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*Exoskeleton Enhancements for Marines:
Tactical-level Technology for an Operational Consequence*

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ABSTRACT (MAXIMUM 200 WORDS) This monograph is presented to further a discussion that has persisted for decades, namely: Is it possible to reduce the weight of the combat load on the infantry soldier that will allow for nearly unimpeded speed and tempo in foot mobile operations? Since the mid-1990's the Marine Corps has advanced future operating concepts that seek to achieve the promise of maneuver warfare, that is, the capability to maneuver against the weaknesses of an adversary so rapidly that they are unable to respond to the multiple threats presented across the battlefield, thus shattering their cohesion and decision making ability. An impediment to achieving this endstate has been the fact that foot mobile infantry forces are so overloaded with equipment that they have been unable to maneuver at the desired speed and with the desired distribution on the battlefield to achieve this maneuver effect. Through the ages three solutions have been attempted to reduce the load on the average infantryman: reduce the weight of equipment, transfer the load to some vehicle or beast of burden, and improve individual fitness and endurance. Even as the weight of individual components is decreasing, more pieces of equipment are being added to the combat load for communications, target acquisition, navigation, self protection, and night operating capability. Organizational loads are also increasing as infantry companies are now being given command and control responsibilities that were once reserved for a battalion or higher. Therefore, it is time to explore another alternative to weight mitigation that has never been tried before: wearable exoskeleton technology. The Marine Corps has acknowledged that not enough aviation or vehicles assets exist to move the force in the initial stages of a forcible entry operation, thus, the Marine Corps needs to provide every Marine with the capability to carry the load in the form of some wearable mechanical augmentation, which is what an exoskeleton provides.			
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EXECUTIVE SUMMARY

Title: *Exoskeleton Enhancements for Marines: Tactical-level Technology for an Operational Consequence*

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Thesis: The Marine Corps' attempt to realize distributed operations will be unattainable if Marines are not given the proper equipment to carry the combat loads necessary for persistent foot mobility. Rather than focus on weight reduction and load transference, the Marine Corps should commit to the development of wearable exoskeleton technologies. The exoskeletons will permit Marines to carry loads far in excess of normal human capacity and that will be essential for long-duration foot mobile distributed operations in the future.

Discussion: This monograph is presented to further a discussion that has persisted for decades, namely: Is it possible to reduce the weight of the combat load on the infantry soldier that will allow for nearly unimpeded speed and tempo in foot mobile operations? Since the mid-1990's the Marine Corps has advanced future operating concepts that seek to achieve the promise of maneuver warfare, that is, the capability to maneuver against the weaknesses of an adversary so rapidly that they are unable to respond to the multiple threats presented across the battlefield, thus shattering their cohesion and decision making ability. An impediment to achieving this endstate has been the fact that foot mobile infantry forces are so overloaded with equipment that they have been unable to maneuver at the desired speed and with the desired distribution on the battlefield to achieve this maneuver effect. Through the ages three solutions have been attempted to reduce the load on the average infantryman: reduce the weight of equipment, transfer the load to some vehicle or beast of burden, and improve individual fitness and endurance. Even as the weight of individual components is decreasing, more pieces of equipment are being added to the combat load for communications, target acquisition, navigation, self protection, and night operating capability. Organizational loads are also increasing as infantry companies are now being given command and control responsibilities that were once reserved for a battalion or higher. The Marine Corps believes that foot mobile forces will be decisive in the future and it is seeking to rectify the disparity between needed capabilities, weight, and persistent foot mobile operations. Therefore, it is time to explore another alternative to weight mitigation that has never been tried before: wearable exoskeleton technology. The Marine Corps has acknowledged that not enough aviation or vehicles assets exist to move the force in the initial stages of a forcible entry operation, thus, the Marine Corps needs to provide every Marine with the capability to carry the load in the form of some wearable mechanical augmentation, which is what an exoskeleton provides.

Conclusion: No programs now or in the future will likely be able to substantially decrease the weight carried by Marines in foot mobile environments. A Marine Corps investment in exoskeleton technologies will contribute to enhancing the speed, tempo, range, and endurance of foot mobile forces and make it possible for the Marine Corps to achieve a force capable of distributed operations as envisioned in the USMC future warfighting concepts.

