Design, Evaluation, and Research Challenges Relevant to Exoskeletons and Exosuits: A 26-Year Perspective From the U.S. Army Research Laboratory

Article *in* IISE Transactions on Occupational Ergonomics and Human Factors · January 2019

DOI: 10.1080/24725838.2018.1563571

Taylor & Francis
Taylor & Francis Group

IISE Transactions on Occupational Ergonomics and Human Factors

ISSN: 2472-5838 (Print) 2472-5846 (Online) Journal homepage: https://www.tandfonline.com/loi/uehf21

Design, Evaluation, and Research Challenges Relevant to Exoskeletons and Exosuits: A 26-Year Perspective From the U.S. Army Research Laboratory

Harrison P. Crowell, Joon-Hyuk Park, Courtney A. Haynes, Jennifer M. Neugebauer & Angela C. Boynton

IISE Transactions on Occupational Ergonomics and Human Factors, (2019), 0: 1–14

ISSN: 2472-5838 print / 2472-5846 online
DOI: 10.1080/24725838.2018.1563571

REVIEW

Check for updates

Design, Evaluation, and Research Challenges Relevant to Exoskeletons and Exosuits: A 26-Year Perspective From the U.S. Army Research Laboratory

Harrison P. Crowell[1]*,
Joon-Hyuk Park[2],
Courtney A. Haynes[1],
Jennifer M. Neugebauer[1]
and Angela C. Boynton[1]
[1]U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, USA;
[2]National Research Council, Washington, D.C., USA

OCCUPATIONAL APPLICATIONS Efforts to develop exoskeletons and exosuits for military uses have been underway for many years. Assessments, evaluations, and research studies conducted at the U.S. Army Research Laboratory have been instrumental in that development. This work has provided design guidance for system developers, refined methods and metrics to characterize the state-of-the-art in exoskeleton and exosuit development, and identified gaps in knowledge needed for system designers and evaluators. Several design and evaluation challenges and areas needing further research are identified in this article, which are intended for use by ergonomics and human factors practitioners so they can contribute to the development and fielding of exoskeletons and exosuits for military applications.

TECHNICAL ABSTRACT ***Background*:** Exoskeletons and exosuits intended to augment strength and endurance would be very useful for military tasks, particularly carrying heavy loads for long distances over terrain that cannot be traversed by vehicles. Such systems could relieve the burden felt when carrying these loads or reduce the energetic cost of walking while carrying loads and may also reduce the risk of injury. ***Purpose*:** This article is intended to highlight key challenges that designers, evaluators, and researchers need to consider and address in order to further the development of exoskeletons and exosuits designed to assist with military load carriage. ***Methods*:** This overview is based on many years of experience with exoskeleton and exosuit assessments, evaluations, and research studies conducted at the U.S. Army Research Laboratory. ***Results*:** The challenges faced by designers of exoskeletons and exosuits for military load carriage include issues related to the unique equipment that must be carried, the variety of movements that must be accommodated, and the range of environments in which the systems must operate. Evaluators must take into consideration an array of issues from subjects and training to methods and metrics appropriate for the technical maturity and intended use of the system. Exoskeleton and exosuit system design and evaluation both need to be done in a manner that promotes the development

Received October 2018
Accepted December 2018

*Corresponding author. E-mail: harrison.p.crowell.civ@mail.mil

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uehf.

of systems that are safe for the user. The research challenges are gaps in knowledge relevant to both design and evaluation issues. These gaps include a need for additional kinematic and kinetic data to be used in system design, and the need to develop control systems that anticipate movements and adapt to the user. Other knowledge gaps include user-system interface issues and training methods and assessments. ***Conclusion***: The development and fielding of exoskeletons and exosuits will depend on designers, evaluators, and researchers who address the challenges presented herein.

KEYWORDS Exoskeleton, exosuit, military load carriage, dismounted warfighter, Warrior Web, TALOS

1. INTRODUCTION

The purpose of this article is to make designers, evaluators, and researchers aware of the most important challenges that need to be addressed during the development of exoskeletons and exosuits to assist dismounted warfighters with load carriage. Researchers at the U.S. Army Research Laboratory's (ARL) Human Research and Engineering Directorate (HRED) have many years of experience with exoskeleton and exosuit technology assessments and evaluations. This article will describe the lessons learned from this experience and provide recommendations for current research efforts in military exoskeleton and exosuit development. In particular, it will provide criteria that system developers can use to guide their designs. In addition, it will identify considerations that system evaluators need to be aware of as they plan and conduct evaluations, and suggest areas requiring further research.

Dismounted warfighters (i.e., military personnel who maneuver around the battlefield on foot) typically carry everything they need for their missions on their backs and/or attached to vests they wear. These loads can range from fighting loads (i.e., essential clothing and equipment) of up to 44 kg (Jaworski, Jensen, Niederberger, Congalton, & Kelly, 2015) to emergency approach march loads (i.e., fighting load plus additional supplies and equipment) of 68 kg (Coalition Task Force 82 and Coalition Joint Task Force 180, 2010). Carrying these loads can pose a number of problems for dismounted warfighters. The loads can reduce their mobility (Carlton & Orr, 2014) and make them more vulnerable to enemy fire (Billing, Silk, Tofari, & Hunt, 2015). Studies have shown that increasing the amount of body-borne loads increases the time it takes for Soldiers and Marines to complete common combat movements, such as 30 m rushes, sprinting, crawling, dragging a casualty, and carrying ammunition (Jaworski et al., 2015; Loverro, Brown, Coyne, & Schiffman, 2015). Other effects of load include decreases in situational awareness (Lim et al., 2017) and marksmanship performance (Jaworski et al., 2015).

The loads carried by dismounted warfighters can also increase the risk of musculoskeletal injuries (Seay, 2015). Musculoskeletal injuries linked to the stresses of carrying heavy loads are one reason that the U.S. Army observed an increase in the number of non-deployable Soldiers during 2007 (Tyson, 2009). A study of Australian Regular Army Soldiers found that the lower extremities and back were the most common sites for injuries related to load carriage (Orr, Johnston, Coyle, & Pope, 2015), although shoulder and upper extremity injuries also occur (Orr, Pope, Johnston, & Coyle, 2014). One reason for the increased risk of injuries to the lower extremities may be because the changes in the warfighter's biomechanics as a result of the load (Brown, O'Donovan, Hasselquist, Corner, & Schiffman, 2014) and sudden stops (Ramsay, Hancock, O'Donovan, & Brown, 2016). Shoulder and upper extremity injuries may be the result of tissue deformation, which causes reductions in blood flow (Hadid et al., 2017; McCulloch, Sheena, Simpson, & Power, 2014).

Potential solutions to these problems include the development and use of exoskeletons and exosuits to assist with load carriage. The Robotic and Autonomous Systems Strategy describes the U.S.

