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UNITED STATES ARMY AEROMEDICAL RESEARCH LABORATORY

Evaluation of Litter Carriage Performance and Post-Carry Fatigue Effects in Prolonged Combat Field Care Environments (Part 1): Preliminary Design Considerations, Specifications, and Recommendations for Exoskeleton Feasibility, Suitability, and Efficacy in Dismounted Military Casualty Transport Scenarios

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14. ABSTRACT
Litter transport is a standard procedure for initial military casualty evacuation and consists of two- or four-person teams transporting a casualty over a long distance or carrying multiple casualties over a short distance. The litter team may be required to provide critical care while also engaging in combat to protect themselves and the patient. Musculoskeletal disorders can develop over time due to frequent, repetitive, or extended litter transport scenarios. The use of an assistive device, such as an exoskeleton, has the potential to improve combat performance following litter carry and improve evacuation times of the injured. Currently, there are no assistive devices integrated into the standard Military Equipment Set or litter carriage procedures, and exoskeleton research for military patient transport scenarios is scarce. The U.S. Army Aeromedical Research Laboratory conducted a comprehensive review of the state of exoskeleton research to determine essential preliminary design considerations as well as provide preliminary recommendations for exoskeleton technology focused on improving or enhancing dismounted military casualty transport scenarios.

15. SUBJECT TERMS
litter transport, litter carriage, military casualty evacuation and transport, assistive devices, exoskeleton, musculoskeletal disorders

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Summary

Litter transport is a standard procedure for initial casualty evacuation from the point of injury to the medical aid or pickup zone and is generally done on foot. The process of litter transport consists of either a two- or four-person team carrying a casualty over a long distance or carrying multiple casualties over a short distance. A litter team may transport a single casualty from a remote location, occurring over hours while stopping to provide critical care or protect themselves and the casualty from enemy fire. Litter teams can carry a single patient only a few hundred meters over rough terrain before needing to rest. Mass casualty evacuations may occur following a plane crash or improvised explosive device event.

Like transporting standard military loads, such as weapons and equipment, transporting patients using a litter can be physically demanding for Service Members (SMs). During the evacuation, the litter team may be required to provide critical care while actively engaging in combat to protect themselves and the patient. In anticipation of a future fight with near-peer adversaries, improving the physical abilities of an SM and limiting impediments are of high priority. During multi-domain operations (MDO), the anticipated number of casualties along with the anticipated periods and areas of denial by near-peer competitors highlight the criticality and potential demand of effective and efficient dismounted litter transport.

Additionally, musculoskeletal disorders can develop over time due to frequent, repetitive, or extended litter transport scenarios. Furthermore, the onset and severity of such disorders, injuries, or diseases could affect an SM's career and retention. A straightforward approach to the dilemma of litter bearer fatigue may be to develop technology to lessen the physical demands on the litter bearer.

Using an assistive device (e.g., harness or exoskeleton) during litter transport would decrease fatigue and increase the litter bearer's ability to carry the litter, provide critical care, and sustain SM tasks. Additionally, an assistive device has the potential to not only improve combat performance following litter carry but also improve evacuation times of the injured. Exoskeleton use may also decrease the necessity of a four-person team to a two-person team. Currently, no assistive devices are integrated into the standard Military Equipment Set or litter carriage procedures, and there are no standards for evaluating the efficacy of any device to be considered. Although a plethora of exoskeleton research for military applications is being tested against standard lifting and carrying tasks, exoskeleton research for military patient transport scenarios is lacking.

Ongoing work at the U.S. Army Aeromedical Research Laboratory (USAARL) compares the effects of using an assistive device to not using during a simulated prolonged litter transport scenario to develop a standardized evaluation of assistive devices for litter transport. The lack of an adaptable exoskeleton for use in this effort further highlights the research gaps in the design and development of exoskeleton devices for military litter and patient transport scenarios.

The USAARL conducted a comprehensive review of the state of exoskeleton research to determine essential preliminary design considerations and provide initial recommendations for exoskeleton technology specifically focused on improving or enhancing dismounted military casualty transport scenarios. This comprehensive literature review identified six crucial design factors and specifications that must be considered for exoskeleton feasibility, suitability, and

efficacy in augmenting to assist the user with litter carriage. These factors are (1) internal and external design, (2) personal protective equipment and evacuation duties, (3) load effects, (4) dynamic movement and environment durability, (5) storage, transport, and deployment, and (6) safety and reliability. This work also provides essential recommendations for developing successful exoskeleton devices to augment or enhance human motion or physical activity of SMs during dismounted litter load carriage tasks. This work is the first of its kind and is a critical foundational approach toward the development and future deployment of devices with the potential to reduce the negative impacts of frequent, repetitive, or extended casualty transport using a litter.

Future work will examine applicable exoskeleton designs, prototypes, and devices to determine whether they are suitable or adaptable for use in litter transport scenarios with follow-up human subject research studies to assess and evaluate the efficacy and feasibility of the proposed devices. These data will aid in establishing a standard to evaluate the efficacy and feasibility of assistive devices to be considered for selection and integration into the standard Military Equipment Set for litter transport procedures.

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Introduction

During the Civil War, it was determined that there was not a clear and organized system to quickly remove injured Service Members (SMs) from the battlefield; this awareness led to the development of a litter for casualty transport, which has since served as an essential combat casualty care device in the United States military (Reilly, 2016). Litter transport is a standard procedure for initial casualty evacuation from the point of injury to the medical aid or pickup zone, generally done on foot. The process of litter transport consists of either a two-person or four-person team carrying a casualty during two common scenarios: carrying a single casualty over a long distance or carrying multiple casualties over a short distance (Rice et al., 1996a, 1996b).

Though there have been improvements in transporting casualties from the battlefield, during the Afghanistan and Iraq conflicts it is estimated that 87% of the combat casualties that died did so during one of the many types of transport to a higher care facility (Eastridge et al., 2012; Kotwal et al., 2018). Factors while in transport that can negatively affect the quality of combat casualty care and increase the transport phase include the security of the casualty and litter bearers, environmental factors (e.g., temperature and terrain), initial time care could be started, and the distance traveled. These factors have a pronounced effect on the comfort and survivability of the injured SM; however, the battle readiness of the litter bearers during or after litter transport is often overlooked. Similar to transporting standard military loads, such as weapons and equipment, transporting patients using a litter can be physically demanding for SMs. Commonly experienced post-carry symptoms include shortness of breath, rapid heartbeat, dry mouth, hand trembling, hand/arm/shoulder aches, backaches, and muscle tightness or stiffness (Rice et al., 1996a). Immediately following litter carry, SMs experience reductions in shooting accuracy and hand-grip force (Tharion et al., 1993; Rice et al., 1996a; Rice et al., 1996b; Leyk et al., 2006). During the evacuation, the litter team may be required to provide critical care while also actively engaging in combat to protect themselves and the patient, which creates another level of risk if team members' shooting accuracy and grip strength are reduced. Such detriments can impede an SM's ability to provide the necessary care to a casualty during prolonged field care situations. Additionally, musculoskeletal disorders can develop over time due to frequent, repetitive, or extended litter transport scenarios; the onset and severity of such disorders, injuries, or diseases negatively impact the retention of SMs (Wilson, 2006). In anticipation of a future fight with near-peer adversaries, improving the physical abilities of an SM and limiting impediments are of high priority.

