	16.475 ± 2.681
	θ	9.469 ± 3.601	12.417 ± 3.806	10.919 ± 8.065	10.935 ± 1.474
	ψ	17.087 ± 3.559	27.627 ± 3.615	22.729 ± 9.445	22.481 ± 5.274
All 3 angles		**13.417 ± 3.817**	**19.696 ± 7.626**	**16.778 ± 5.906**	**16.630 ± 5.775**

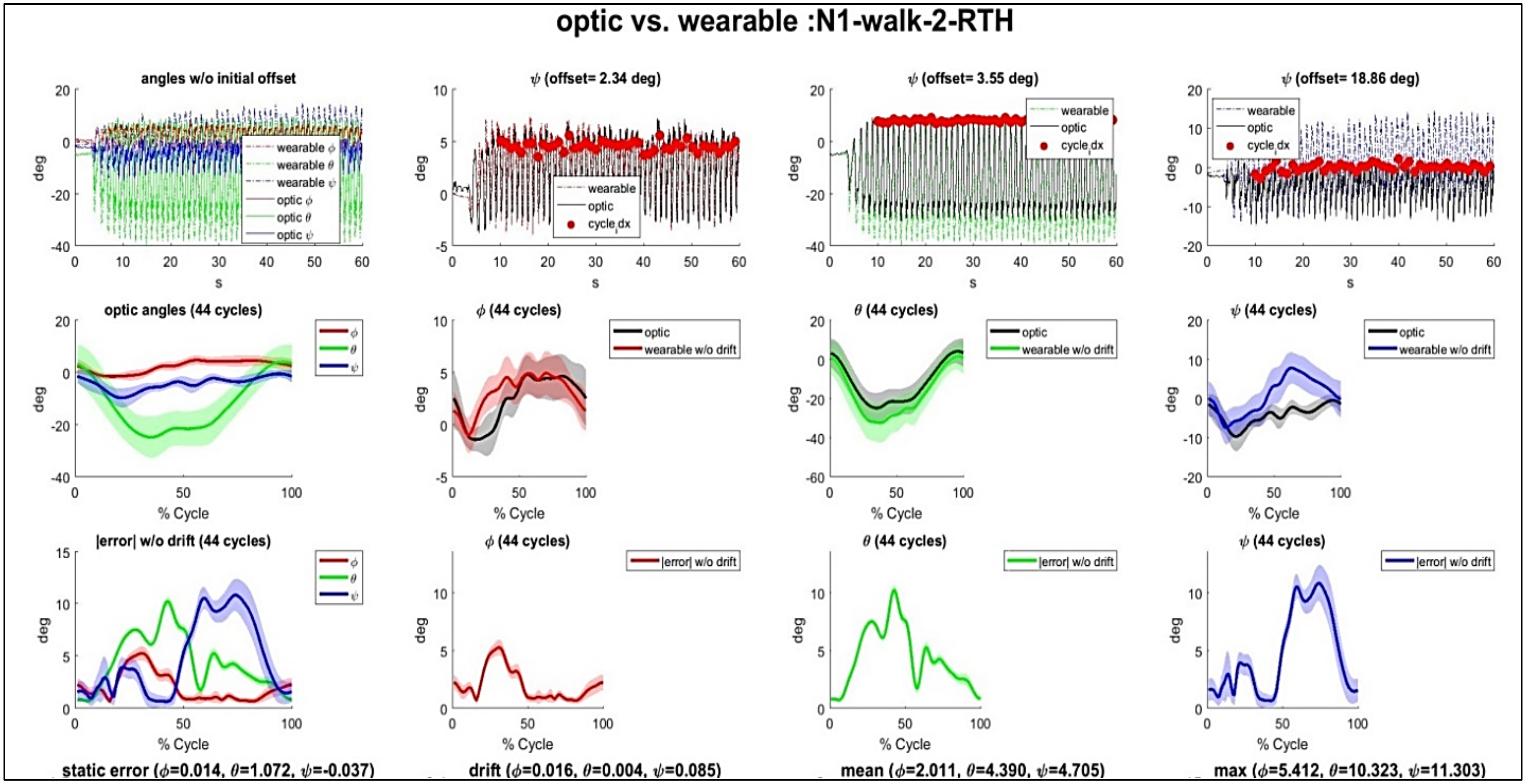


Fig. 9 Right thigh orientation data measured during treadmill walking: (top row) orientations (angles in degree) in frontal (φ, red), sagittal (θ, green) and transverse (ψ, blue) planes plotted with red dots indicating the peak sagittal plane angles of the optical motion capture system, (middle row) time-normalized angles averaged over the gait cycles (mean ± std), (bottom row) mean ± std of errors time normalized to 100% gait cycle