Army's vision for using exoskeletons to lighten the burden on Soldiers (U.S. Army Training and Doctrine Command, 2017). Exoskeletons can be defined broadly as wearable devices containing rigid components that enable, assist, or enhance motion or posture. Exosuits are similar, but they consist mostly of flexible components that enable, assist, or enhance motion or posture. This article focuses mainly on exoskeletons and exosuits that are intended to assist dismounted warfighters with carrying heavy loads over long distances on all types of terrain.

2. OVERVIEW OF EXOSKELETON AND EXOSUIT TECHNOLOGY ASSESSMENTS AND EVALUATIONS AT ARL

For more than 26 years, ARL and its predecessor organizations have been involved in research on and evaluation of exoskeletons and exosuits: first through internal projects, and then in programs sponsored by the Defense Advanced Research Projects Agency (DARPA) and the U.S. Special Operations Command (USSOCOM). In the late 1980s, a board was convened at the Human Engineering Laboratory (HEL) to review a proposal for an individual fighting system. That system included an exoskeleton to support the weight of a life support system, fire control system, weapon system, and power system (Tullington, Butz, & Hill, 1987). According to the schedule in the proposal, it was expected to take one or more decades to develop all of the components and to then integrate them into a complete system. The board reviewed the proposal favorably and recommended parallel development of low-risk and high-risk technology demonstrators. Although the proposal was not funded, it initiated a deeper examination of: (1) components available at that time to begin creating prototype exoskeletons and (2) components that would need further development to be practical for use in an exoskeleton.

In the early 1990s, scientists and engineers from HEL, the Materials Technology Laboratory (MTL), and the Harry Diamond Laboratories (HDL) began conducting a detailed front-end analysis of the component technologies needed to eventually develop exoskeleton systems for dismounted warfighters. They developed initial system requirements, against which they assessed the state-of-the-art in power sources, sensors, actuators, control systems, and materials for structural components. This front-end analysis also included interviews with Soldiers. These Soldiers were subject matter experts in various branches of the Army such as infantry, armor, artillery, combat service support, and special operations. These subject matter experts identified potential uses for exoskeletons in the Army. The front-end analysis continued during the formation of ARL in 1992. At that time, HEL, MTL, and HDL were joined with four other Army laboratories to become ARL. Two of the outputs of the front-end analysis were human engineering design guidelines for exoskeletons (Crowell, 1995) and a broad agency announcement (BAA) seeking proposals for the design and development of a prototype exoskeleton to enhance the performance of dismounted infantry. Through the BAA, Sarcos Research Corporation was funded for a two-phase project from 1994 to 1996. The first phase was to develop a full-body sensor suit that could be used to conduct studies of human movement. These studies would provide design data regarding the kinematics that the prototype exoskeleton would need to accommodate. The second phase was to construct a powered, lower-body exoskeleton prototype. The sensor suit was completed; however, the second phase of the project was not pursued because of changes in funding priorities, and work related to exoskeletons slowed until 2000.

In 2000, DARPA initiated the Exoskeletons for Human Performance Augmentation (EHPA) program. The goals of the program were to develop component technologies and then integrate them into exoskeletons to increase the speed, strength, and endurance of dismounted warfighters in combat environments. The critical technology areas that were the focus of this program included high density, man-portable energy sources; power generation and actuation; controls and haptic interfaces; and design and integration (Garcia, Sater, & Main, 2002). Researchers at ARL contributed to the program in a number of these areas. Early in the program, ARL researchers estimated the power and torque requirements for a load bearing exoskeleton (Crowell, Boynton, & Mungiole, 2002). These requirements were extrapolated from human biomechanics for two scenarios: (1) marching with a full load (fighting load plus approach march load = 45 kg), taking off the approach march load, and engaging enemy forces while carrying the fighting load (24 kg) and (2) carrying a fighting load