To mitigate the physical impact of litter transport, the current Army Medical Evacuation Army Techniques Publication (Department of the Army [DA], 2019) recommends frequently resting by using secure, covered evacuation routes, a shuttle system to reduce the transport distance for each team, and alternating litter team members to reduce fatigue. Furthermore, the guidance states the need for "close coordination between Role 2 medical treatment facilities and battalion aid stations to establish casualty collection and ambulance exchange points in areas where rough terrain prohibits air or ground medical evacuation. This coordination is to reduce the distance traveled and evacuation time as well as conserve personnel." Even with these recommendations made by the Army Medical Evacuation Army Techniques Publication, they may not be enough to help alleviate the eventual muscular fatigue, especially during evacuations that are expected to be over an extended distance as anticipated in future multi-domain operations (MDOs).

An alternative approach to the obstacle of litter bearer fatigue is to develop technology that lessens physical demands on the litter bearer. Using an assistive device, such as a harness or exoskeleton, can shift the litter load to larger muscle groups in the body, decreasing the grip force needed by an individual during litter transport. Introducing such devices to litter transport could decrease fatigue and increase the litter bearer's ability to carry the load, provide critical care, and sustain SM tasks. An assistive device has the potential to not only improve combat performance following litter carry but also improve evacuation times of injured SMs. However, there currently are no assistive devices integrated into the standard Military Equipment Set or litter transport procedures, and there are no standards for evaluating the efficacy of assistive devices to be considered.

Exoskeletons are an assistive device to be considered for use in litter transport. Exoskeletons (i.e., wearable robots, wearable augmentation devices, or human augmentation systems [Crowell et al., 2018]) are wearable devices typically developed for rehabilitation, assistive, and augmentation purposes (de la Tejera et al., 2020). Rehabilitation and assistive exoskeletons provide aid to people suffering from chronic or acute disabilities, while augmentation exoskeletons enhance the power output of healthy individuals during heavy load-carrying tasks (Kalita et al., 2021) and are primarily designed for use by SMs or laborers.

Exoskeletons are being developed to augment human strength for handling heavy materials in unstructured environments, address military tasks in narrow spaces, increase marksmanship (Baechle, 2013), and rescue victims from disaster situations (Marcheschi, 2011). Employing exoskeletons to enhance human capabilities and prevent injury is also becoming more integrated into dismounted military tasks. Litter transport meets the intended application of such performance-based exoskeletons, which may decrease fatigue and increase the SM's ability to carry the litter, provide care, and maintain lethality. Furthermore, exoskeletons may decrease the need for a four-person litter transport team down to a safe two-person team; thus, decreasing the manning need for this particular task and freeing those hands for other duties. In addition to improving the physical performance of SMs, exoskeletons could improve cognitive performance (Mudie et al., 2018). Cognitive performance is an important factor to help ascertain how well an SM can focus on the current task with limited working memory while also determining their ability to deal with other mental and physical factors (Kirschner, 2002). During en route care, a litter bearer may experience decreased response time and accuracy in anticipated combat after exhaustion caused by the fatiguing factors derived from carrying a litter over rough terrain for a lengthy period. Litter carriage procedures subject the SM to heavy loads along small muscle groups, leading to rapid muscular fatigue (Conti et al., 2020). An exoskeleton may improve these characteristics by reducing the negative impacts of load carriage. Although there is a plethora of exoskeleton research for military applications being tested against standard lifting and carrying tasks, exoskeleton research for military patient transport scenarios is scarce.

Ongoing research at the U.S. Army Aeromedical Research Laboratory (USAARL) is focused on investigating the benefits of assistive devices in dismounted casualty transport to maintain and optimize SM lethality and readiness. This report is a foundational step in addressing the lack of exoskeleton technology applicable to dismounted casualty transport. Though it is not a comprehensive review of all exoskeletons, this report examines the current state of knowledge on relevant performance-enhancing exoskeletons to develop specifications, considerations, and recommendations for designs that can improve or enhance dismounted military casualty transport scenarios.

Exoskeleton Overview

The origins of exoskeleton research can be traced to 1965 with the development of the Hardiman exoskeleton (Fick & Makinson, 1971). The research contract for this exoskeleton was initiated as a joint effort between the U.S. Army, the U.S. Navy, and the General Electric Company (Boston, MA). A prototype for the Hardiman exoskeleton was produced in 1971 and resulted in significant technological advances that paved the way for exoskeleton research as we know it today (Fick & Makinson, 1971). Progress was minimal until the 1990s, which brought advances in material science. Developments in micro-electronics and wearable robotics were not seen until the 2000s (Fox et al., 2020). Detailed analysis of the technologies needed for designing exoskeletons for dismounted Warfighters began in the 1990s by researchers from the Human Engineering Laboratory, the Materials Technology Laboratory and the Harry Diamond Laboratories (Crowell et al., 2019). In 2000, the Department of Defense's (DoD) Defense Advanced Research Projects Agency (DARPA) established the Exoskeletons for Human Performance Augmentation program to enhance and augment the capabilities of the dismounted Warfighter (Crowell et al., 2019).

External Design Characteristics and Classifications

When designing exoskeletons, there are four major external design considerations: active or passive, tethered or untethered, rigid or soft, and whole-body or regional. Active exoskeletons use an external energy source (i.e., batteries) to supply power to actuators and move the segments of the system (Crowell et al., 2018; Del Ferraro et al., 2020). Active exoskeletons are likely more popular than passive exoskeletons because they allow the developer to apply any generic torque-time profile (Sawicki et al., 2020). However, active exoskeletons are usually heavier, bulkier, and require a large power source (Bogue, 2015; Sawicki et al., 2020). Unfortunately, few power supply sources can provide sufficient long-lasting energy needed for military operations (Bogue, 2015). Passive exoskeletons use the energy obtained and stored during human movement through springs, elastic elements, or dampers to augment or assist the user (Crowell et al., 2018; Del Ferraro et al., 2020). While these devices may provide benefit to the lower extremities during active walking, they are not capable of providing constant load support to the upper extremities as needed in litter casualty transport to counter grip fatigue.