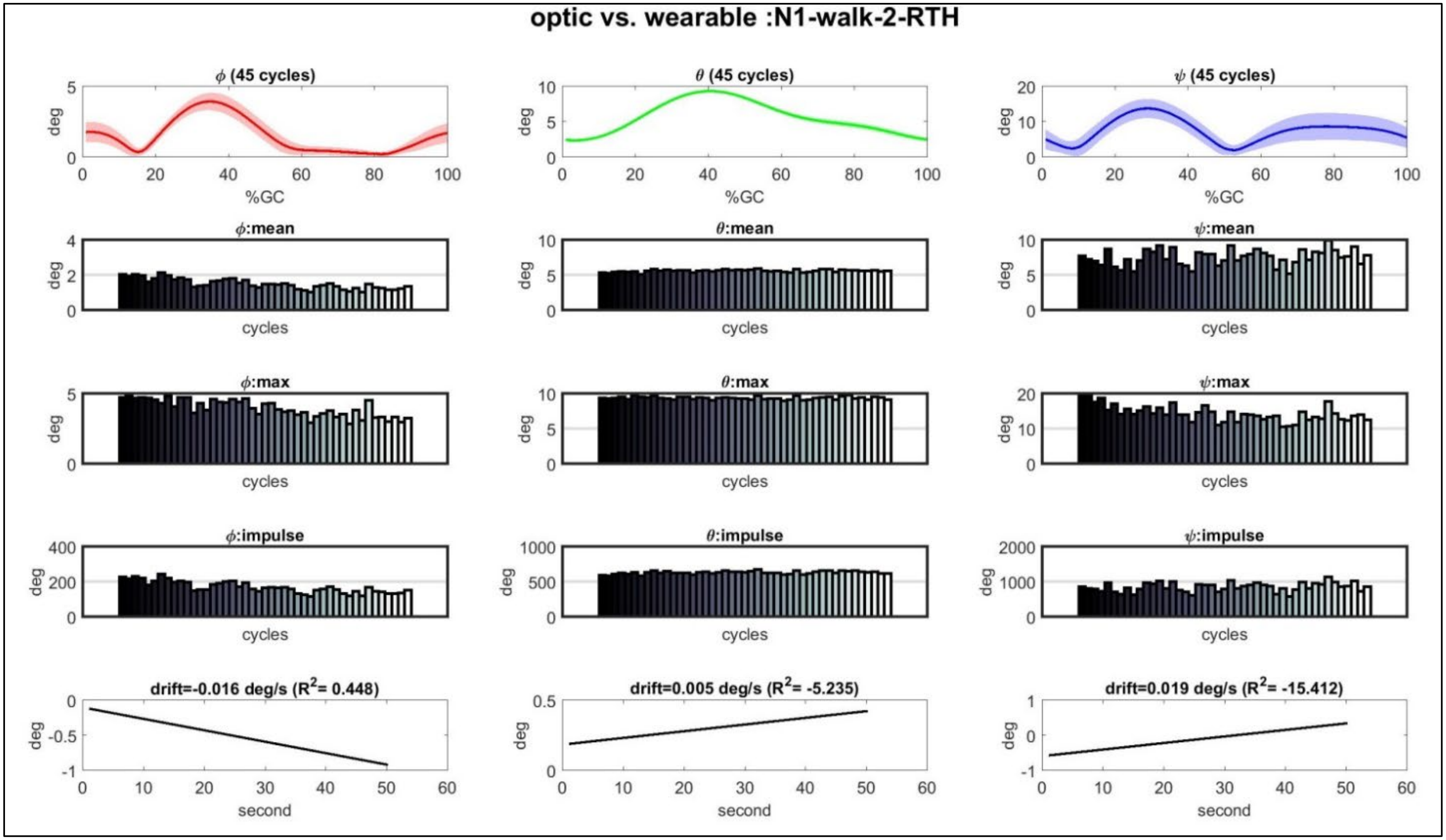


Fig. 10 **Right thigh orientation angle errors between optical motion capture and IMU wearable motion capture systems averaged over gait cycles. The error shows a repeatable and cyclic pattern with peak errors observed at 30% to 40% gait cycle**

4.3 Pressure Insole Sensor Usability in Indoor and Outdoor Environments

This study consisted of qualitative evaluation of the usability of three commercial pressure insole sensor systems during various movement tasks. The ParoTec (Paromed Inc.), Medilogic WLAN Insole (Medilogic Inc.), and Pedar (Novel Inc.) systems (Table 6) were chosen for evaluation as they represent configurable (sensors could be fitted to each subjects' shoes) and portable (wireless or in-unit data logging) systems. Five civilian participants participated to complete 13 different movements tasks (Table 7) while instrumented with a system. Each pressure insole sensor system was evaluated independently (i.e., three separate assessments using the same group of subjects). For outdoor overground walking (Task #13), the subjects walked outside around the building, along the paved road, unpaved road, large gravel, pea gravel, and grassy area. Manufacturer specifications for calibration and use were followed for each system. Comfort and concerns were ascertained from the subjects through open discussion of the systems. Functionality and data quality during the tasks was visually assessed by the laboratory team. The Pedar system was also used during the Load Effects Assessment Program – Army (LEAP-A) and a military operation in urban terrain (MOUT) course navigation tasks.

Table 6 Three commercially available pressure insole systems evaluated in this study

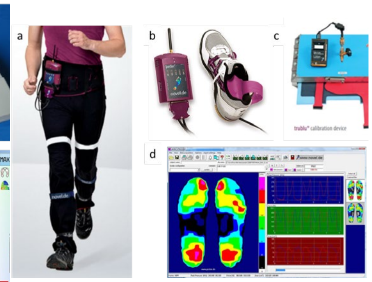
ParoTec (Paromed Inc.)	Medilogic Insole (Medilogic Inc.)	Pedar (Novel Inc.)
		