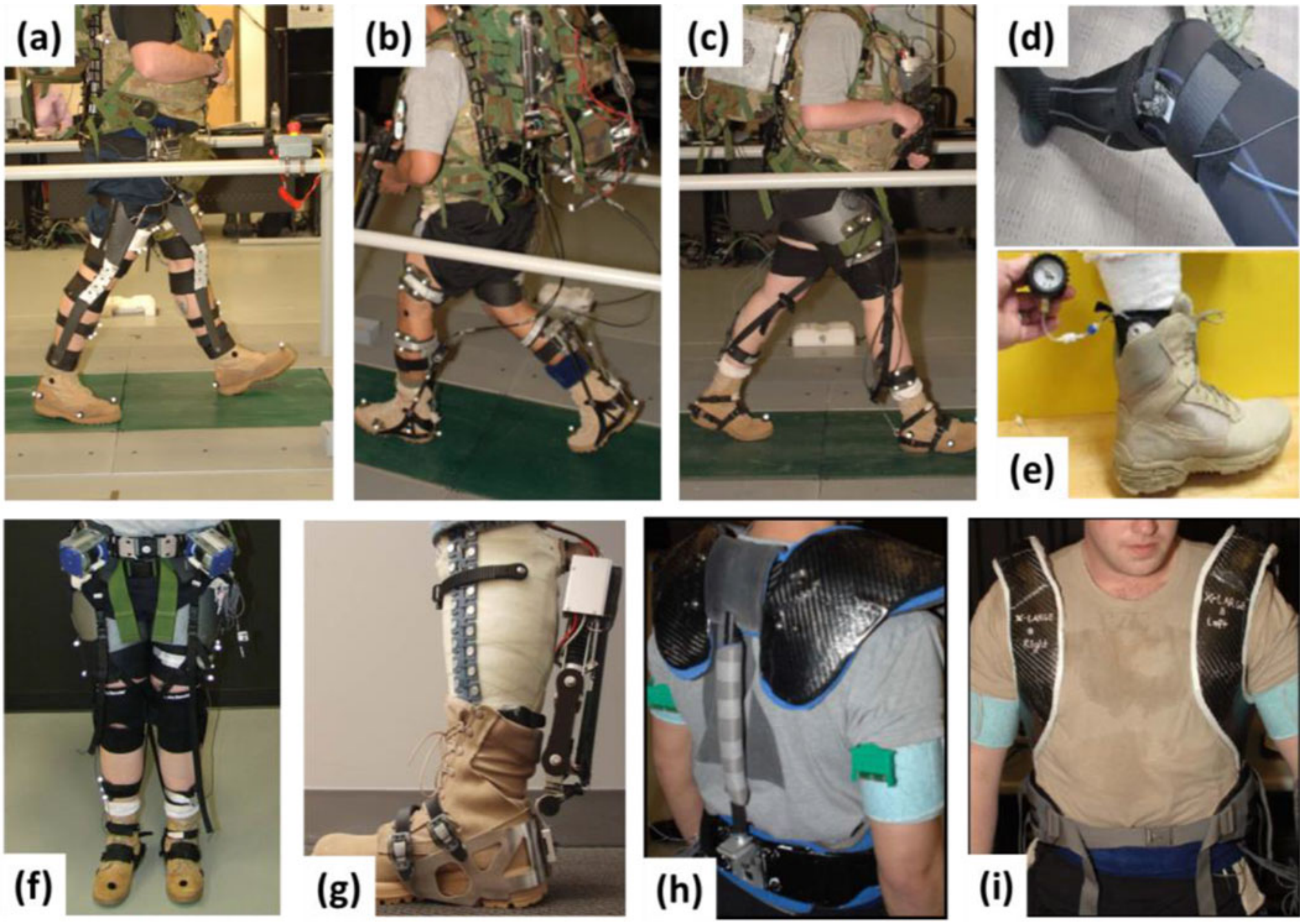

FIGURE 1 **DARPA Warrior Web Task A Phase 1 prototypes: (a) RheAct by Boston Dynamics, (b) Joint Torque Augmentation Robot (JTAR) by SpringActive, (c) Walk Assist Suit (WAS) by Wyss Institute (Harvard University), (d) Energy Injection System (SNL-EIS) by Sandia National Laboratories, (e) Joint Impedance Modulator (SNL-JIM) by Sandia National Laboratories, (f) Smart Exotendon Suit (SES) by Massachusetts Institute of Technology (MIT), (g) Warrior Sock by SRI International-iWalk, (h) UD_Ag by University of Delaware, and (i) UD_Yar by University of Delaware.**

while searching each room and engaging enemy forces in a three-story building. As part of a team led by Oakridge National Laboratory, ARL researchers participated in an effort to develop proof-of-concept demonstrations of key enabling technologies needed for a prototype exoskeleton (Jansen et al., 2004). The research team focused on the following enabling technologies: controls and sensing, the interface between the operator and the machine, power systems, and actuation. The ARL researchers conducted a study of boot sole thickness (Boynton & Crowell, 2006), which was used to guide the design of the foot force-torque sensor that the team developed. After the EHPA program concluded, exoskeleton related research at ARL waned until 2012.

In 2012, DARPA revisited exoskeleton technologies, launching the Warrior Web program. The goal of this program was to develop an exosuit, to be worn under the uniform, that would assist dismounted warfighters with carrying their fighting and approach march loads (a distance of 20 km with a 25% reduction in energy expenditure for the user) while reducing the risk of musculoskeletal injuries. ARL researchers aided the Warrior Web Program Manager (PM) with defining both the testing schedule and the metrics that would be used to determine if the systems developed met the program's goal. The Warrior Web PM also requested that ARL lead the evaluations for the program. In the initial evaluations (designated Task A, Phase 1), seven different contractors (one at a time) brought nine different devices to ARL's Soldier Performance and Equipment Advanced Research (SPEAR) facility for three weeks of evaluation (Fig. 1). These evaluations involved warfighters carrying loads in rucksacks and performing

FIGURE 2 **DARPA Warrior Web Task A Phase 2 prototypes: (a) Superflex exosuit by SRI, (b) Joint Torque Augmentation Robot (JTAR 2.0) by SpringActive, (c) Soft Exosuit by Wyss institute (Harvard University), (d) RheAct by Boston Dynamics/Eksobionics, and (e) UD WW system by University of Delaware.**

various tasks (e.g., walking overground and stepping over an object, walking on a treadmill) in the laboratory while wearing the Warrior Web prototypes. Although several of the prototypes were uncomfortable to wear, a few subjects showed reductions in energy expenditure (less than 10%) when using some of the prototypes. The Warrior Web PM received ARL's assessment of all of the systems evaluated (Neugebauer, Boynton, Webster, Crowell, & LaFiandra, 2013), and each contractor received the raw data and ARL's assessment of their system. Based on the performance of each system, the PM chose five contractors to continue in Phase 2.

In Phase 2 of Warrior Web Task A, the five selected contractors utilized the outcomes from their Phase 1 evaluations to further develop their systems and address identified performance and human-system integration issues (Fig. 2). At the conclusion of the Phase 2 effort, each contractor returned to ARL for another 3-week evaluation. During these evaluations, Soldiers carried military loads and completed treadmill and cross-country walking trials with and without the Warrior Web prototypes. The refined prototypes had far fewer user interface problems than the early prototypes, and subjects were able to walk the 4 km cross-country course while using them. Energy expenditure results, though, were mixed. Some subjects showed small (<10%) reductions in energy expenditure when they used the systems, while other subjects had increased or no change in energy expenditure. As in Phase 1, ARL provided evaluation summary reports to the PM and provided each contractor with the raw data and assessment outcomes for their prototype.

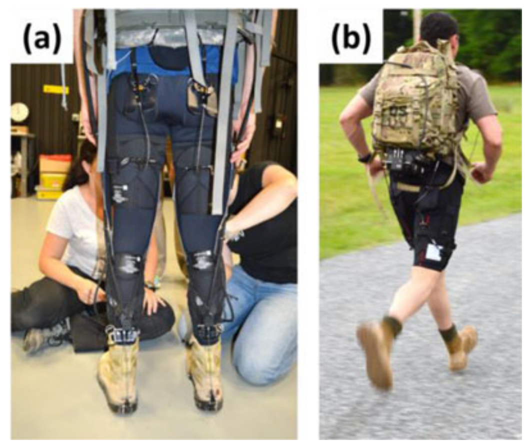

FIGURE 3 **DARPA Warrior Web Task B prototypes from Wyss Institute, Harvard University: (a) Soft Exosuit (ankle + hips) and (b) Soft Exosuit (hip only).**

In August 2013, DARPA issued the Warrior Web Task B BAA, soliciting proposals for individual and integrated wearable technologies to improve warfighter effectiveness, enhance human performance, and mitigate injury. For Task B, the proposed integrated technology solutions were expected to extend the capabilities developed under Task A, while also conforming to the Warrior Web vision of an adaptive, conformable undersuit. DARPA selected a single contractor (Harvard's Wyss Institute) to develop an exosuit prototype for the Task B effort. During Task B, the contractor produced two variants of their exosuit (Fig. 3): one with actuation at the ankle and hip, and one with actuation at the hip only (Awad et al., 2017; Ding, Kim, Kuindersma, & Walsh, 2018). Between July 2015 and July 2017, ARL conducted six separate evaluations of these exosuit prototypes. As in Task A, Phase 2, the primary evaluation task included walking on a treadmill and cross-country under a military load while wearing the prototype exosuit. Over the course of the evaluations, the cross-country distance progressively increased from 3 to 12 miles (4.8 to 19.3 km). Following each evaluation event, ARL provided the PM with summary reports describing exosuit performance relative to Warrior Web program goals, and shared raw data and assessment outcomes with the contractor. Additionally, ARL researchers worked closely with the contractor throughout the Task B period, participating in design review events and providing recommendations to support improvements to and further the development of the exosuits (Panizzolo et al., 2016). This collaborative, iterative development-evaluation cycle approach proved highly beneficial to the technology development process, providing checkpoints to assess current prototype performance and targeted feedback to guide and focus efforts for the next design iteration. The Warrior Web program concluded in September 2017, culminating with an operational demonstration consisting of a group of Soldiers completing a 20 km loaded road march while wearing the hip-only variant of the exosuit. The Harvard Wyss Institute exosuit achieved the program goal of assisting subjects to walk 12 km while carrying a load. Though it did not achieve the goal of a 25% reduction in energy expenditure, all subjects did have reductions in energy expenditure (approximately 10%) while using the system.