Active exoskeletons may be tethered or untethered. Tethered exoskeletons must remain connected or secured to a power source to be operational, whereas untethered exoskeletons are portable systems (Crowell et al., 2018). Despite their lack of portability, tethered exoskeletons have also increased the human energy economy. Witte et al. (2020) saw an improvement in the energy economy of human running when using a human-in-loop optimization process for the system's torque parameters; however, Sawicki et al. (2020) found that tethered systems have not been able to improve the walking and running economy greater than the autonomous, untethered system. Untethered exoskeletons have led to an 8-15% decrease in the energy cost of loaded walking and a 4% decrease during running (Mudie et al., 2021). The drawback to an untethered exoskeleton is their reliance on a mobile power source (e.g., battery) which has frequent charging requirements and a short time of use, typically less than one working day.

Rigid exoskeletons are comprised of rigid materials and structures, while soft, non-rigid exoskeletons (also called exosuits) are comprised of elastic, sleeve-like material. Lifting a litter off the ground and carrying the patient, even over short distances, can be extremely strenuous for the bearer leading to muscle fatigue (Conti et al., 2020). Non-rigid exoskeletons are not typically used for load bearing; therefore, a rigid exoskeleton would be preferred for litter carriage. Conversely, available rigid exoskeletons are limiting in normal range of motion and do not allow for moving the extended distances needed in litter carriage.

Exoskeletons are designed to be either whole-body or regional. Whole-body exoskeletons are designed to support many of the major joints in the body. Table B1 (Appendix B) lists examples of commercially available and prototype whole-body exoskeletons. Regional exoskeletons support either the upper or lower extremities and can be either single- or multi-joint exoskeletons. Upper extremity exoskeletons augment or support the shoulder, elbow, wrist, or hand (Gull et al., 2020); Table C1 (Appendix C) provides selected examples of these types of devices. Lower extremity exoskeletons provide stability and support to the trunk, hip, knee, ankle, or foot (Kalita et al., 2021). Examples of lower extremity exoskeleton devices are provided in Tables C2-C3 (Appendix C). Single joint exoskeletons provide stability or support to a specific joint in the upper or lower extremity. Multi-joint exoskeletons may be designed to provide stability or support to one or more joints in the extremity.

Internal Design Characteristics and Classifications

The major internal design considerations for exoskeletons are actuators and control system strategies. Three common types of actuators in exoskeletons are electric actuators, hydraulic actuators, and pneumatic actuators (Kalita et al., 2021). Electric actuators are commonly used because they can produce large torques for precise movements (Kalita et al., 2021). Hydraulic actuators were more commonly used in the early days of exoskeleton research but are rarely used currently due to their heavy weight, high impedance, and lack of reliability when fluid leaks occur (Kalita et al., 2021). Pneumatic actuators are prevalent because they are lighter than hydraulic and electric actuators (Kalita et al., 2021). Spring et al. (2012) leveraged the advantages of pneumatic actuators by developing a quasi-passive exoskeleton with a hybrid actuation technique. This technique combines two or more types of actuations and is called the knee extension assist (KEA) exoskeleton. The KEA device combines a passive component (i.e., a spring) with a pneumatic actuator. Another type of pneumatic actuator is pneumatic artificial muscles (PAMs). These actuators are popular because their performance is similar to biological muscles (Nascimento et al., 2008). PAMs have been previously used in a hip exoskeleton by Nascimento et al. (2008) and an ankle exoskeleton by Choi et al. (2020). A new hand exoskeleton that uses a series of elastic actuators to allow for control of each finger has been researched (Refour et al., 2019). Refour et al. (2019) reported that the hand exoskeleton could produce more than 20 Newtons (N) per finger, compared to an average 20-39-year-old male's full grip strength averaging around 55-58 N (Nilsen et al., 2012).

According to Kalita et al. (2021), many types of control system strategies exist for exoskeletons. Control systems require methods to find optimal parameters as inputs into the system. Model-based stability control, adaptive oscillator-based control, sensitivity magnification control, hybrid-assisted control, and proportional electromyography-based control are a few examples of different control system techniques used for exoskeleton research (Kalita et al., 2021). One of the significant limitations of control systems is that they are currently limited to using historical sensor data, which may introduce slight delays in the system (Mudie et al., 2021). Mudie et al. (2021) postulate that slight delays can be dangerous during unexpected events or abrupt changes in movement patterns. Researchers are aware of the downsides of current control systems and are still developing new control systems strategies. The parameter tuning method by Lee et al. (2018)

generated a wide range of subject-specific profiles to allow for subject-specific control parameters for different users. Yang et al. (2021) presented a hybrid oscillator control strategy that was effective at compensating for controller delays during irregular gait patterns. Delayed compensation ranged from 200 to 400 milliseconds (ms). Proper control system strategies can improve the effectiveness, accuracy, and comfortability of exoskeletons (Kalita et al., 2021).

Exoskeleton Research Focused on Load Carriage in Dismounted Military Operational Scenarios

The most prevalent type of exoskeletons in development or commercially available currently assist or augment the user during physically demanding load-carrying tasks (Proud et al., 2020). During a load-carrying task, an external object (e.g., weaponry or equipment) is lifted and combination actions such as lifting and holding, lifting and carrying (short distances), or lifting-carrying-lifting tasks are executed by the exoskeleton (Lo et al., 2020). Load-carrying tasks performed by dismounted SMs have been linked to an increased risk of musculoskeletal injury (Lo et al., 2020; Roy et al., 2012; Seay, 2015), reductions in situational awareness (Lim et al., 2017), and reductions in shooting accuracy (Hadid et al., 2017; Jaworski et al., 2015). Seay (2015) reviewed the literature investigating the relationship between load carriage and the risk of musculoskeletal injury and found that as the loads carried by SMs have increased, so has the incidence of musculoskeletal injuries. Similar to Seay (2015), Lo et al. (2020) and Roy et al. (2012) found a high incidence of musculoskeletal injuries amongst SMs. Lo et al. (2020) reviewed the literature, whereas Roy et al. (2012) performed a retrospective cohort study collecting survey data. Lo et al. (2020) found lifting to be one of the most common physically demanding tasks completed by SMs, making up about 62.9% of the tasks performed. Of the lifting tasks (62.9%), 40.8% involved lifting and carrying (Lo et al., 2020).

Due to the harmful and fatiguing effects of load-carrying, exoskeleton research for military dismounted load-carrying applications is a highly researched area. Extensive literature reviews and human subject assessment data collections have been conducted to evaluate exoskeleton suitability for use in military load-carrying applications to reduce fatigue as well as improve physical and cognitive performance (e.g., Gregorczyk et al., 2010; Rupal et al., 2017; Crowell et al., 2018; Mudie et al., 2018; Crowell et al., 2019; Bequette et al., 2020 Gruevski et al., 2020; Proud et al., 2020; Sawicki et al., 2020; and Murugan, 2021). Rupal et al. (2017) reviewed current exoskeletons and evaluated the technological developments needed for the suits to be used to their fullest potential. Such needs included the wearer’s comfort, a range of motion like human physiology, adaptability, and easy integration. Crowell et al. (2019) extensively reviewed the design, evaluation, and research challenges with exoskeletons for military load carriage applications. Proud et al. (2020) primarily reviewed active exoskeletons for load-carrying tasks.