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“In an army every material novelty demands first a clear, tactical appreciation of its use, and secondly a suitable organization, based on this appreciation, wherein to express its powers.”¹

J.F.C. Fuller, *Foundations of the Science of War*, 1926

Introduction

Since the 1990s the Marine Corps has incorporated many materiel innovations at the tactical level to aid individual Marines with everything from target acquisition to enduring the challenges of weather. Concurrently, it has published several concepts and vision statements that define how the Service will conduct future operations, utilize technical innovations, and improve its battlefield agility and flexibility.² However, many personal combat enhancements have also contributed to the age old problem of overloading the individual Marine resulting in a loss of mobility and endurance, particularly in dismounted operations.³ Despite dedicated efforts over the years to lighten this equipment or transfer the load, Marines and soldiers of today have remained some of the most heavily laden in history.⁴ (See Fig 1) A concern arises as to whether the Marine Corps can implement the operational vision of a rapidly moving and expanded battlefield proposed in its future operating concepts if combat overloading continues to impact the speed and endurance of the current force. Given the historical lack of success in reducing the load, another possibility to solve this problem should be explored. It is now within the realm of technical feasibility to develop a wearable mechanical capability to assist Marines in the form of a robotic anthropomorphic exoskeleton system. This capability may be a key enabler to realizing persistent foot mobile operations in a distributed environment, reducing reliance on vehicular and aerial lift to move the force while still retaining speed of movement, reducing physical impacts, and overcoming many logistical challenges associated with today’s heavier force.

Operational Concepts Defined

In order to determine if exoskeleton technology is a prudent investment to enable future operations, it is first worth considering whether the Marine Corps even envisions a role for foot

mobile forces in the future. Sufficient historical evidence exists to show that wars cannot entirely be fought from vehicles or from airplanes and that some form of dismounted presence is required to see a conflict through. However, does a force lose operational agility or tactical options in a future conflict when it lacks an enduring and long range foot mobile capability; especially as a consequence of weight?

In 1996 and 1997 the Marine Corps published two concepts for sea-based maneuver at the operational level of war that expanded on its doctrine of maneuver warfare⁵ entitled *Operational Maneuver From the Sea* (OMFTS) and *Ship-to-Objective Maneuver* (STOM). The premise of OMFTS was that the Marine Corps and Navy would “exploit the sea as a maneuver space while applying combat power ashore to achieve operational objectives.”⁶ OMFTS posited that forces projected from sea and enabled by future capabilities could maneuver within a theater to project combat power over hundreds of miles rather than at just the fixed tactical point defined as an amphibious operations area. STOM continued the vision of OMFTS and clarified how, at the tactical level, the Marine air-ground task force (MAGTF) would achieve a joint force commander’s operational objectives from amphibious platforms. STOM was defined as “the conduct of combined-arms maneuver through and across the water, air, and land of the littoral battlespace directly to inland objectives.”⁷

STOM in particular stressed that a key characteristic of tactical maneuver would be an over-the-horizon deep projection of forces launched from sea via air and surface means. This deep projection would render enemy defenses inert due to the broad space that Marines could influence thereby making it impossible for the enemy to cover all likely insertion points. In STOM the means of maneuver would be more rapid and flexible than in previous eras and would allow commanders to change objectives enroute thus generating a speed and tempo that the

enemy could not keep pace with or adjust to.⁸ This would allow the MAGTF to avoid surfaces, exploit gaps, and prevent the need for establishing a lodgment under opposed conditions.

In April of 2005 the Marine Corps further refined its tactical employment concept by publishing a *Concept for Distributed Operations* (DO)⁹. DO declared that deep penetrations would be enhanced by a dispersion of forces at the small-unit level augmented by improved lethality, access to supporting arms, and connected by robust command and control (C2). The DO concept stated that, “Small, highly capable units spread across a large area of operations will provide the spatial advantage commonly sought in maneuver warfare, in that they will be able to sense an expanded battlespace, and can use close combat or supporting arms, including Joint fires, to disrupt the enemy’s access to key terrain and avenues of approach.”¹⁰ In DO maneuver units would operate in a disaggregated fashion down to the squad level, beyond the range of mutually supporting direct fires, but connected by networked C2. In addition, these forces would be capable of re-aggregation in order to concentrate combat power at the decisive point facilitated by an increase in the number of tactical mobility assets, specifically in the form of dedicated aviation and organic vehicles.¹¹ By implication, forces operating independently would require more organic sustainment and potentially more equipment to perform a variety of missions. It would seem therefore that in order to enable the promise of increased capability, more weight would be added to the squad and individual causing a ripple effect up the organization. Thus, expanded battlespace would come at the cost of weight and mobility requiring vehicles to support movement since spatially diverse and heavily laden forces would be challenged to be at a critical point in time if forced to arrive by foot alone.