In 2014, the USSOCOM Joint Acquisition Taskforce started development of the Tactical Assault Light Operator Suit (TALOS; Machi, 2018; Miles, 2014), and researchers from ARL have been involved with this program from the beginning. The primary purpose of TALOS is to increase dismounted warfighter survivability through the use of increased body armor coverage. Thus, TALOS will carry a load (i.e., body armor) that will be distributed over the whole exoskeleton. Researchers at ARL have collected baseline kinematic and kinetic data from special operations forces subjects carrying vest-borne loads and provided the results to the TALOS system developers for use in their designs (manuscript in development). In addition to collecting baseline biomechanical data, ARL researchers also participated in the collaborative, iterative evaluation approach (design-develop-test-redesign-redevelop-retest) used in Task B of the Warrior Web program. Currently, ARL continues its involvement with the TALOS program, supporting the development of exoskeleton technologies.

3. DESIGN CHALLENGES

In this section, we describe the unique challenges that have been identified through experiences at ARL in evaluating exoskeletons and exosuits designed for military load carriage. A number of exoskeleton and exosuit systems have been built to assist with military load carriage (Gregorczyk et al., 2010; Kazerooni, Racine, Huang, & Steger, 2005; Mooney, Rouse, & Herr, 2014; Panizzolo et al., 2016); however, they have not advanced enough to be fielded for use by dismounted warfighters. There are still design challenges for this type of system, and a number of such challenges have been described earlier (Herr, 2009; Young & Ferris, 2017). While these challenges apply to exoskeleton and exosuit systems in general, there are some additional challenges in designing systems specifically for load carriage by dismounted warfighters.

3.1. Initial Design Considerations

The first step in developing an exoskeleton for military load carriage should be to identify augmentation strategies based on its intended use. This involves determining which joint(s) or muscle(s) to augment (i.e., the degrees-of-freedom for the exoskeleton or exosuit), when to augment (i.e., a specific period/instance during gait cycle), and how to provide augmentation (i.e., either passively or actively, and the magnitude and direction of the forces/torques). Based on the chosen augmentation strategy, appropriate design and control methods can be exploited. It should be noted that the augmentation strategy is subject to change during development, as more appropriate design and control methods are identified from device evaluations.

3.2 Operating Speeds

Exoskeletons and exosuits intended to assist with military load carriage need to be designed to operate over a range of speeds. While military doctrine may specify certain walking speeds while carrying a load, studies of dismounted warfighters carrying loads can differ. For example, Army Techniques Publication 3-21.18 about foot marches (Department of the Army, 2017) recommends speeds of 4 km/h on roads and 2.4 km/h cross-country for distances of 20-32 km. However, during the Warrior Web evaluations, Soldiers were walking without the prototype exosuits at 6.5 ± 0.8 km/h to 7.4 ± 0.3 km/h over a 20 km course (Boynton, Park, & Neugebauer, 2017). At times, dismounted warfighters need to run while carrying loads. In studies where dismounted warfighters ran short distances and made sudden turns or stopped while carrying loads, they ran at 12.6 ± 0.6 km/h (Brown et al., 2014; Ramsay et al., 2016). An exoskeleton or exosuit designed for dismounted warfighters needs to be able to operate through a range of speeds (0 km/h to at least 13.2 km/h) and accommodate frequent changes in speed.

3.3 Effects of Load

In addition to accounting for a range of speeds, exoskeleton developers should also account for the load carried while walking. As mentioned previously, dismounted warfighters carry fighting loads of up to 44 kg and emergency approach march loads of up to 68 kg. As such, exoskeletons should aim to offset the load or the perceived load. It is important for developers to have a solid understanding of how load carriage changes the kinematics and kinetics of walking gait, since the load effects will impact actuation and control systems (e.g., torques and powers needed, and the timing of when they are applied), as well as the design of structural components (e.g., size, weight, and material properties). For example, as load increases there are increases in stance-phase peak knee flexion, hip flexion of the leading leg, and hip extension of trailing leg (Birrell & Haslam, 2009; Knapik, Harman, & Reynolds, 1996; Tilbury-Davis & Hooper, 1999), as well as increases in knee and ankle ranges-of-motion (Harman, Han, Frykman, & Pandorf, 2000; Liew, Morris, & Netto, 2016; Majumdar, Pal, & Majumdar, 2010). In addition, peak propulsive and braking forces, peak vertical ground reaction forces, and peak medial-lateral forces all increase as load increases (Harman et al., 1992; Liew et al., 2016; Neugebauer & Boynton, 2015; Yang, Zhao, Liu, Zhou, & Zhao, 2015). Along with increases in forces, moments at the ankle, knee, and hip joints increase in both flexion and extension (Harman et al., 2000). System developers should understand these changes in gait biomechanics associated with load carriage before exploring different augmentation strategies and design/control approaches.

3.4. Other Movements

In addition to walking and running, exoskeletons and exosuits designed for dismounted warfighters should accommodate and even assist with other movements, such as crawling; side stepping; getting up from a prone position and sprinting; and stepping up, over, and down from obstacles and vehicles. These movements are often coupled together, and thus exoskeletons and exosuits should be designed for transitions between movements as well. Another movement that is common for dismounted warfighters is walking while holding and aiming a weapon. For this type of movement, walking speed may not differ from walking without a weapon, but body position and resultant forces do. For example, knee and hip flexion are increased throughout the gait cycle and ground reaction forces are decreased (Neugebauer & Talarico, 2017).

3.5. Physical Interface

The physical interface between an exoskeleton or exosuit and the user's body is a very important design consideration, which has typically involved rigid cuffs and/or elastic straps. These types of attachment can be for transmitting forces to the user's body or to mount system components. At the same time, these attachments can also hold sensors for monitoring limb positions, joint angles, and/or forces generated between the user and the exoskeleton (or exosuit). In any case, the main challenge in designing a physical interface for an exoskeleton or exosuit is that it must not cause discomfort (e.g., pressure points, hot spots, blisters, chaffing, abrasions, bruising, nerve impingement, or reductions in blood flow) at points where it is attached to the user's body, but should allow for efficient force transmission and/or accurate sensing, as appropriate.