Gruevski et al. (2020) investigated the influence of the Ultralight Passive Ruggedized Integrated Soldier Exoskeleton (UPRISE) Gen 3.0 passive exoskeleton (Mawashi Science and Technology, Quebec, Canada) on the load-carrying performance of two Canadian male SMs. The SMs completed the Canadian Load Effects Assessment Program (Can-LEAP) obstacle course wearing Full Fighting Order (FFO) with and without the assistance of the UPRISE Gen 3.0 passive exoskeleton to compare their mission effectiveness. FFO has a total mass of 23 kilograms (kg) and is comprised of a combat shirt, trousers, boots, fragmentation vest, tactical vest, helmet, and the C7A2 rifle (Gruevski et al., 2020). The Can-LEAP completion times increased for tasks with confined spaces when wearing the exoskeleton, whereas completion times for running tasks were similar with and without the exoskeleton. Bequette (2020) found comparable results when assessing the effects of a lower-body exoskeleton on physical and cognitive performance; such measurements included visual misses, visual reaction time, audio misses, audio reaction time, and incremental lag time. Bequette et al. (2020) reported that subjects had more difficulty with the step-over obstacles when using an exoskeleton while carrying either a 19.1-kg or 36.3-kg load. Some participants rated all obstacle tasks as more difficult when wearing the exoskeleton compared to not wearing it. However, unlike Gruevski et al. (2020), Bequette et al. (2020) used an active exoskeleton. Nonetheless, the findings from Gruevski et al. (2020) and Bequette et al. (2020) are important to consider when designing exoskeletons. The exoskeleton should not interfere with any of the common tasks and movements performed by SMs.

Gregorczyk et al. (2010) determined the metabolic costs of using an exoskeleton prototype while carrying three different loads (20 kg, 40 kg, and 55 kg) in a study population of nine male U.S. Army infantry SMs. The authors found that wearing the exoskeleton significantly increased metabolic costs, through higher VO2 max scores (scaled to body mass and scaled to total mass by 60% and 41%, respectively) and increased participant stride width. Similarly, participants in a study by Bequette et al. (2020) felt like they exerted more energy completing a step-over obstacle with the powered exoskeleton as compared to without it. Unlike Gregorczyk et al. (2010), Bequette et al. (2020) relied on subjective feedback instead of measuring energy expenditure. Literature findings also report the load’s magnitude may substantially influence performance more than exoskeletons when used outside their intended purpose (Li et al., 2018). In a review by Fox et al. (2020), the authors found that exoskeletons may have the unintended negative effects of transferring unexpected loads to different parts of the user’s body, decreasing productivity.

Using exoskeletons to offset the loads during load-carry tasks has the potential to increase performance without overburdening the wearer with metabolic costs. As a result, companies such as Lockheed Martin (Bethesda, MD) and Raytheon Technologies (Waltham, MA) are developing exoskeletons to enhance the capabilities of SMs. The Onyx (Table C2, Appendix C) is a lower extremity exoskeleton developed by Lockheed Martin to assist SMs, workers, and first responders by providing strength and endurance during strenuous tasks (Lockheed Martin, 2022b). Lockheed Martin claims that the Onyx enforces orthopedic alignment of the joints, which can distribute weight more evenly and decrease the risk of overuse injuries. However, no scientific research articles have been published evaluating these claims. Raytheon Technologies XOS 2 (Table B1, Appendix B) is the second generation of Sarcos XOS developed for the U.S. Army (Army Technology, 2020). The XOS 2 is a whole-body, rigid exoskeleton powered by an internal combustion hydraulics engine. Unlike the Onyx, the XOS 2 requires a tethered connection to the power source.

While exoskeleton research for military dismounted applications has been highly researched, the reviews, assessments, and device designs have not focused on scenarios involving dismounted SMs carrying heavy loads such as equipment or weaponry on their backs. Ongoing work at USAARL compares the effects of ‘using’ versus ‘not using’ an assistive device during a prolonged simulated litter transport scenario to develop a standard evaluation of assistive devices for litter transport. Out of the commercially available products, the FORTIS exoskeleton (Lockheed Martin, Bethesda, MD) was initially planned for use in this laboratory-based human subject volunteer study (Table C2, Appendix C). The exoskeleton was the closest to being able to suit the needs of the project. It was hypothesized that the FORTIS exoskeleton, a passive lower extremity exoskeleton with trunk support and its connecting tool arm attachment, would increase productivity and reduce muscle fatigue caused by litter carriage. However, the device was designed for static load carriage and therefore was not compatible with the dynamic movements required for the study design. All devices on the market cannot currently accommodate prolonged dynamic movements in combination with load bearing capabilities necessary for patient transport. This necessity for grip strength augmentation and continual dynamic movements was a major limitation within current exoskeleton designs and resulted in the use of alternative assistive devices in the study. The lack of an available adaptable exoskeleton for this research effort further highlights the need to develop exoskeletons for military litter transport scenarios. The design requirements of such an exoskeleton remain a research gap that must be addressed.

Exoskeleton Design Considerations for Military Transport and Casualty Evacuation Scenarios

The Army Tactics Techniques and Procedures for casualty evacuation via litter must first be understood to identify exoskeleton design considerations for military transport applications. Two common scenarios occur when evacuating casualties: carrying a single casualty over a long distance or carrying multiple casualties over a short distance due to a need for a facility with a higher acuity of care (Rice et al., 1996a, 1996b). A litter team may transport a single casualty from a remote location, which can take hours and involve stopping to provide critical care or protect themselves and the casualty from enemy fire. Litter teams can carry a single patient only a few hundred meters over rough terrain before needing to rest. Medical evacuations involving MDOs may occur following a plane crash or improvised explosive device event. In the case of an evacuation event due to frontline injuries, the casualties may be evacuated from a remote location; the terrain and distance may cause difficulties initially for the carrier evacuating the casualty while remaining undetected. When transporting multiple casualties over a short distance, the location may not be remote, such as moving between temporarily deployed hospitals, a level one trauma center or any other facility with a higher acuity of care. In addition to patient transport, once exoskeleton technology is augmented for dismounted use, these suits may become multipurposed to assist in the mobilization and take-down of these temporary hospital theatres.