Although DO was a natural extension of OMFTS/STOM it was also a generational leap conceptually that bypassed a necessary evolution in small-unit capability. In August of 2008, A

Concept for Enhanced Company Operations (ECO) was published which identified the company as the focal point of tactical employment in support of USMC operational concepts. In the introduction, the Commandant, General James Conway declared, “Conventional wisdom tells us that the battalion is the smallest tactical formation capable of sustained independent operations; current operations tell us it is the company.”¹² ECO is defined as an “approach to the operational art that maximizes the tactical flexibility offered by true decentralized mission accomplishment, consistent with commander’s intent and facilitated by improved command and control, intelligence, logistics, and fires capabilities”¹³

Embedded in the ECO discussion are several key areas of concern that DO omitted but that must be solved in order to have the kind of force desired in this concept. Notably the issues of mobility as well as organizational and individual weight come to the fore as mitigating factors in realizing the full potential of ECO. Where DO postulated that the entire force would be vehicle or air mobile, ECO stressed that along the spectrum of conflict “combat developers must remain mindful that *the requirement will always exist for dismounted units* (emphasis added) to accomplish selected missions.”¹⁴ Throughout the remainder of the ECO concept, emphasis is given to ensuring that companies can function in the distributed environment without adding to the burden of the individual Marine whether in terms of logistics, C2, or enabling lethal capabilities. The conclusion of the ECO concept emphasizes that “ECO will present unique challenges that cannot be wished away. Factors such as weight (*i.e. unit and individual*) and cube (*i.e. total square and cubic area consumed*) have the potential to be show stoppers.”¹⁵ This last sentence clarifies that the weight of the force overall, and that which is carried by the Marines in particular, can potentially impact the ability of the Marine Corps to realize its envisioned concepts in the future. Further commenting on this issue, General Conway published the Marine

Corps Vision and Strategy 2025 in September 2008 which stated that “Lightening the load of the individual Marine while enhancing protection is a Service imperative.”¹⁶

Introductory efforts have begun to develop and equip an ECO-type force¹⁷ and many key lessons are being learned regarding what it takes to truly enable a company to operate in a distributed environment.¹⁸ Although many of the companies engaged in the current fight are operating in vast spaces (up to hundreds of square kilometers)¹⁹ the ponderous logistics requirements, heavy C2 footprint, and individual equipping have limited the range of foot mobile operations. One must concede that the current implementation of ECO is influenced by current technology and requirements and not some failure to create an idealized future force. To be sure, miniaturization of many of assets will eventually produce at least the semblance of portability, but Marines are already heavy (as statistics later in this monograph will point out) and any additional capability regardless of size will continue to contribute to the basic problem.

The previous discussion seems clear on two points: the Marine Corps does see a future for foot mobile operations and a force does lose operational agility and tactical options when combat overweighting limits persistent foot mobile capability. One questions remains: Why should some form of mechanical innovation be considered to aid the individual dismounted Marine to carry his assigned load vice merely attempting the older methods of load transference or weight reduction?

In 2009, Marine Corps Combat Development Command (MCCDC) issued three concept papers: *Evolving the MAGTF for the 21st Century*, *Amphibious Operations in the 21st Century*, and *Seabasing for the Range of Military Operations* all of which discussed the current weight and overloading issues as well as its impact to future force operations. The papers reinforce the position made in ECO that dismounted forces remain an employment option but they also state

that it will likely become necessary to employ a significant number of companies in a dismounted configuration in the future. The reason given for expanding dismounted operations is that an insufficient number of aviation and vehicles assets will be available to persistently move the force, especially during the early phases of an assault or crisis. The primary culprit for this projected deficiency is the weight of vehicles and airplanes. Ships will be unable to carry the numbers of required lift assets due to this overarching factor for the first time in Marine Corps and Navy history.²⁰ The concepts further state that “constraints on amphibious lift will likely result in some companies being foot-mobile after landing.”²¹