3.6. Adjustability

The importance of fit cannot be overstated. At best, poor fit will result in ineffective actuation, while at worst, it could result in serious injury. Adjustability is thus an important design consideration. Even users with similar body dimensions can require a unique fit for optimal system operation. Designers also need to be cognizant that muscle movement results in large changes in diameter of body segments. These changes make it difficult to form an attachment that won't migrate over time resulting in misalignment and poor actuation and/or sensing. The exoskeleton or exosuit should be adjustable to accommodate people of different sizes and shapes and should allow for minor adjustments during use.

3.7. Equipment Compatibility

A challenge unique to exoskeletons and exosuits for dismounted warfighters is compatibility with the equipment they need to conduct their missions. This equipment includes a rucksack (or assault pack), a helmet, body armor, one or more weapons and ammunition, first aid supplies, and other items carried in pouches attached to the front and sides of the body armor vest. The exoskeleton or exosuit must not interfere with access to or use of any of this equipment. In addition, the exoskeleton or exosuit should not interfere with getting into or out of vehicles or interfere with sitting in a vehicle.

3.8. Safety Aspects

In the design of any exoskeleton or exosuit, there are a number of safety risks that should be identified and eliminated (or at least minimized), such as pinch, trip, and snag hazards. There are some additional safety concerns to be considered in the design of exoskeletons and exosuits for military applications. Designers must also consider whether the system would pose additional harm to the user if it became damaged by gunshot or blast exposure. For example, designers of hydraulic systems must consider the potential for contact of hydraulic fluid with an open wound. Additionally, if the user becomes injured, the system should be easily removable so that it does not interfere with the user receiving prompt medical care. Other considerations include controlling noise, heat, and electromagnetic signatures so they are not easily detected and exploited by the enemy.

3.9. Control System

Those who have worked with exoskeleton and exosuit systems in any capacity can attest to the difficulty of achieving synchronous human-machine movement for different people. Even if a system has proven to be reliable for one person, there are no guarantees that the system will be reliable for other people. Individual differences in body dimensions, movement patterns, general perception of motion, and even their propensity for accepting technology can all influence a person's experience with a given system. In order to develop robust systems, it is essential to understand which individual differences have important effects on the utility of a system and to anticipate what modifications are needed in control algorithms to accommodate different users.

3.10. User Controls

Another design consideration for exoskeleton and exosuit systems is the user control interface. This interface should be easily accessible to the user and protected from accidental actuation. It must not interfere with the dismounted warfighter's weapon or other equipment. The interface should be easy to operate by a person wearing gloves, as well as intuitive, so that cognitive, perceptual, and physical effort associated with operating the system can be minimized. Being able to quickly change between different modes of actuation or control may help dismounted warfighters in various operational situations. A stop switch, to promptly turn off the system, is also a necessary feature to ensure the user's safety if the system malfunctions.

3.11. Environmental Considerations

Dismounted warfighters are expected to be able to operate anywhere on earth, at any time, and in any weather condition. Therefore, exoskeleton and exosuit systems need to be designed for the environments in which they will be used (e.g., desert, jungle, temperate, arctic, urban, or rural). The terrain could be level or inclined, and the surface could be solid and stable like a road, or loose, slippery, uneven, or any combination of these. The system could need to operate underwater or at altitudes of 3,000 m or more. There could be no humidity or 100% relative humidity. Temperatures could range from -40 °C to 50 °C. Lighting could be bright sunlight or total darkness, or anywhere in between. In addition, as the system matures in its development, it should be ruggedized so as to resist the deleterious effects of dust, sand, mud, and water (fresh and salt).

4. EVALUATION CHALLENGES AND CONSIDERATIONS

This section discusses the challenges and considerations relevant to evaluating exoskeleton and exosuit systems developed for military load carriage. Exoskeleton and exosuit development can benefit from iterative evaluations throughout the development process to ensure that design changes support system function and preserve user comfort and compatibility. Evaluations should be customized to accommodate the current technical maturity of the system. Inappropriate evaluation methods could result in continued development of a system that will not be effective or in the premature rejection of useful technology.

4.1. Technical Maturity

An initial consideration when testing a prototype system is its current level of technical maturity. A system may be evaluated at any stage of development, but care should be taken to ensure that the evaluation is appropriate for its current state of development. Often technical maturity can be determined through discussions with the developers or through system inspection. Developers should be aware of technological limitations of the system, including power and actuation requirements, control limits, and current system capabilities relative to fielding requirements. For example, a system intended to aid dismounted warfighters with load carriage must ultimately be durable in various terrains and environmental conditions, provide reliable actuation during specific activities, operate with current military power sources, and permit dismounted warfighters to move freely through their environment. Proof-of-concept or early prototypes, however, may require tethers to electrical power, compressed air, or hydraulic cylinders to provide actuation. For this level of technical maturity, limited dynamic movements or treadmill walking may be the most appropriate means of evaluating the system.

Other considerations when determining technical maturity are the robustness of the system components, the presence of snag hazards, resistance to environmental conditions, and compatibility with other equipment. Proof-of-concept and early prototypes may have components that are prone to breakage, pose entanglement risks that are not easily mitigated, or are not shielded against moisture or debris. Evaluations may need to be restricted to a controlled laboratory environment to ensure the safety of the participant. This may also be the case if the system is not yet designed to interface with existing dismounted warfighter equipment (e.g., rucksack, body armor vest, ammunition, weapon). As development of the exoskeleton or exosuit progresses, the evaluations should include some of the military equipment worn and carried by dismounted warfighters. Advanced prototypes should be evaluated for their effectiveness while users are fully equipped with relevant military clothing and equipment, to quantify how the prototype functions under more realistic load and usage scenarios.

4.2. Subjects

While proof-of-concept and early prototypes can be evaluated with users who are not dismounted warfighters, there are advantages to conducting evaluations with dismounted warfighters regardless of a system's technical maturity. Working with dismounted warfighters can ensure that the system is designed to meet the physical size and mobility requirements of the intended population. Additionally, dismounted warfighters may possess skills and experience that are not represented in a general population. Often, dismounted warfighters are able to provide valuable feedback on fit and compatibility with current military equipment, and they can also provide insight on how the system may need to be modified to better cooperate with the user.

4.3. Training

A challenge inherent to system evaluations is ensuring that all subjects are sufficiently trained with the system prior to the evaluation. Without training, it is impossible to know whether differences quantified with and without the system reflect true system effects, or instead are due to the subject's lack of familiarity with the system. Currently, there is no established prescription for training nor is there a specific set of metrics to help researchers confirm that an adequate level of training has occurred. Experience conducting evaluations at ARL, however, has led to the development of a general procedure that has proved helpful for conducting evaluations of load carriage systems. Generally, it is recommended that the user train with a system multiple times over a few days. Initially, subjects should be encouraged to use the system for a period of at least 30 min until they feel comfortable with the function of the system. Depending on the system function, it is recommended that the subject's exposure to experimental conditions (e.g., speed, load, and grade) be increased with each training session. Subjects should also be given the opportunity to use the system inside the lab as well as over terrain that closely approximates eventual test conditions. They should also complete subsets of the tasks they would complete in the final system evaluation. Subjective feedback from the users is critical during this stage. Users, developers, and evaluators should work together to address any fit or control issues, to provide optimal system performance for each subject during each training session. Individual preferences may shift over days of training, and repeating the donning and system training procedures each day will help the team to converge on a consistent methodology for accommodating each user's specific needs relevant to system use. The final training session should consist of subjects carrying the full evaluation load (at least briefly) and completing some of the tasks that would be required of them in the full evaluation. Rest also seems to be important, so it is suggested to provide approximately 24 to 48 h of rest between the final training session and the evaluation sessions.