The method of carrying used in transporting a litter patient depends upon the type of terrain and obstacles involved. As outlined in Army Techniques Publication 4-02.13 (DA, 2021), litter bearers are normally grouped into squads of four to evacuate a casualty (Figure 1A). Litter evacuations involving four bearers ("four-man carry") are used for smooth, level terrain. Casualties are usually carried feet first, and the litter team leader is stationed at the handle nearest the casualty's right shoulder. The remaining three litter bearers then move to a handle, facing the same direction as the leader. The team kneels on the knee closest to the litter, then upon command, the team stands and lifts the litter in unison, moving the casualty to an aid station or collection point (DA, 2021). In circumstances where personnel are limited or four-person teams are not possible due to terrain (e.g., narrow passages such as trails, bridges, catwalks, etc.), two-person teams transport the litter (Figure 1B).

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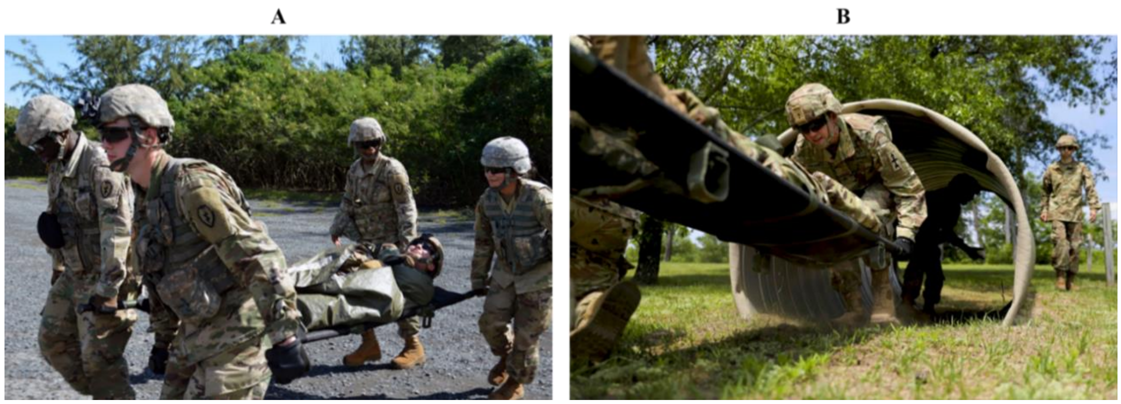

Figure 1. Litter evacuations involving four-person (A) or two-person (B) teams. (Defense Imagery Management Operations Center, n.d.)

Both carry styles are equally exhausting and can result in soreness, pain, and discomfort in the lower arms, shoulder, chest, upper back, and legs. Despite a lack of research on using exoskeletons for patient transport, research has been done on the effects of using harnesses to assist during patient transport scenarios. Rice et al. (1996a) saw participants carry the litter for longer while using a harness in single casualty scenarios. The participants completed the carries with lower heart rates and less fatigue in their forearms and hands. However, the authors also reported increased perceived exertion post-carry with the harness compared to without it. For a mass evacuation scenario, Rice et al. (1996b) reported that using the harness increased the time it took participants to pick up the litter. The authors saw the usefulness of the harness vary for male versus female teams. The male teams completed a smaller number of carries with the harness, whereas the female teams had no significant difference in the number of carries completed. Furthermore, using the harness allowed female teams to carry the litter as fast as the male teams under comparable conditions. Based on these data, patient transport scenarios, team size, and litter bearer size should be considered when designing exoskeletons. Exoskeletons should augment the user during long-distance and short-distance transports regardless of team size and litter bearer size.

Similar to Rice et al. (1996a, 1996b), Leyk et al. (2006) also studied the effects of litter transport but focused on hand steadiness and hand grip strength following litter carry. The work reported that while hand steadiness recovered less than 30 minutes after an exhaustive litter carry, hand-grip strength took over 24 hours to recover (Leyk et al., 2006). Loss of hand steadiness and strength puts litter teams and the casualty at greater risk during evacuation. Hand steadiness and hand-grip strength should be measured when evaluating exoskeletons for patient transport and any changes in marksmanship. Designers and researchers should minimize the recovery time for hand-grip strength for litter teams.

Based on the roles, duties, and requirements of SMs who have been tasked with dismounted military transport or casualty evacuation scenarios that involve the use of a litter, there are six important design factors and specifications that must be considered for exoskeleton feasibility, suitability, and efficacy in augmenting assisting the user with litter carriage. These factors are (1) internal and external design, (2) personal protective equipment and evacuation duties, (3) load effects, (4) dynamic movement and environment durability, (5) storage, transport, and deployment, and (6) safety and reliability.

Internal and External Exoskeleton Design

The materials used to make the exoskeleton should not inhibit the transport of patients. The materials should also be durable enough to protect the actuators, the power supply, and any internal system housed within the exoskeleton from dust, dirt, debris, or sharp objects. Combining soft and rigid materials when designing an exoskeleton may allow designers to leverage the advantage of a durable rigid design with the flexibility and lightness of a soft exosuit design. The comfort limits of the elastic, compressive materials used in exosuits should be considered. Another consideration is the vast anthropometric variances among SMs. Exoskeletons must be capable of fitting almost all body types within the SM population so that no mission is hindered by anthropometric determinants (Gordon et al., 2014). Mudie et al. (2021) identified the inability of current exoskeleton technologies to adapt to the user as a major limitation. If using soft components in the exoskeleton design, the compressive pressures and size of the compressive material should be considered and not cause discomfort or loss of circulation to the body region it encompasses. Kermavnar et al. (2020) reported thresholds for mean inflation pressures for circumferential cuffs attached around the thigh and calf to be approximately 54.9-59.6 kilopascal (kPa) and 56.0-60.3 kPa for narrow cuffs and 43.4-54.9 kPa and 48.5-58.9 kPa for wide cuffs to prevent such discomforts.

A significant limitation of current exoskeletons is the weight of actuators, power supply systems, and exoskeletons as a whole (Rupal et al., 2017). Gruevski et al. (2020) found the least acceptable ratings for the exoskeleton in the following categories: equipment bulkiness, agility, speed, mobility, and over-performance. Most SMs carry 40-50 pounds of body armor, weapons, and gear. Heavy and bulky exoskeletons will create additional restrictions for the litter team by adding to the physical workload required to operate. This additional physical workload increases the overall difficulty of operating in a military theatre, thus increasing the team's cognitive workload and interaction while walking with the exoskeleton (Bequette et al., 2018). Exoskeletons should be designed to be as light and small as possible to aid the SM effectively and should not negatively affect mobility or lethality (Lo et al., 2020).