Given the probability of dismounted operations after insertion a focus not only on weight minimization but mitigation is a key element to ensuring future operating capability. It is reasonable to assume that without some form of mechanical augmentation to the individual Marine his capacity to carry his assigned load will affect the speed and tempo of the whole force. If Marines can remain persistently foot mobile and do not require constant vehicle and aerial augmentation for mobility provided by individual mechanical enhancement, the implications for reduced lift and logistical sustainment requirements are vast. Reducing reliance on vehicular lift and replacing it with an exoskeleton may even free space on amphibious shipping and catalytically gain the force a new capability and capacity in foot mobile maneuver that has not been realized before. Based on this assessment, dismounted operations are a necessary and decisive employment option that can expand the maneuver repertoire of a future force.

The Requirements for an Exoskeleton Capability

The discussion to this point has clarified that tactical weight issues do have operational implications, especially for future concepts and that individual mechanical assistance has been an unconsidered option to address this issue up to this point. But, what exactly is the problem that

an exoskeleton capability must overcome in order to be a viable solution to the issue of combat overweighting? Of the many studies performed on the individual load issue, one of the most recent and comprehensive was published in September 2007 by the Naval Research Advisory Committee (NRAC) entitled *Lightening the Load*. The NRAC study “sought to assess the weight and volume contributors of the Marine’s combat load, and to evaluate technology initiatives and other changes to reduce the burden without having an unacceptable impact on combat effectiveness, safety, or tactics.”²² The basic combat unit that was evaluated was the Marine Rifle Squad which was not viewed in terms of individual weight alone, but as a system.²³ The rifle squad was chosen as the focus of study since it is the lowest level infantry organization with an assigned mission, table of organization and equipment (TO/E), and quantifiable mission task list requirements from which the cumulative effect of weight can be evaluated against metrics of performance, unit mission requirements, and deviations in TO/E.²⁴

The study first defined the types of loads that Marines carry in combat. Since USMC definitions vary slightly from U.S. Army and Military Standard 1472F (which is used to define anthropomorphic design data for military equipment) the Marine Corps definitions were used. The types of loads are the: Assault Load, Approach March and Existence Load. “As defined, Assault Load is that load associated with ‘conducting combat operations indefinitely with minimal degradation in combat effectiveness’; Approach March Load is that load for conducting a ‘20-mile march within 8 hours maintaining 90% combat effectiveness’; Existence Load is the load associated with ‘limited movement within confines of transportation platforms and limited marching from landing zone into secure area.’”²⁵ Combat effectiveness is an elusive metric and the NRAC study states, “that there is a paucity of data that address weight vs. combat

effectiveness.”²⁶ There was ample study data to show that weight does affect endurance; it just could not be related to a specific combat task.²⁷ (See Fig 2)

The study did focus on the Approach Load since it was considered the most likely within a combat scenario.²⁸ However, the author considers that focus to be an artifact from current paradigms of combat and not the likely load to be carried in a STOM/ECO environment of the future. The reason for that assertion is that the Existence Load is defined as the load that is carried from insertion and then removed in a secure area. By implication this means that the existence load has non-mission essential components removed and secured and the approach load is then the load carried from a secure area to the combat zone. However, if the vision of STOM/ECO is realized, Marines would proceed from the sea and move directly to the objective of combat, with a possible mission change enroute, making the transition to a secure area and the modification of load an unlikely event. Multiple mission requirements and uncertainty would affect load design. Thus, the focus for future efforts should not be on the approach load, but on the existence load.

For each of the load types, optimal weights were computed as a percentage of body weight for an average male Marine. The average male was deemed to be 169 lbs and the recommended weights were: 50 lbs (Assault), 75 lbs (Approach), and 127 lbs (Existence) with corresponding percentages of body weight to be 30%, 45%, and 75% respectively. However the study determined that the average actual weights were 97lbs (57%), 123lbs (73%), and 167lbs (97%) for the aforementioned load types.²⁹ (See Figure 3) In the end, the NRAC study determined in the top level findings that the average assault load for a rifle squad alone was between 97 and 134 pounds due to weight increases in personal protective equipment (PPE) (i.e. body armor) and firepower that impacted combat effectiveness and resulted in shorter duration

missions .³⁰ A source study for the NRAC conducted by MCCDC's Fires and Maneuver Integration Division further evaluated the assault loads for a rifle company and found weights between 97 to 167 pounds were average across the company. The highest weights were for the gunners of the heavier weapons systems.³¹ (See Figure 4) Again, these studies were based on basic TO/E components and did not account for things like the man-portable Guardian Improvised Explosive Device Jammer (25lbs) which is used in the current COIN fight and which requires the squad to reallocate the equipment of the Marine carrying the device to the already overloaded group.³² Neither did the study describe the ECO command post operations with expanded suites of equipment for C2 and intelligence.³³