4.4. Metrics, Methods, and Environment

Selecting methods and metrics for evaluating user-system performance is also a challenge. Crowell et al. (2018) provides a compendium of methods and metrics that have been used previously to evaluate a number of exoskeleton and exosuit systems. The intended functionality of the system will dictate the methods used for evaluation, and the evaluation should mimic as closely as possible the tasks that are intended to be augmented by the system and the environmental conditions under which it will operate. For proof-of-concept or early prototypes, however, it may be necessary to scale the tasks appropriately for the system's current technical maturity. For example, an initial evaluation of a prototype load carriage system may be evaluated using a fraction of the total load the system is being designed to support. Similarly, a system designed to aid sprinting should be evaluated at slower speeds before progressing to its maximum speed. Scaling test conditions and methods allows for documenting current system capabilities and identifying system limitations while minimizing risk to the user. Once the system has demonstrated an ability to support the lower-risk tasks, conditions may progress to evaluate the system's maximal capabilities.

Metrics used to evaluate exoskeleton or exosuit systems are largely the same as those that could be used to quantify human performance under other experimental conditions. A combination of biomechanical, physiological, operational, and human factors metrics may be used to quantify user-system performance (Crowell et al., 2018). Generally, biomechanical metrics quantify the physical differences in movement (e.g., joint angles, ground reaction forces), while physiological metrics (e.g., electromyography, oxygen consumption) help to quantify the user's level of effort required to use the system. Operational metrics (e.g., task completion time, jump height) can describe the functional capacity of the user-system, and human factors metrics (e.g., anthropometrics, subjective surveys) can be used to quantify fit, comfort, and user perceptions. As with any research study, the selection of metrics must be based on the specific empirical research questions to be answered regarding system functionality. With system evaluations, however, it is strongly encouraged to solicit subjective responses to document user feedback on the system. Likert scale responses are helpful to provide metrics of a user's experience with the system, and short answer questions give users the opportunity to describe strengths and weaknesses of the system in their own words. Often responses to these questions reveal issues or alternative system uses about which the evaluation team would not have known to ask. To inform system design modifications, user feedback, particularly dismounted warfighter feedback, should be given as much consideration as objective performance measures.

4.5. Conditions

Exoskeleton and exosuit systems may be either active or passive in nature. This means that they can provide assistance either through powered actuation (active) or by leveraging mechanical design to store and release energy without powered components (passive). The best assessment of either type of system is to compare performance without the system (No Device "ND") to performance with the system worn and providing augmentation ("ON"). Comparison between ON and ND conditions allows for a determination of whether the system is effectively aiding the user in a task they are otherwise expected to complete without assistance. There are, however, circumstances in which an alternative "OFF" condition may be appropriate. The "OFF" condition describes the situation in which the system is donned and either powered off or the assistance is disengaged. Effectively, this allows evaluators to determine the effects of carrying the weight of the system with its specific load distribution on user performance, which may be helpful in two ways. First, it helps the evaluation team quantify performance deficits that may be expected when the system is donned and disengaged. Second, it can highlight a need to redesign components that may become an encumbrance when disengaged. Examples of the latter include cables that become slack or mechanical linkages that limit range-of-motion when the power is cut. Although "OFF" can be a valuable condition to utilize in a study design, it can substantially increase total test time to introduce a third test condition. A challenge with system evaluations is to assess the tradeoffs between the time required and the information provided by the different system conditions.

4.6. Evaluating Safety

The most important challenge to be overcome during system evaluations is identifying and mitigating all potential safety risks. Regardless of technical maturity, the system should be inspected for possible pinch points, snag hazards, entanglements, shock risks, and other potential sources of injury. It is recommended that the evaluation team conduct pilot testing with the system prior to engaging subjects in research. If it can be accommodated by current system design, it is preferable to have multiple individuals of varying body sizes wear and experience the system prior to formal evaluation. Proof-of-concept and early prototypes are more likely to have poor human interfaces. Pilot testing can reveal pressure points, fit issues, and problems with control algorithms that may cause unexpected system behavior resulting in falls or injuries. If the system is not properly ruggedized for outdoor conditions, the evaluation should be conducted indoors to prevent system damage and possible subject injury. If outdoor evaluations are possible, first aid kits should be available. An all-terrain vehicle is also useful to serve as a support vehicle for outdoor evaluations. The vehicle can carry spare parts for the system, permitting rapid system repairs in the field, and can also be used to carry water, food, and other supplies for the subjects. The vehicle may also be used to remove the subject from the field if the system stops working or if the subject is injured.

At any level of technical maturity, system evaluations are potentially risky because the technology is still being developed. Risk mitigation strategies should be identified for each safety hazard, and the subjects should be informed of any risks of pain, discomfort, or injury with the system prior to participation. Additional safety risks may be revealed through system failure or breakage during the evaluation. Identifying safety risks and maintaining safety should be an ongoing effort during training and evaluation.

5. RECOMMENDATIONS FOR FUTURE RESEARCH

During the exoskeleton and exosuit system evaluations conducted at ARL, it became apparent that research is needed in four key areas, three of which are most relevant to the design challenges noted for these systems. One of these areas is the collection of kinematic and kinetic data from movements other than walking and running that can guide designs. These movements should be completed by subjects with and without loads that dismounted warfighters carry, and include: climbing ladders, walls, and obstacles; entering and exiting vehicles; moving tactically with rifles and pistols; jumping across, up onto and down from obstacles; and crawling. In addition, transitions between these movements and walking and running also need to be quantified.

A second area is the physical interface between the user and the system. A secure attachment between an exoskeleton or exosuit and a user is often one that is tight; however, this can become painful for systems that will be worn for a long time. If the attachment is loose, it may be comfortable, but it may move over time, which could lead to inaccurate sensor readings and/or inefficient force transfers. Research is needed to find attachment methods that are secure, comfortable, and, if applicable, able to effectively transmit forces across the attachment.