The actuators (electric, hydraulic, pneumatic, or passive) should be lightweight and portable, offer ease of use, have a high power-to-weight ratio, and have high efficiency. According to Kalita et al. (2021)'s review, PAMs are reported to reduce the weight of the actuator. Users of the passive upper-limb exoskeleton device developed by Yin et al. (2020) reported exerting more force against the exoskeleton when putting down their arms because the supportive forces were too high. With a lower extremity exoskeleton tested by Bequette et al. (2020), some participants reported that their range of motion was limited with the exoskeleton, and they sometimes felt the exoskeletons actuating inappropriately during the step-over obstacle. Exoskeleton designs must consider the need to move freely from one position to another and that all movements should not require a higher exertion force than needed without the exosuit. Thus, any supportive forces offered by the exoskeleton should not be too large that the user exerts more effort to perform their transport duties.

While actuators and signal processing technology have improved significantly, improvements to power supplies and exoskeleton control systems are needed. Few power sources can efficiently provide the energy requirements needed for military operations (Bogue, 2015). If the exoskeleton runs on a limited power supply, the designers need to consider options for backup power sources. Current control system strategies are either limited to using historical sensor data, are sensitive to inherent noise in the instrument, or cannot adapt to sudden changes in movement. Relying on historical data for a control system may introduce slight delays into the system, which could be dangerous during unexpected events or movement patterns (Mudie et al., 2021). Zhang et al. (2017) found the model-based control strategies ineffective during their pilot tests because of their sensitivity to noise and adaption dynamics. Bequette et al. (2020) evaluated a lower extremity exoskeleton that used a fixed control policy and tuned the parameters (i.e., knee offset angle, flexion assistance, and extension assistance) based on manufacturer training and qualitative assessment. Yang et al. (2021) presented a hybrid oscillator control strategy that effectively compensates for controller delays during irregular gait patterns. Whichever control strategy is selected should be effective, accurate, and adaptable to sudden changes in movement.

Personal Protective Equipment, Weaponry and Ammunition, and Casualty Evacuation Duties

Litter bearers are equipped with personal protective equipment (PPE) (i.e., helmet and body armor), their issued weaponry and ammunition, and the equipment needed for casualty evacuation. The exoskeleton must not interfere with current military equipment or weaponry (Crowell et al., 2019). Additionally, there may be instances where the litter bearers must engage in combat to protect themselves and the patient. Therefore, the exoskeleton should not require the litter team to surrender their weapons or remove body armor at any time before or during the evacuation. Army medics must also continue their care of the patient, which requires them to perform dexterity skills, like placing an intravascular device. For that reason, future exoskeletons must not interfere with patient evaluations, typical medical procedures, and any extra duties required of the SM (Blackbourne et al., 2012).

Load Effects

As the weight of the load carried increases, the maximum and mean muscle activation levels in the body increase (Li et al., 2018). Consequently, SMs take longer to complete common combat movements (Crowell et al., 2019). Li et al. (2018) investigated the ergonomic performance of a previously developed load-carrying exoskeleton. The authors collected subjective and electromyography data from nine healthy male subjects walking with and without the exoskeleton. Even though the exoskeleton offsets the burdens of the load-carrying task, the authors found that load magnitudes had a greater effect on the subject’s performance than the with-exoskeleton and without-exoskeleton metrics when performing duties outside of the intended purpose of the exoskeleton.

Dynamic Movement Capabilities and Environmental Durability

Exoskeletons for military transport and casualty evacuation applications must be designed to operate at various speeds to accommodate frequent changes in movement patterns or transitions between movements (Crowell et al., 2019). No movements should be restricted by the exoskeleton. The exoskeleton should increase the user’s ability to complete exhaustive movements, which do not result in the perception of increased workload, such as reported by Bequette et al., 2020. Additionally, using an exoskeleton cannot delay the fast-paced nature of a medical evacuation.

The effects on the movement of the upper and lower extremities due to different load magnitudes and the day’s designated uniform need to be understood when designing augmentation and control systems (Crowell et al., 2019). The biomechanics of the user with and without the exoskeleton needs to be evaluated to ensure that the exoskeleton does not alter the natural movement of the user. The litter teams should easily and naturally perform specific tasks, such as kneeling to transport the patient to the litter, picking up the litter, kneeling to provide critical care, or setting down the litter to engage in combat. Exoskeletons developed for patient transport scenarios should be tested against the conditions that litter teams face in the field.

Terrain and climate in certain regions may have high peaks, deep gorges, extremely cold or hot climates, and high-altitude levels (Katoch, 2005). The survivability of patient transport teams and the casualty being evacuated is dictated by altitude, climate, and terrain (Katoch, 2005). Exoskeleton materials should be selected for durability in any terrain, whether hilly, rocky, wet, sandy, or rural. The exoskeleton also should withstand and function in any environment in which they are deployed, whether a desert, jungle, or extreme temperatures (Crowell et al., 2019).

Exoskeleton Storage, Transport, and Deployment

Military facilities will not adopt new and expensive machinery if it does not secure the following: Does the suit make the job easier without interfering with the overall mission’s effectiveness? Can most SMs use the item with little to no prior training? Can an SM don and doff the suit without the assistance of others? Is the item reliable in most environments? Is this the cheapest while also being the most effective option? Is there an ability to maintain the item easily over a long life cycle?

Other specific considerations need to be answered by the designers for exoskeletons to be used in patient transport scenarios. Will an emergency vehicle store the exoskeleton? Where and how will the exoskeleton be deployed? The answers may depend on the exoskeleton's weight, size, and internal systems. If the exoskeleton is too large or heavy to be carried by the litter bearer, the exoskeleton may need to be deployed at the checkpoint closest to the pickup site.

Safety and Reliability

The physical interface should not cause discomfort or harm to the user (Crowell et al., 2019). When evaluating the ReWalk (ReWalk, Malborough, MA) exoskeleton (Table C2, Appendix C), Awad et al. (2020) found instances of pain in the lower extremity, skin abrasions, and limb discomfort during testing. The authors reported that the negative effects of wearing the exoskeleton were due to the improper fit of the exoskeleton on the user. Care should be taken to ensure the exoskeleton is adjustable and can easily be placed on the user to alleviate or reduce the possibility of improper fit. The exoskeleton should accommodate litter bearers of different sizes (Crowell et al., 2019), preferably from the 5^{th} to the 95^{th} percentile SM in height and waist circumference. The augmentation benefits should be the same for male and female litter bearers, unlike the results found in Rice et al. (1996b, 1996a). The exoskeleton should not increase the risk of acute or chronic injury or health effects to the litter bearer through its use. This includes increasing the risk of traumatic injury as well as health decrements that decrease operational tactical and medical performance.

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Device reliability is another primary safety consideration for exoskeleton designs. Awad et al. (2020) reported device malfunctions in 11.6% of the study visits were related to the actuation unit, the handheld device, and the sensory connectivity. Luckily, none of the malfunctions resulted in adverse events. Designers and engineers should incorporate safety mechanisms to ensure the litter team can safely and quickly remove the exoskeleton in the event of a system malfunction. The exoskeleton should enhance performance without affecting the survival rate of the patient. In addition, servicing parts to maintain the suit throughout its life cycle should be easily and fiscally attainable. Most repairs must be able to be done by a SM in the theatre environment as to not halt on the mission at hand.