In the end the NRAC determined that the average rifle squad was approximately 900 lbs over suggested weight. The panel found no single mitigating factor to reduce the weight but they considered four focus areas: science and technology (S&T) to lighten weapons and equipment; load transfer methods such as unmanned ground vehicles; tactics where dispersion and stealth would reduce protective requirement; and individual performance support such as nutrition, ergonomics, and physical conditioning.³⁴ The NRAC suggested in the best case approximately 300lbs could be saved in S&T programs and 300lbs could be saved in load transfer devices.³⁵ (See Figures 5 & 6) Even with the "best case" in their alternatives approach 300 lbs has to be transferred and 300lbs (23 lbs per man) still has to be resolved. This unresolved factor implies that another element to solving this problem has to be introduced given that the alternatives considered, as novel as they may be, were still age old ideas. However, individual mechanical enhancements to Marines were not considered which could be ground breaking option. Exoskeletons then could be the way to address the uncertain 300 to 600 pound variable.

What is an exoskeleton?

An exoskeleton is defined as “an active mechanical device that is essentially anthropomorphic in nature, is “worn” by an operator and fits closely to his or her body, and works in concert with the operator’s movements.”³⁶ In general, the term “exoskeleton” is used to describe a device that augments the performance of an able-bodied wearer. The term “anthropomorphic” according to Merriam-Webster is “described or thought of as having human form or human attributes.”³⁷ In this case exoskeletons are a device that follows the human form and direction. "Exoskeleton" within the robotics community does not mean the hard outer protective shell but “is taken to include mechanical structures, as well as associated actuators, visco-elastic components, sensors and control elements.”³⁸ Although there are a few types of exoskeletons this paper will focus on parallel-limb exoskeletons which are basically worn and run in parallel to the limbs and body of the wearer. Two types of parallel limb exoskeletons are being developed that show the most promise: lower body exoskeletons that assist in carrying loads and transfer weight through the frame and full-body exoskeletons which cover the entire body and are used for torque and work augmentation.³⁹ (See Figure 7 for historical and current examples).

Although efforts to construct exoskeletons for military application have been conducted since the 1960s, only in recent years have advances in lightweight materiel technologies, microprocessors, hydraulic design innovations, and power made exoskeletons feasible as an alternative. In 2001 the Defense Advanced Research Projects Agency (DARPA) sponsored a program called Exoskeletons for Human Performance Augmentation (EHPA). The goal of the program was to “increase the capabilities of ground soldiers beyond that of a human”. The program focused on augmenting the performance of soldiers during load-carrying, increasing the

size of the load that can be carried, and reducing the fatigue on the soldier during the load-carrying task.⁴⁰

Fast-forwarding to the present, the exoskeleton project has been handed over from DARPA to the Army's Research and Development Command (RDECOM) with program management at Natick Labs. Two designs have emerged as the most promising variants: Berkeley Bionics-Lockheed Martin's Human Universal Load Carrier (HULC) and SARCOS Labs-Raytheon's Exoskeleton (XOS).

HULC is a lower body exoskeleton design that the user puts on like a leg brace, extending to the hip. It runs on battery power and allows the user to wear a standard combat load and carry a backpack up to 200 lbs (not including the user's own weight). It is intended to provide a 10:1 ratio of support (200 lbs feels like 20) and the load is transferred through the frame while the hydraulic systems aid the user with a power assisted walking or running gait. The computer for the system is programmed to the individual user and senses the motion of the wearer to mimic his movements. Its primary application is infantry support. The frame itself weighs 52 lbs and can still be manipulated even with a loss of power. It can be easily doffed and donned by releasing straps and stepping out of the boot platforms.⁴¹