Table 7 Thirteen tasks performed for pressure insole sensor assessment

	Task/Motion	Details
1	Broad Jump	Moderate effort
2	Vertical Jump	Moderate effort
3	Walking (level)	3, 3.5, and 4 miles per hour, each 30 s long
4	Running (level)	Self-selected speed for 30 s, level grade
5	Walking (10% incline)	3, 3.5, and 4 miles per hour, each 30 s long
6	Running (10% incline)	Self-selected speed for 30 s
7	Walking (10% decline)	3, 3.5, and 4 miles per hour, each 30 s long
8	Running (10% decline)	Self-selected speed for 20 s
9	Step up and down	6, 12, and 24-inch step heights, each three reps
10	Jump up, step off, and land	6, 12, and 24-inch heights, each three reps
11	Step over	Overground walking with a step over a 10-inch bar
12	Stairs	Walk up stairs, pause, turn around, and walk back down
13	Overground walking	Walk around the building with varying ground surfaces

The primary concern with using pressure insole sensors for operational environments continues to be compatibility with Soldier gear and tasks. Because systems like these are typically used in clinical or ambulatory research settings, control boxes and wires are only tolerable annoyances. However, in operational settings, these configurations result in snag hazards, pressure discomfort, and restriction in range of motion. Soldiers noted changing movement strategies for tasks like crawling, window entering, and wall clearing. Hence, this type of pressure insole has a limited usability in outdoor gait studies but has less practicality in operational tasks (e.g., obstacle negotiation, bounding rush).

Accurate measurement of foot plantar pressure in terms of peak, impulse and distribution, and the center of pressure trajectories is not critical in many operational tasks (e.g., tunnel, crawl, wall, window, bounding rush). A more compact version of pressure insoles in exchange for resolution and precision would be a good trade-off (e.g., Moticon, LoadSol, or Orpyx) while being able to collect temporal parameters (gait events: HS and TO) and total pressure of different regions. This will also increase user acceptance and compatibility with Soldier gear and tasks.

4.4 Wearable Sensor Usability in Operationally Relevant Environments

This study consisted of characterizing the general performance and usability of wearable motion capture sensors during militarily relevant operational tasks. Five Soldiers were recruited to perform various tasks in two different facilities: the

LEAP-A course and a MOUT village, all located at Aberdeen Proving Ground, Maryland. This report only includes a qualitative assessment and discussion on the use of these types of sensors in operational tasks.

The LEAP is a standardized obstacle course composed of a series of timed obstacles and related accessory tasks representing operationally relevant mobility and movement tasks. It was designed in cooperation with NATO countries to understand the effect of a Soldier's ensemble load (clothing, equipment, etc.) on mobility, survivability, and battlefield performance in general. It has been demonstrated to be reliable and relevant for Soldier physical performance (Bossi et al. 2015; Mitchell et al. 2016, 2017). As such, the LEAP-A course was chosen as a repeatable platform to assess the usability of wearable sensors. A list of obstacles and a schematic layout of the course is included in Fig. 11.

- 1 – hatch
- 2 – tunnel (narrow and wide diameters)
- 3 – sprint
- 4 – stairs
- 5 – ladders
- 6 – agility run
- 7 – casualty drag
- 8 – windows (high and low)
- 9 – bounding rushes
- 10 – balance beam
- 11 – crawl
- 12 – walls (high and low)

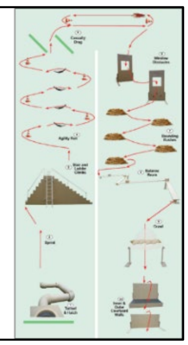


Fig. 11 LEAP-A course indoor facility (left) and diagram (right)

A MOUT village is a type of training facility meant to replicate real-world tactical missions in desert and urban environments. The objective of a MOUT village is to conduct individual and small unit training and research. There is no standard layout or mission profile for conducting exercises in the MOUT, so mission plans were drawn up in collaboration with the Army Testing and Evaluation Command (Aberdeen Proving Ground, Maryland). A single trial consisted of a sweep and clear objective in three distinct areas: 1) a one-floor building (top, Fig. 12), 2) an outside compound (not shown), and 3) a two-floor lookout building (bottom, Fig. 12). Each Soldier was given a dummy M4 and instructed to sweep and clear the first building, traverse the outside compound, and finally sweep and clear the second building.