A third research area relevant to exoskeleton and exosuit design is the control system. The exoskeleton or exosuit should move synchronously with the warfighter so that it does not degrade his or her agility. The system should also recognize the user's movement intention, and will require control algorithms that anticipate the user's movements, not just react to them. It is likely that additional sensors (e.g., visual sensors collecting signals from the environment, neuromuscular sensors or brain computer interfaces) will be needed to provide data to these algorithms. Research to identify different movements (e.g., walking forward uphill vs. climbing) and transitions between them will be useful for the control algorithms. In addition, research is needed to further our understanding of the parameters that control human gait, particularly under the conditions and in the environments in which dismounted warfighters operate. Also, a greater understanding of how anatomical and physiological variability influence the control of gait will be useful for the development of adaptive control systems that can accommodate any potential user.

The fourth area in which research is needed is training, which is relevant to the evaluation challenges. Specifically, research is needed to standardize how training is completed and to positively identify well-trained individuals. Research is also needed to determine the best training tasks, the optimum number of training sessions, length of sessions, and time between sessions. In addition, research is needed to determine what type of feedback subjects should get during training and the best metric(s) to determine when someone is adequately trained. A better understanding of the required system training will also provide information regarding how warfighters will need to be trained with the system prior to field deployment should the system progress to military acquisition. Work in these areas will fill key knowledge gaps that will improve the current state-of-the-art exoskeletons and exosuits.

6. CONCLUSIONS

The development of exoskeleton and exosuit systems to assist dismounted warfighters with load carriage is continuing. This article highlighted key challenges that must be addressed by designers, evaluators, and researchers, so that development of such systems can continue to move forward. The guidance provided in this article is based on 26 years of experience with exoskeleton and exosuit assessments and evaluations at ARL. Several design challenges exist that are unique to exoskeletons and exosuits for dismounted warfighters, and include compatibility with mission essential equipment and clothing, accommodation of particular movements (e.g., shooting on the move), and the range of environmental conditions in which such systems need to operate. Challenges for both designers and researchers include characterization of movement kinematics and kinetics, the user-system interface, and the control system. A key challenge for evaluators and researchers is training system users. Other challenges for evaluators include having the appropriate subject population for the evaluation and creating evaluations that are appropriate for the technical maturity and intended use of the system. By focusing on these challenges and the others described in this article, designers, evaluators, and researchers will hasten the fielding of exoskeletons and exosuits to assist dismounted warfighters with load carriage.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

FUNDING

The funding for this paper was provided by the U.S. Department of Defense (DOD). The contents of this paper are solely the responsibility of the authors and do not necessarily represent the official views of the DOD.

ORCID

Harrison P. Crowell http://orcid.org/0000-0001-8763-8733
Joon-Hyuk Park http://orcid.org/0000-0001-7977-3302
Courtney A. Haynes http://orcid.org/0000-0001-8820-6297
Jennifer M. Neugebauer http://orcid.org/0000-0001-8886-7976
Angela C. Boynton http://orcid.org/0000-0003-1192-1369

REFERENCES

Awad, L. N., Bae, J., O'Donnell, K., De Rossi, S., Hendron, K., Sloot, L., … Walsh, C. (2017). A soft robotic exosuit improves walking in patients after stroke. *Science Translational Medicine*, *9*(400)eaai9084, 1–12. doi:10.1126/scitranslmed.aai9084

Billing, D. C., Silk, A. J., Tofari, P. J., & Hunt, A. P. (2015). Effects of military load carriage on susceptibility to enemy fire during tactical combat movements. *Journal of Strength and Conditioning Research*, *29*, S134–S138. doi:10.1519/JSC.0000000000001036

Birrell, S., & Haslam, R. (2009). The effect of military load carriage on 3-D lower limb kinematics and spatiotemporal parameters. *Ergonomics*, *52*(10), 1298–1304.

Boynton, A. C., & Crowell, H. P. (2006). *A human factors evaluation of exoskeleton boot interface sole thickness* (Technical Report ARL-TR-3812). Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Boynton, A. C., Park, J.-H., & Neugebauer, J. (2017). Biomechanical, physiologic, and mobility performance changes during prolonged load carriage. *Journal of Science and Medicine in Sport*, *20*(S2), S172. doi:10.1016/j.jsams.2017.09.580

Brown, T. N., O'Donovan, M., Hasselquist, L., Corner, B., & Schiffman, J. M. (2014). Soldier-relevant loads impact lower limb biomechanics during anticipated and unanticipated single-leg cutting movements. *Journal of Biomechanics*, *47*(14), 3494–3501. doi:10.1016/j.jbiomech.2014.09.002

Carlton, S. D., & Orr, R. M. (2014). The impact of occupational load carriage on carrier mobility: A critical review. *International Journal of Occupational Safety and Ergonomics*, *20* (1), 33–41. doi:10.1080/10803548.2014.11077025

Coalition Task Force 82 and Coalition Joint Task Force 180 (2010). *The Modern Warrior's Combat Load: Dismounted Operations in Afghanistan*. Scotts Valley, CA: CreateSpace Independent Publishing Platform.

Crowell, H. P. (1995). *Human engineering design guidelines for a powered, full body exoskeleton* (Technical Note ARL-TN-60). Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Crowell, H. P., Boynton, A. C., & Mungiole, M. (2002). *Exoskeleton power and torque requirements based on human biomechanics* (Technical Report ARL-TR-2764). Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Crowell, H. P., Kanagaki, G. B., O'Donovan, M. P., Haynes, C. A., J-H, Neugebauer, J. M, P., Hennessy, E. R., … Girolamo, H. J. (2018). *Methodologies for evaluating the effects of physical augmentation technologies on Soldier performance* (Technical Report No. ARL-TR-8444). Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Department of the Army (2017). Foot Marches (Army Techniques Publication 3-21.18). Washington, DC: Headquarters, Department of the Army.

Ding, Y., Kim, M., Kuindersma, S., & Walsh, C. J. (2018). Human-in-the-loop optimization of hip assistance with a soft exosuit during walking. *Science Robotics*, *3*(15)eaar5438, 1–8.

Garcia, E., Sater, J. M., & Main, J. (2002). Exoskeletons for human performance augmentation (EHPA): A program summary. *Journal of the Robotics Society of Japan*, *20*(8), 822–826. doi:10.7210/jrsj.20.822

Gregorczyk, K. N., Hasselquist, L., Schiffman, J. M., Bensel, C. K., Obusek, J. P., & Gutekunst, D. J. (2010). Effects of a lower-body exoskeleton device on metabolic cost and gait biomechanics during load carriage. *Ergonomics*, *53*(10), 1263–1275.

Hadid, A., Katz, I., Haker, T., Zeilig, G., Defrin, R., Epstein, Y., & Gefen, A. (2017). Effect of load carriage on upper limb performance. *Medicine and Science in Sports and Exercise*, *49*(5), 1006–1014.

Harman, E., Han, K. H., Frykman, P., Johnson, M., Russell, F., & Rusenstein, M. (1992). The effects on gait timing, kinetics, and muscle activity of various loads carried on the back. *Medicine & Science in Sports & Exercise*, *24* (5), S129. doi:10.1249/00005768-199205001-00775

Harman, E., Han, K. H., Frykman, P., & Pandorf, C. (2000). *The effects of backpack weight on the biomechanics of load carriage* (Technical Report No. T00-17). Natick, MA: U.S. Army Research Institute of Environmental Medicine.