XOS is a full-body system that receives power through a tethered source (power cable) and its primary purpose is for work augmentation. Like the HULC it has a similar micro-processor sensing capability but it allows the user to lift and pull items with up to a 25:1 ratio in some cases. The primary vision for this system is as a logistics support device that will assist in everything from vehicle maintenance, to human "fork lift" like functions, to allowing EOD techs to wear heavy bomb suits without fatigue.⁴² Its obvious limitation is its need for an external power source at this point which is why it is conceived as more of a combat support and combat

service support technology where vehicle or generator power is readily available. XOS cannot function without power, but should a failure occur, the XOS will retain the last position assigned to it by the wearer with the same force. The wearer can in essence step in and step out of the suit.⁴³

Developmental challenges and timeline

Although the promise of exoskeletons is obvious from the description there are many technical issues to resolve that will impact military development. However, as generally assessed, none of the issues seem impossible to overcome, but they will likely take seven to ten years to realize fully.⁴⁴ In general the issues involve evaluating movement and gait, long-endurance power, ruggedization, metabolic cost.

Understanding the movement of the human body and building a system that mimics human movement is a challenge. Designers are challenged by such things as “misalignment of joints between operator and hardware, kinematic constraints from attachments such as harnesses and cuffs, design not optimized for load-carrying gait, added forces to the operator that resist motion, and addition of power in a suboptimal manner(e.g., mistiming, too little, too much), among others.”⁴⁵ Even computers to control the systems are undergoing improvements in body matching algorithms. All in all the scientific community remains hopeful that study, testing, and design will resolve these issues.

Long endurance power is a serious issue for any of these systems. Currently the HULC with BB2590 batteries in the latest configuration has a four hour life, when marching at 3 mph, fully loaded. The demands for power on the battlefield have increased exponentially over the last 20 years of which both XOS and HULC would be additional consumers whether from generators, vehicles, batteries, or recharging systems.⁴⁶ Batteries in particular are a significant

weight driver for foot-mobile forces. However, efforts toward improved batteries, power cells, portable solar rechargers and the like continue and the horizon is hopeful in that regard.

Ruggedization is an intuitive issue and boils down to making the technology “Marine proof”. In essence the systems will need to be able to endure all weather conditions, salt water effects, electromagnetic effects, be tactically quiet, and maintainable in the field. Initial designs have shown a basic durability, but operational environment testing is not scheduled until a year after the program is funded.⁴⁷ Additionally “snap on” body armor designs are being developed which would improve durability and provide potentially more protection.

Metabolic cost is a key issue. In essence a system will not only have to reduce the perceived load (the feeling of weight on the body) but will have to be energetically more efficient than the human body carrying the same load unassisted. This is really more of an issue for the HULC system due to its envisioned use by infantry, which has been a challenge to date.⁴⁸ However, research is hopeful in that regard, and XOS has already shown significant impact in metabolic reduction.⁴⁹

Operational Implications

The promise of this technology seems fairly evident from discussion above, but how would this system contribute, beyond individual enhancements to carry the load, to realizing the operational concepts of OMFTS/STOM/ECO as a whole? Exoskeletons will aid in three areas: permitting persistent foot mobile operations as a viable employment option; facilitating distributed operations; and reducing logistical footprint and support requirements.

Operational delivery of forces to distant objectives by vertical means will, in the end, result in the slowing of forces due to increased weight once that force is on the ground. This has the potential impact of creating little “islands” of forces unable to expand beyond a certain

bubble with any thing resembling the tempo envisioned in STOM. However, a force enabled with an exoskeleton would be able to carry the tactical load and remain unsupported for however long is feasible until resupply can be resumed after the surge delivery of forces from the sea base has been reset.⁵⁰ The ability to carry sustainment for greater than a 1 day period and conduct foot mobile operations will provide a level of persistence currently not achievable without a temporary base to cache supplies. Having a mechanical element to augment a Marine's base endurance may also reduce the acclimatization period to new environments and thus restore a persistent capability in a shorter timeframe. A study conducted in 2008 indicated that in current operations, Marines wearing the combat load are already operating well above safe thresholds for heat stress and heat stroke, something an exoskeleton could easily mitigate⁵¹

The wearing of an exoskeleton has the ability to not only restore tempo to foot mobile forces but can provide a realistic calculus to planners on the rate and range of dismounted forces. An exoskeleton would have a mechanical movement rate and battery life that would exist regardless of the load carried, up to the limits of the system.⁵² Distribution of forces and the range they can be separated in time and space to re-aggregate would reach a level of planning certainty that now is attributable to aircraft or vehicles. The ranges for distributing forces in STOM is somewhat nebulous, an exoskeleton enabled force would provide more concrete planning factors.