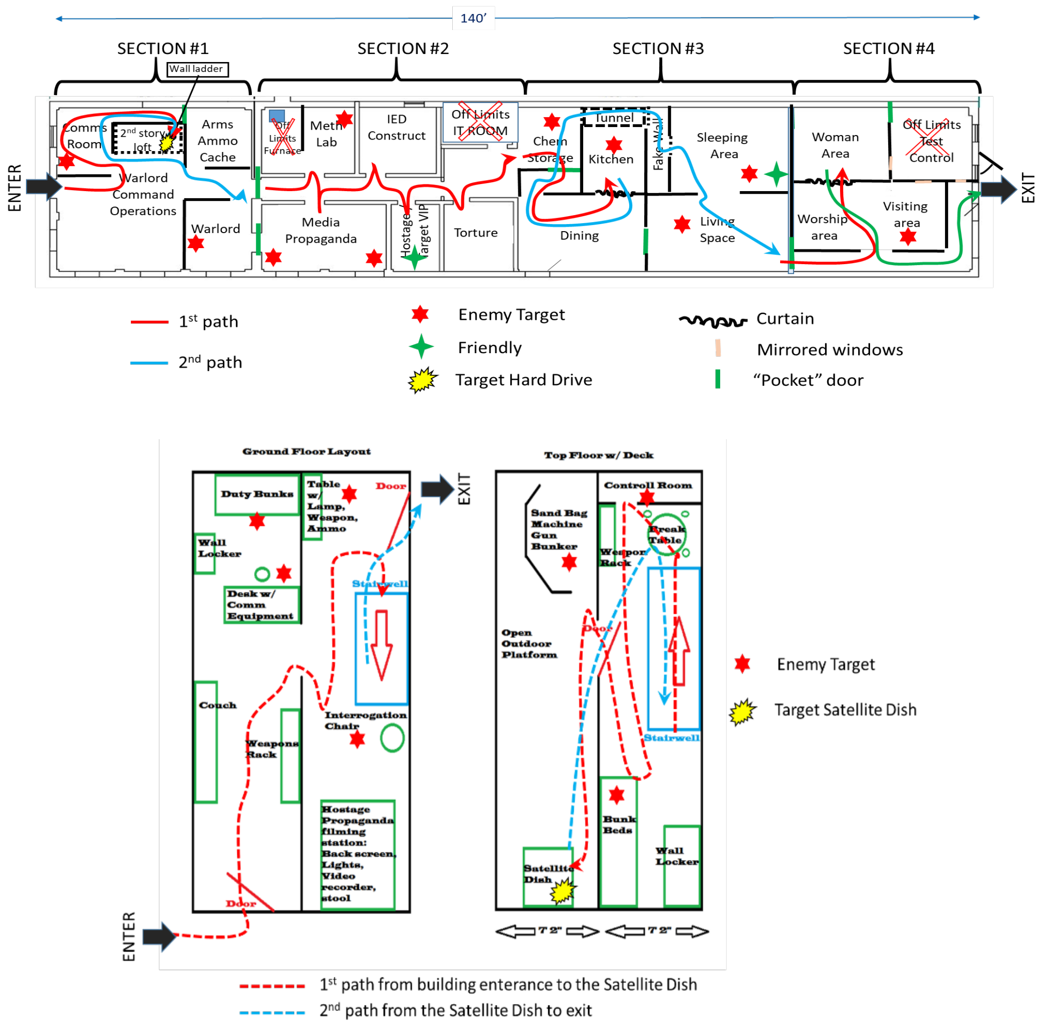


Fig. 12 (top) Layout and mission plan of first building in MOUT village, (bottom) layout and mission plan of second building in MOUT village

For both the LEAP-A course and the MOUT exercises, wearable sensors were instrumented on Soldiers to collect biomechanics and muscle activity while they perform obstacle negotiations and room/building clearing. Similar to the previous study, the participants were instrumented with wearable motion capture IMUs (Noraxon myoMotion; 16 channel). Real-time viewing of the accelerations and joint angles were checked using the Noraxon graphical user interface (GUI) (Fig. 13).

Soldiers also wore the Pedar (Novel Inc.) pressure insole sensor system within their own shoes. Pressure insole systems have the capability to quantify gait parameters (e.g., stride frequency and length) as well as kinetic estimates (e.g., peak forces). Parameters such as these may be useful for performance quantification in close combat environments as well as control parameters for active augmentation systems. The Pedar system was chosen after a qualitative usability assessment of three different pressure insole sensor systems (Section 4.3). Data quality and usability concerns for operational environments from these systems are addressed in Section 4.3.

They performed each course (LEAP-A and MOUT village) three times at a self-selected pace. Usability of the wearable motion capture sensors in the LEAP and MOUT facilities was evaluated using the following parameters: the mean and standard deviation; peak and the range of motion of head, trunk, and pelvis sagittal plane orientation angles; hip, knee, and ankle sagittal plane joint angle bilaterally; and head, trunk, pelvis, and left and right shank accelerations (sensor-based) in all three axes (φ, θ, ψ).

Exact variables assessed (e.g., body segment and joint kinematics, muscle activity, and temporal parameter of gait) were analyzed independently using the recommended signal processing and analysis method based on the sensor type. The peak, range, mean, and standard deviation of each variable were analyzed over the time series of each distinguishable motion (e.g., individual obstacles in LEAP-A). The signal quality (noise level, motion artifact, etc.) was assessed for each sensor system for each distinguishable motion.