Herr, H. (2009). Exoskeletons and orthoses: Classification, design challenges and future directions. *Journal of NeuroEngineering and Rehabilitation*, *6*(21), 1–9.

Jansen, J. F., Birdwell, J. F., Boynton, A. C., Crowell, H. P., Durfee, W. K., Gongola, J. D., … Zambrano, T. (2004). *Phase I report: DARPA exoskeleton program* (No. ORNL/TM-2003/216). Oak Ridge, TN: Oak Ridge National Laboratory.

Jaworski, R. L., Jensen, A., Niederberger, B., Congalton, R., & Kelly, K. R. (2015). Changes in combat task performance under increasing loads in active duty Marines. *Military Medicine*, *180*(3S), 179–186. doi:10.7205/MILMED-D-14-00432

Kazerooni, H., Racine, J.-L., Huang, L., & Steger, R. (2005). On the control of the Berkeley Lower Extremity Exoskeleton (BLEEX). *Proceedings of the 2005 IEEE International Conference on Robotics and Automation* (4353-4360). Barcelona, Spain.

Knapik, J., Harman, E., & Reynolds, K. (1996). Load carriage using packs: A review of physiological biomechanical and medical aspects. *Applied Ergonomics*, *27*(3), 207–216. doi:10.1016/0003-6870(96)00013-0

Liew, B., Morris, S., & Netto, K. (2016). The effect of backpack carriage on the biomechanics of walking: A systematic review and preliminary meta-analysis. *Journal of Applied Biomechanics*, *32*(6), 614–629. doi:10.1123/jab.2015-0339

Lim, J., Palmer, C. J., Busa, M. A., Amado, A., Rosado, L. D., Ducharme, S. W., … Van Emmerik, R. E. A. (2017). Additional helmet and pack loading reduce situational awareness during the establishment of marksmanship posture. *Ergonomics*, *60*(6), 824–836. doi:10.1080/00140139.2016.1222001

Loverro, K. L., Brown, T. N., Coyne, M. E., & Schiffman, J. M. (2015). Use of body armor protection with fighting load impacts soldier performance and kinematics. *Applied Ergonomics*, *46*, 168–175. doi:10.1016/j.apergo.2014.07.015

Machi, V. (2018). 'Iron Man Suit' Prototype Delivered by 2019, SOCOM Officials Vow. *National Defense*. Retrieved from http://www.nationaldefensemagazine.org/articles/2018/5/24/socom-leadership-confident-of-delivering-talos-prototype-by-2019

Majumdar, D., Pal, M. S., & Majumdar, D. (2010). Effects of military load carriage on kinematics of gait. *Ergonomics*, *53*(6), 782–791.

Miles, D. (2014). Special Operations Command leads development of 'Iron Man' suit American Forces Press Service. *American Forces Press Service*. Retrieved from https://www.army.mil/article/125325

McCulloch, R., Sheena, Y., Simpson, C., & Power, D. (2014). Brachial plexus palsy following a training run with a heavy backpack. *Journal of the Royal Army Medical Corps*, *160*(4), 317–319. doi:10.1136/jramc-2013-000139

Mooney, L. M., Rouse, E. J., & Herr, H. M. (2014). Autonomous exoskeleton reduces metabolic cost of human walking during load carriage. *Journal of NeuroEngineering and Rehabilitation*, *11*(80), 1–11. doi:10.1186/1743-0003-11-80

Neugebauer, J. M., Boynton, A. C., Webster, C. A., Crowell, H. P., & LaFiandra, M. E. (2013). *Warrior Web Task A, Phase I prototype evaluations* (Technical Report No. ARL-TR-6759). Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Neugebauer, J. M., & Boynton, A. C. (2015). Changes in peak vertical force and loading rates at the beginning and end of loaded walking. *Proceedings of the International Society of Biomechanics*, Glasgow, Scotland.

Neugebauer, J. M., & Talarico, M. K. (2017). Differences in lower body kinetics when walking and walking while holding weapon aim. *Proceedings of the 41st American Society of Biomechanics Annual Meeting,* Boulder, CO.

Orr, R. M., Johnston, V., Coyle, J., & Pope, R. (2015). Reported load carriage injuries of the Australian army soldier. *Journal of Occupational Rehabilitation*, *25*(2), 316–322.

Orr, R. M., Pope, R., Johnston, V., & Coyle, J. (2014). Soldier occupational load carriage: A narrative review of associated injuries. *International Journal of Injury Control and Safety Promotion*, *21*(4), 388–396. doi:10.1080/17457300.2013.833944

Panizzolo, F. A., Galiana, I., Asbeck, A. T., Siviy, C., Schmidt, K., Holt, K. G., & Walsh, C. J. (2016). A biologically-inspired multi-joint soft exosuit that can reduce the energy cost of loaded walking. *Journal of NeuroEngineering and Rehabilitation*, *13*(1), 1–14.

Ramsay, J. W., Hancock, C. L., O'Donovan, M. P., & Brown, T. N. (2016). Soldier-relevant body borne loads increase knee joint contact force during a run-to-stop maneuver. *Journal of Biomechanics*, *49*(16), 3868–3874. doi:10.1016/j.jbiomech.2016.10.022

Seay, J. (2015). Biomechanics of load carriage-historical perspectives and recent insights. *Journal of Strength and Conditioning Research*, *29*, S129–S133. doi:10.1519/JSC.0000000000001031

Tilbury-Davis, D., & Hooper, R. (1999). The kinetic and kinematic effects of increasing load carriage upon the lower limb. *Human Movement Science*, *18*(5), 693–700. doi:10.1016/S0167-9457(99)00026-3

Tullington, B. J, Butz, D. J., & Hill, T. E. (1987). *A Notional Individual Fighting System*. Dover, NJ: U.S. Army Armament Research, Development and Engineering Center, Joint Service Small Arms Program Office.

Tyson, A. S. (2009). Weight of combat gear is taking toll. *Washington Post*. Retrieved from http://www.washingtonpost.com/wp-dyn/content/article/2009/01/31/AR2009013101717.html

U.S. Army Training and Doctrine Command (2017). *The US Army robotic and autonomous systems strategy*. Fort Eustis, VA: Army Training and Doctrine Command (US).

Yang, X., Zhao, G., Liu, D., Zhou, W., & Zhao, H. (2015). Biomechanics analysis of human walking with load carriage. *Technology and Health Care*, *23*(s2), S567–S575. doi:10.3233/THC-150995

Young, A., & Ferris, D. (2017). State of the art and future directions for lower limb robotic exoskeletons. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *25*(2), 171–182. doi:10.1109/TNSRE.2016.2521160