Feasibility Evaluation Metrics for Assessment of Performance Augmentation and Optimization Capabilities

Following the identification of design specifications and considerations, the exoskeleton prototype or device must be tested to assess its augmentation and optimization capabilities. Proud et al. (2020) reported that 68% of devices were evaluated using a human-exoskeleton integration analysis and included biomechanical (i.e., motion capture), physiological (i.e., metabolic cost), and psychophysical measures (i.e., subjective feedback). Crowell et al. (2018) recommend using biomechanical or physiological metrics to evaluate specific changes in physical performance from using the exoskeleton.

Crowell et al. (2019), Mudie et al. (2018), and Crowell et al. (2018) have developed guidelines for evaluating exoskeletons for military applications. Crowell et al. (2018) provide a selection of methods and metrics that are currently used at the U.S. Army Combat Capabilities Development Command Soldier Center and the U.S. Army Research Laboratory to evaluate exoskeleton devices for military applications. The report gives an extensive guide for evaluating and measuring the performance of exoskeletons from the initial design phase to the advanced prototype phase. It must be reiterated that the use of an exoskeleton can not only just be introduced into military applications, additional concerns must be taken into consideration. Among these is the ability of the exoskeleton to safely and easily integrate with the SM and their equipment; for example, the exoskeleton should not interfere with the SM’s PPE, this includes personal safety equipment worn with the uniform and the use of medical protective equipment worn during medical procedures.

Recommendations

The following recommendations are essential for the development of successful exoskeleton devices to augment or enhance human motion or the physical activity of SMs during dismounted litter load carriage tasks:

- Designers should consider developing a quasi-passive, multi-joint, upper extremity exoskeleton for military patient transport and casualty evacuation scenarios. The presence of a lower extremity exoskeleton would be beneficial to a litter bearer due continuous lower body movement during transition. However, to the upper body, grip strength in particular, is the first component to fatigue to exhaustion. This exhaustive state is why upper extremity exoskeletons take priority over lower extremity, but both are beneficial to the SM. Based on the findings, designers should consider using a combination of lighter actuators, such as pneumatic actuators or series elastic actuators, and passive actuators, such as springs or dampers. Combining these types of actuators may allow the exoskeleton to be lighter and consume less energy than if electric or hydraulic actuators were used. The use of the passive actuator could also serve as a backup augmentation component if the exoskeleton runs on a limited power supply.

- A combination of soft and rigid materials should be considered to help leverage the advantages of a durable rigid design and the flexibility and lightness of a soft exosuit design.
- The materials should be selected for durability in any terrain, whether hilly, rocky, wet, sandy, or rural when expected to travel outside military protective zones. The exoskeleton should withstand any environment in which they are employed, whether desert, jungle, or extreme temperatures (Crowell et al., 2019).
- Care should be taken to ensure the exoskeleton is adjustable to accommodate vast anthropometric variances among SMs. Exoskeletons should also easily be donned and doffed by the user to alleviate or reduce the possibility of improper fit (Gordon et al., 2014).
- The scenarios, team size, and litter bearer size should be considered when designing exoskeletons for patient transport scenarios. Exoskeletons should be able to augment the user during both long-distance transports and short-distance transports, regardless of team size and litter bearer size.
- The exoskeleton should not require the litter team to surrender their weapons or remove body armor. The exoskeleton must not interfere with current military equipment or weaponry (Crowell et al., 2019). Preferably, the exoskeleton should be easily integrated into the mission at hand.
- Army medics must also continue their care of the patient, which requires them to perform dexterity skills, like placing an intravascular device. For that reason, future exoskeletons must not interfere with patient evaluations, typical medical procedures, or any extra duties required of the SM (Blackbourne et al., 2012).
- Designers and researchers should consider how the exoskeleton will be stored and where/how it will be deployed.
- Designers and engineers should incorporate safety mechanisms to ensure the litter team can safely and quickly remove the exoskeleton in the event of a system malfunction.
- The proposed design should be evaluated in a field- or lab-based characterization study using human subject volunteers to assess the efficacy, suitability, and feasibility of device use in simulated patient transport scenarios. Biomechanical, physiologic, operational performance, and subjective user feedback should be collected incrementally during simulated transport of either or each of the common casualty evacuation scenarios. Data outcomes should be compared to, at a minimum, data collected in identical conditions without using assistive devices. Data comparisons should also be made against other assistive devices.
- For the litter team, hand steadiness and hand-grip strength should be measured, and recovery times minimized when evaluating exoskeletons for patient transport.
- When evaluating the exoskeleton design for use in military patient transport scenarios, it is recommended to use the guidelines developed by Crowell et al. (2018), Mudie et al. (2018), and Crowell et al. (2019).

Conclusion

Transporting patients on litters can be physically demanding for SMs, regardless of team size. Post-carry fatigue symptoms can impede an SM’s ability to provide the necessary care to a casualty during prolonged field care situations. Additionally, the battle readiness of the litter bearers during or after litter transport is often overlooked. Exoskeletons have the potential to enhance and augment litter bearers during patient transport and casualty evacuations by offsetting some of the loads to the upper extremity. The USAARL conducted a comprehensive review of the state of exoskeleton research to determine essential preliminary design considerations and provide preliminary recommendations for exoskeleton technology specifically focused on improving or enhancing dismounted military casualty transport scenarios. This work is the first of its kind and a critical foundational approach toward the development and future deployment of devices with the potential to reduce the negative impacts of frequent, repetitive, or extended casualty transport using a litter.

This comprehensive literature review resulted in identifying six crucial design factors and specifications that must be considered for exoskeleton feasibility, suitability, and efficacy in assisting the user with litter carriage. Essential recommendations for the development of successful exoskeleton devices to augment or enhance human motion or the physical activity of SMs during dismounted litter load carriage tasks were also provided. However, additional reviews are needed to review the specifications and applicability of exoskeletons currently available or in the research stage that meet the outlined criteria. The next research step will leverage and expand these recommendations by conducting proof of concept human subject volunteer studies to determine if the use of an assistive device during litter transport could potentially decrease the fatiguing effects and increase the litter bearer's ability to carry the litter, provide critical care, and sustain SM tasks. Future work will examine applicable exoskeleton designs, prototypes, and devices to determine whether they are suitable or adaptable for use in litter transport scenarios with follow-up human subject research studies to assess and evaluate the efficacy and feasibility of the proposed devices. These data will aid in establishing a standard to evaluate the efficacy and feasibility of assistive devices to be considered for selection and integration into the standard Military Equipment Set for litter transport procedures.