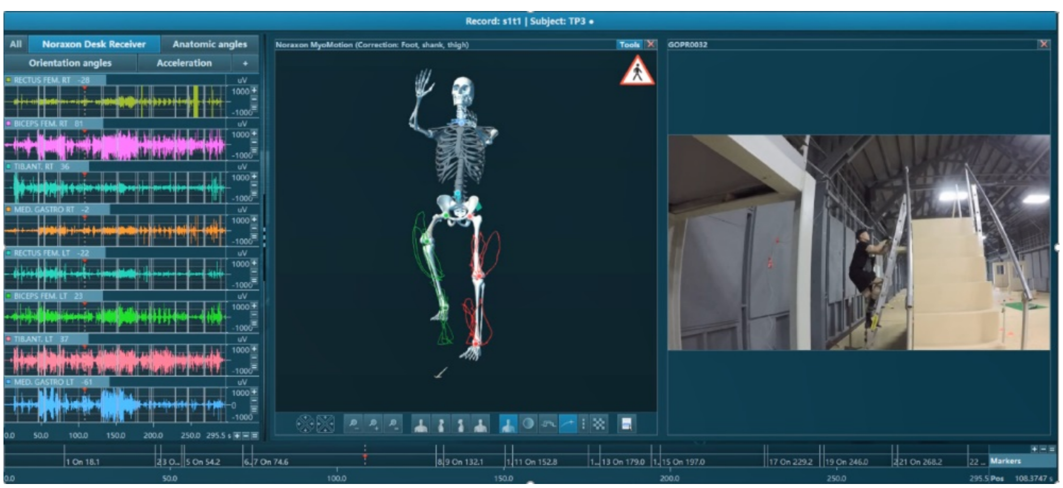


Fig. 13 Noraxon GUI example for Soldier performing the ladder climb of the LEAP-A course: (left) electromyography (EMG) waveforms for lower body muscle activity, (middle) skeletal model derived from wearable motion capture kinematics, and (right) synchronized video capture of ladder climb

The kinematic differences observed during each of the LEAP-A obstacles are visualized in Fig. 14, and the data is summarized in Figs. 15 and 16. In general, the overall average of the subjects' segment angles and segment accelerations differentiated by obstacle type in Fig. 15 indicate the wearable motion capture system is able to capture the key kinematics differences across different obstacles in the LEAP course. Each bar in the plots represents a different body part and the amplitude gives the average and standard error of the sagittal angle (Fig. 15) and acceleration (Fig. 16) experienced by that body part during the corresponding task. Data such as this helps us identify attributes of specific maneuvers that may be augmented by external physical systems. Intuitively, tasks such as a tunnel crawl (Fig. 15, column 1, row 1) induce more extreme joint angles overall than other tasks like the balance beam (Fig. 15, column 2, row 3). Similarly, lower body accelerations experienced during the zig-zag run (Fig. 16, column 1, row 2) were greater than during crawling tasks (Fig. 16, column 3, row 3).

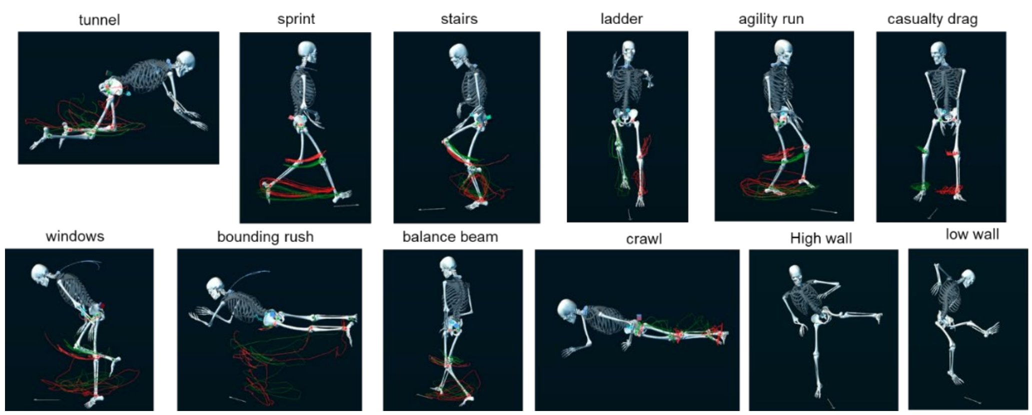


Fig. 14 Skeletal model from wearable motion capture during each of the LEAP-A obstacles

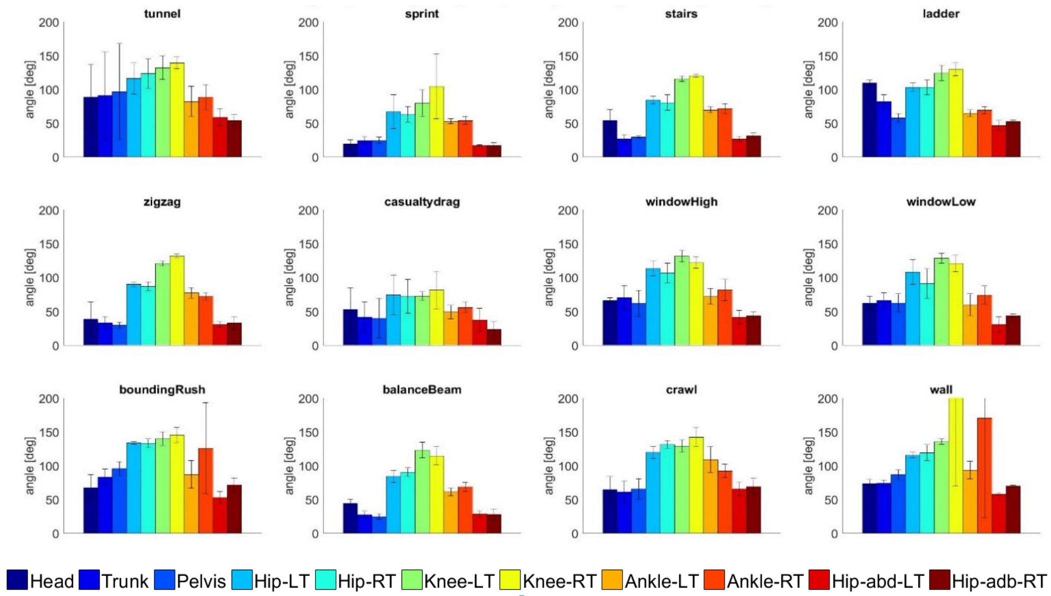


Fig. 15 Group average sagittal plane joint angle range (mean ± standard error)

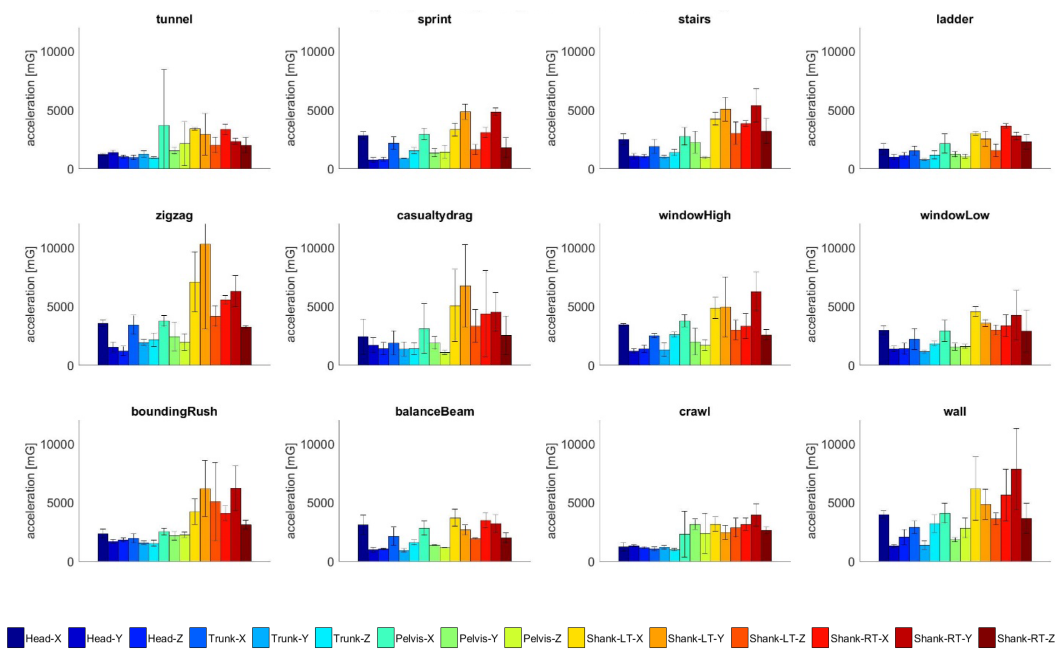


Fig. 16 Group average segment acceleration range (mean ± standard error)

As the activities performed during the MOUT exercises were not discrete like the tasks in the LEAP course, specific tasks during the MOUT exercises were not broken down similarly. However, general differences between how Soldiers operate and behave during LEAP and MOUT exercises can be seen in Figs. 17 and 18.

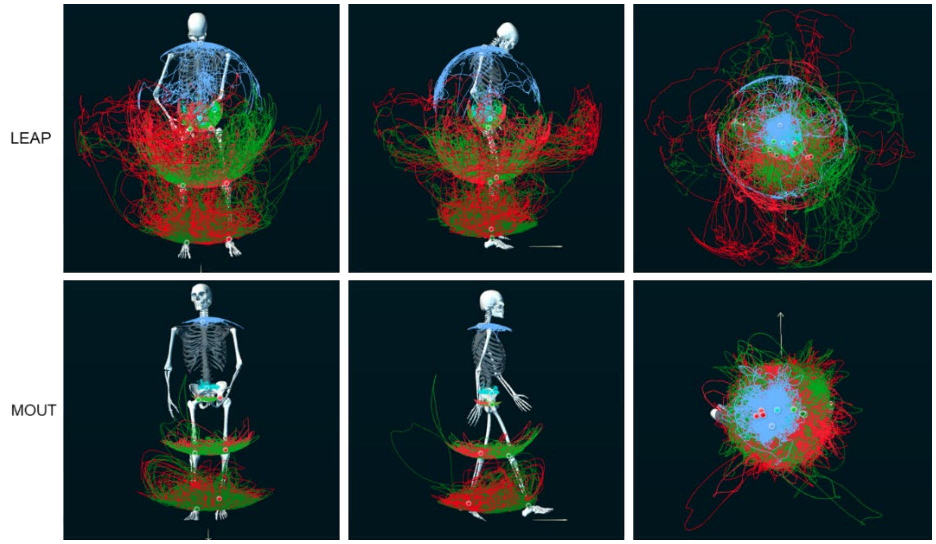


Fig. 17 Comparison of kinematics workspace between LEAP-A and MOUT course movement