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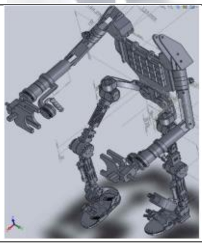
Appendix A. Abbreviations and Acronyms

DoD	Department of Defense
FFO	Full Fighting Order
KEA	Knee Extension Assist
MDO	Multi-domain operations
PAMs	Pneumatic artificial muscles
PPE	Personal protective equipment
SM	Service Member
USAARL	United States Army Aeromedical Research Laboratory

Appendix B. Whole-Body Exoskeletons

Table B1. Examples of Whole-Body Exoskeletons (Commercially Available and Prototype/Research Phase)

	Device Name	Developer	Device Type	Status
	Hybrid Assistive Limb (Kawabata et al., 2009)	Cyberdyne, Inc. (Tsukuba, Ibaraki, Japan)	Rigid Active Untethered	Commercially Available
	Raytheon XOS 2 (Army Technology, 2020)	Raytheon* (Waltham, MA)	Rigid Active Tethered	Commercially Available
	PERCRO Body Extender (Marcheschi et al., 2011)	Perceptual Robotics Lab (Pisa, Italy)	Rigid Active Tethered	Prototype/ Research Phase
	Human-Robot Integrated Exoskeleton (Ryu et al., 2012)	Hanyang University and Korea Institute of Robot and Convergence (Pohang, South Korea)	Rigid Active Tethered	Prototype/ Research Phase

**Note*. Formerly Sarcos.

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Appendix C. Regional Exoskeletons

Table C1. Examples of Upper Body and Upper Extremity Exoskeletons (Commercially Available and Prototype/Research Phase)

	Device Name	Developer	Device Type	Status
	Airframe (Levitate Technologies Inc., n.d.)	Levitate Technologies (San Diego, CA)	Semi-Rigid Passive Untethered	Commercially Available
	EVO (Ekso Bionocs, n.d.)	Ekso Bionics (Richmond, CA)	Semi-Rigid Passive Untethered	Commercially Available
	Skelex 360-XFR (Skelex, n.d.)	Skelex (JW Rotterdam, Netherlands)	Semi-Rigid Passive Untethered	Commercially Available
	Shoulderx Exoskeleton (Van Engelhoven et al., 2019)	Ottobock* (Duderstadt, Germany)	Rigid Passive Untethered	Commercially Available
	MATE-XT (Pacifico et al., 2020)	Comau (Turin, Italy)	Semi-Rigid Passive Untethered	Commercially Available
	Paexo Shoulder (Maurice et al., 2020)	Ottobock* (Duderstadt, Germany)	Semi-Rigid Passive Untethered	Commercially Available
	Rehand Exoskeleton (Wang et al., 2018)	University of Shanghai (Shanghai, China)	Rigid Active Tethered	Prototype/ Research Phase
	Virginia Tech's Hand Exoskeleton (Refour et al., 2019)	Robotics and Mechatronics Lab, Virginia Tech (Blacksburg, Virginia)	Rigid Active Tethered	Prototype/ Research Phase
	Passive Upper Limb Exoskeleton (Yin et al., 2020)	South China University of Technology (Guangzhou, China)	Rigid Passive Tethered	Prototype/ Research Phase

Note. Formerly Suitx.

Table C2. Examples of Lower Extremity Exoskeletons (Commercially Available)

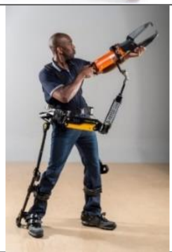
	Device Name	**Developer**	**Device Type**	**Status**
	Rewalk (Zeilig et al., 2012)	Rewalk (Marlborough, MA)	Rigid Active Untethered	Commercially Available
	UPRISE Gen 3.0 (Gruevski et al., 2020)	Mawashi (Saint-Jean-sur-Richelieu, QC)	Semi-Rigid Passive Untethered	Commercially Available
	The FORTIS Exoskeleton (Lockheed Martin, 2022a)	Lockheed Martin (Bethesda, MD)	Rigid Passive Untethered	Commercially Available
	Onyx (Lockheed Martin, 2022b)	Lockheed Martin (Bethesda, MD)	Semi-Rigid Active Untethered	Commercially Available

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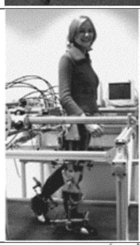
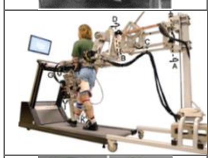
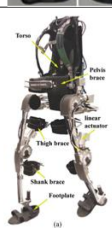
Table C3. Examples of Lower Extremity Exoskeletons (Prototype/Research Phase)

	Device Name	Developer	Device Type	Status
	The Berkeley Lower Extremity Exoskeleton (Zoss et al., 2006)	University of California Berkeley (Berkeley, CA)	Rigid Active Untethered	Prototype/ Research Phase
	MIT's Quasi-Passive Leg Exoskeleton (Walsh et al., 2007)	Massachusetts Institute of Technology (Cambridge, MA)	Rigid Quasi-Passive Untethered	Prototype/ Research Phase
	Lower Extremity Powered Exoskeleton (Veneman et al., 2007)	University of Twente (Enschede, Netherlands)	Rigid Active Tethered	Prototype/ Research Phase
	Active Leg Exoskeleton II (Winfree et al., 2011)	University of Delaware (Newark, DE)	Rigid Active Tethered	Prototype/ Research Phase
	Knee Extension Assist (KEA) Exoskeleton (Spring et al., 2012)	University of Waterloo (Waterloo, Ontario)	Semi-Rigid Passive Untethered	Prototype/ Research Phase
	MINDWALKER (Wang et al., 2015)	Delft University of Technology (Delft, Netherlands)	Rigid Active Untethered	Prototype/ Research Phase
	H2 Exoskeleton (Bortole et al., 2015)	Cajal Institute (Madrid, Spain) and The University of Houston (Houston, TX)	Rigid Active Untethered	Prototype/ Research Phase

	Device Name	Developer	Device Type	Status
	University of Singapore KAF Robot (Chen et al., 2016)	University of Singapore (Singapore)	Rigid Active Tethered	Prototype/ Research Phase
	Walking Power-Assist Locomotor (Yatsuya et al., 2018)	Fujita Health University (Toyoake, Japan)	Rigid Active Untethered	Prototype/ Research Phase
	Human Universal Load Carrier (Army Technology, 2020)	Lockheed Martin (Bethesda, MD)	Rigid Active Untethered	Prototype/ Research Phase
	Powered Ankle-Foot-Orthosis (Choi et al., 2020)	Yonsei University (Seoul, South Korea)	Rigid Active Untethered	Prototype/ Research Phase

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