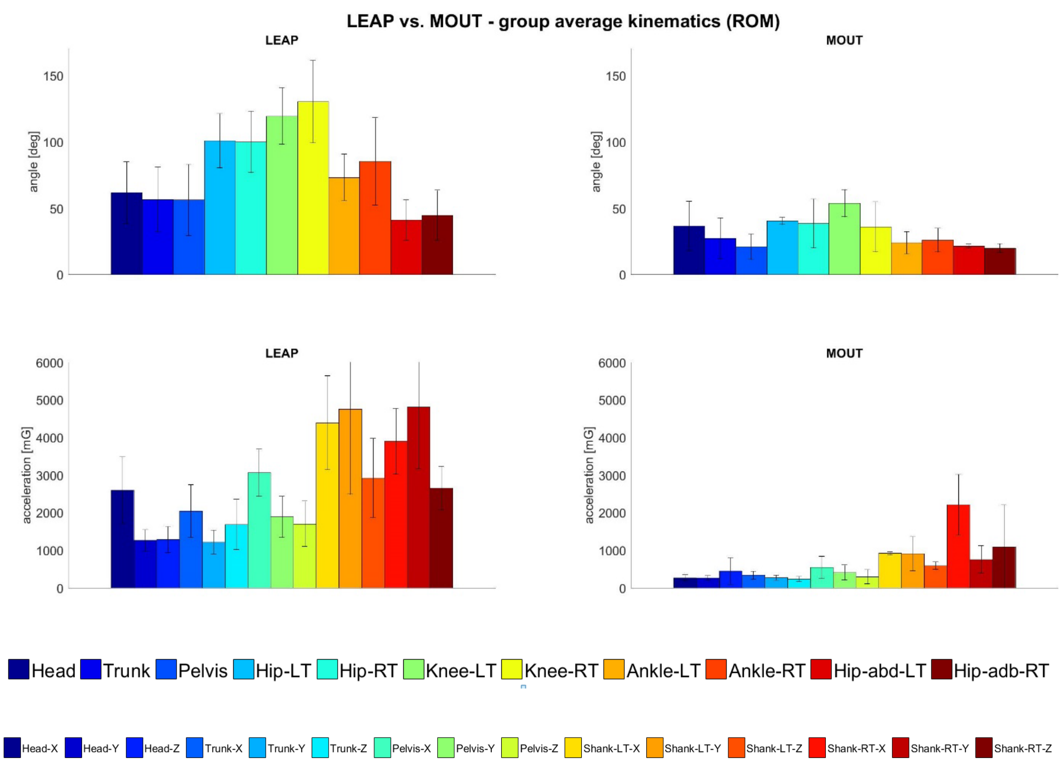


Fig. 18 Comparison of joint range of motion and segment acceleration range, between LEAP (left) and MOUT (right)

The wearable motion capture system was able to capture the key kinematics differences across different obstacles in the LEAP course and between the LEAP and the MOUT courses. However, there are still sensor placement concerns when performing operationally relevant tasks. Sensors like IMUs and EMGs placed on the anterior or posterior side of the body are prone to higher motion artifact during the LEAP course when they make direct contact with the environment (ground or structure), for instance, tunnel, low/high wall, bounding rush, crawl, low/high wall (Fig. 19). Sensor placements should take into consideration potential direct contact with environmental objects. Place IMU sensors laterally or identify the best spot for each body segment that does not make direct contact. High-amplitude, low-frequency EMG signals can be filtered for a single contact, but if the artifact prolongs it will not be usable for muscle performance estimation or as an exoskeleton controller.

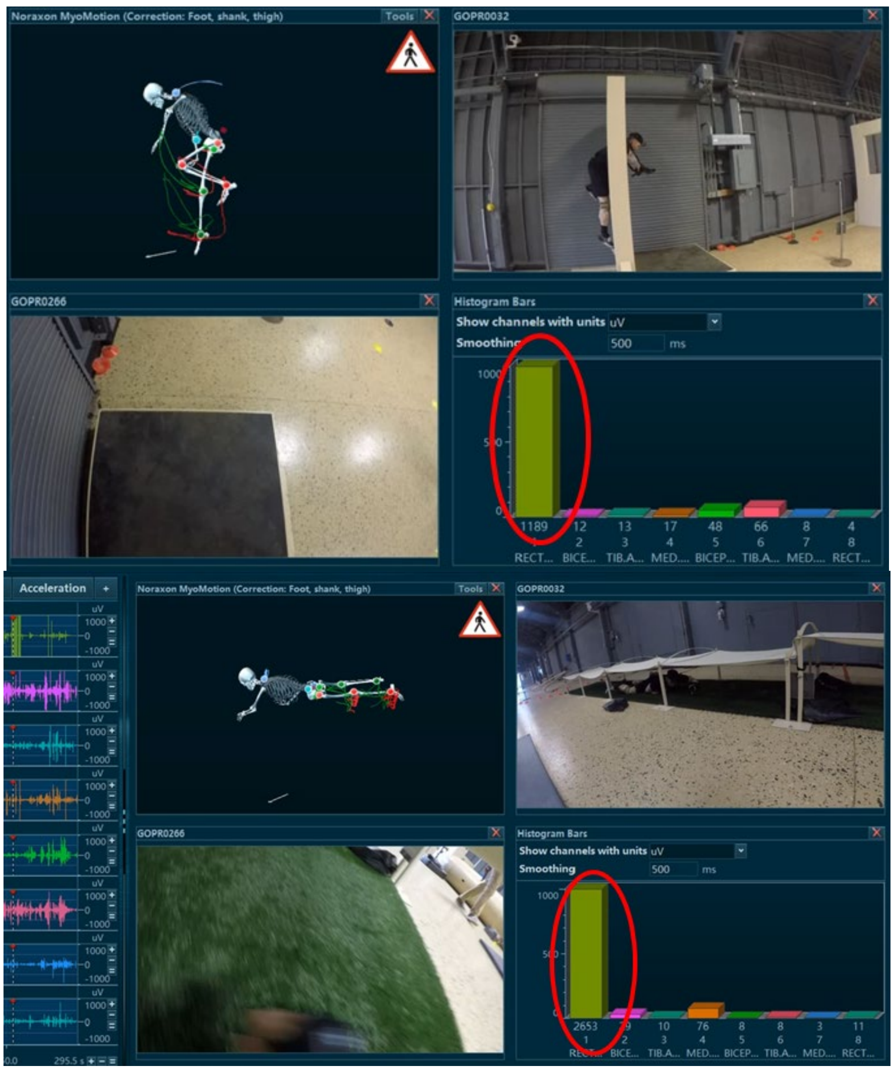


Fig. 19 High-motion artifact seen in some LEAP-A tasks that involve direct contact of the limbs with external structure or environment: low/high wall (top), crawl (bottom)

4.5 Discussion

This section is meant to form general conclusions about the use of the reported sensor types to effectively assess and potentially control exoskeletons for combat situations. With the indoor laboratory sensor validation, we have shown that wearable motion capture systems using IMUs can accurately represent Soldier motion with very few mathematical adjustments. Our conclusions are based on a comparison to the laboratory gold-standard for movement evaluation, IR optical motion capture. This step is necessary for researchers and developers to trust any field-based measurements to assess performance. While inertial measurements are used in some current exoskeleton designs, their implementation is typically limited to threshold-based control of actuation. The use of tactically relevant maneuvers provided by the LEAP-A course and MOUT facility show that the range of motion, angular velocities, and limb coordination are often specific to the task. This may be why current exoskeleton designs are limited in battlefield usage right now; most are aimed at augmenting a single task (e.g., ruck march) or a single joint (e.g., knee). Exoskeleton design must not only augment the Soldier, but also allow proper range of motion and not inhibit joint velocities necessary to perform other tasks. While the joint angles and accelerations experienced by different body segments during these tasks on a small sample size of Soldiers cannot provide direct correlations to performance, they do offer insight into how these tasks are accomplished. With respect to key aspects in Soldier physical performance in the field, such as mobility and explosiveness, the validation and characterization of range of motion and explosive tasks (e.g., max broad jumps and zig-zag run) allows researchers and developers to move forward with more operationally relevant approaches. Inertial measurement units worn on the limbs of Soldiers during these tasks can provide insight into the effects of exoskeletons on coordination (e.g., utilizing phase plots between body segments or within joints), equilibrium (e.g., through analysis of stability/excursion of raw accelerations at head/trunk/pelvis), flexibility (e.g., range of motion), explosive strength/power (possibly from linear/angular velocities/accelerations of body segments or at specific joints). While the LEAP course and MOUT facility studies discussed here are a good start, planned follow up research studies to continue this work include characterizing Soldier movement variability.

5. Conclusions

This technical report briefly presented preliminary results from various projects related to how exoskeletons may operate in close combat environments. In the future, research must be done to further understand the role of variability in how we evaluate and control exoskeletons for combat environments. Portable, validated sensors, like the inertial sensors noted in this report, offer more potential for exoskeletons than are currently being implemented.

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List of Symbols, Abbreviations, and Acronyms

CF	Canadian Forces
DEVCOM	US Army Combat Capabilities Development Command
EMG	electromyography
FORCE	Fitness for Operational Requirements of CF Employment
GUI	graphical user interface
IMU	inertial measurement unit
IR	infrared
LEAP-A	Load Effects Assessment Program – Army
MOS	Military Occupational Specialties
MOUT	military operation in urban terrain
NATO	North Atlantic Treaty Organization
OPAT	Occupational Physical Assessment Test
PES	Physical Employment Standards
ROM	range of motion
RTO	Research and Technology Organisation
STD	standard
USARIEM	US Army Research Institute for Environmental Medicine

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