The impact to logistical sustainment cannot be discounted. Currently the bulk of logistics brought to the force is in the form of water and fuel.⁵³ Dismounted forces needing only limited power generation for batteries would radically reduce fuel consumption and the ability to carry more than one day of supply would eliminate the need for daily water resupply. XOS-type systems powered from a vehicle and used in place of forklifts or working parties could offload

all classes of supply more rapidly thus reducing the numbers of vehicles and Marines required to handle and transport supplies ashore. The cost savings would be fewer vehicles embarked in amphibious shipping dedicated to logistics sustainment. The force protection savings would be in the form of fewer vehicles and numbers of convoys required to support the force. Although the enabling of combat power is the most attractive aspect of the system, logistical savings is by far the most quantifiable and useful to the force.

Conclusion

In 2004, the director of USMC Plans, Policies and Operations (PP&O) Lieutenant General Jan C. Huly sponsored a Universal Need Statement (UNS)⁵⁴ that emphasized the need to begin seriously evaluating exoskeleton technologies. As the UNS attests, the potential is not new but the feasibility of employment has grown exponentially over the last few years. In terms of enabling the future USMC operational vision, overweighting is an unavoidable concern that needs to be addressed now given the lead time necessary for development of this technology. An exoskeleton is not a panacea and will likely still require parallel development with other robotic alternatives to support organizational as well as individual equipment loads.

The exoskeleton is a radically new technology that offers ground forces the potential to influence the fight persistently, over greater range, and more diverse terrain than ever imagined. Enabling foot mobility via this system would be a progression in force employment concepts for the future that would see foot mobile forces operating at a tempo nearly equivalent to aerial and vehicle-borne forces. In the end exoskeletons provide the kind of breakthrough in technology to mitigate loads that has not been achievable with previous lightening and load transfer efforts that will make the future operational and tactical vision of the Marine Corps possible.

Figures

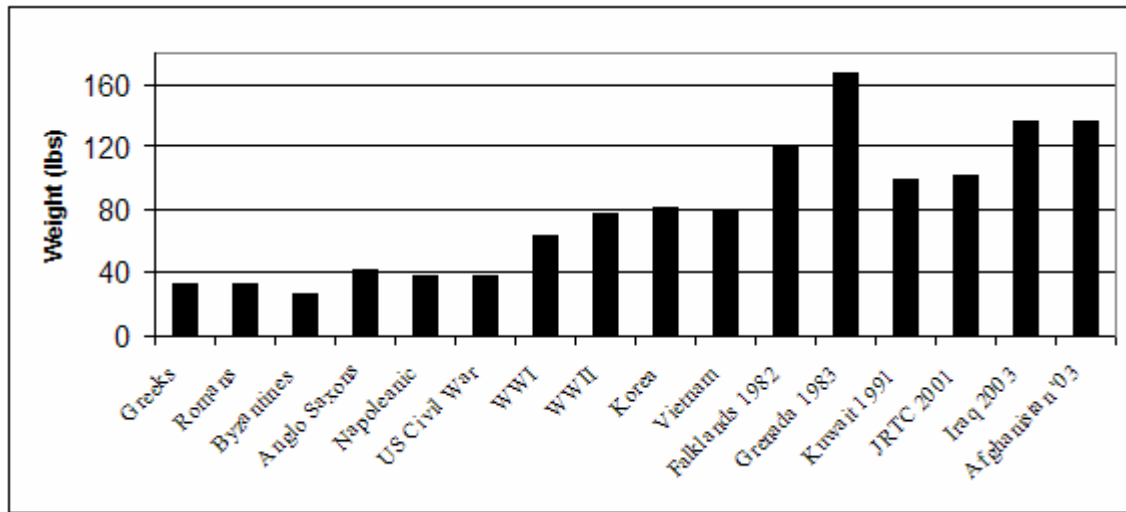


Figure 1. Estimated load weights carried on the march by various infantry units throughout history (modified from Knapik et. al., Ref #21).(Source: Combat Load Report: Marine Corps Combat Development Command, Materiel Requirements Division, Quantico, Virginia 31 DEC 2003

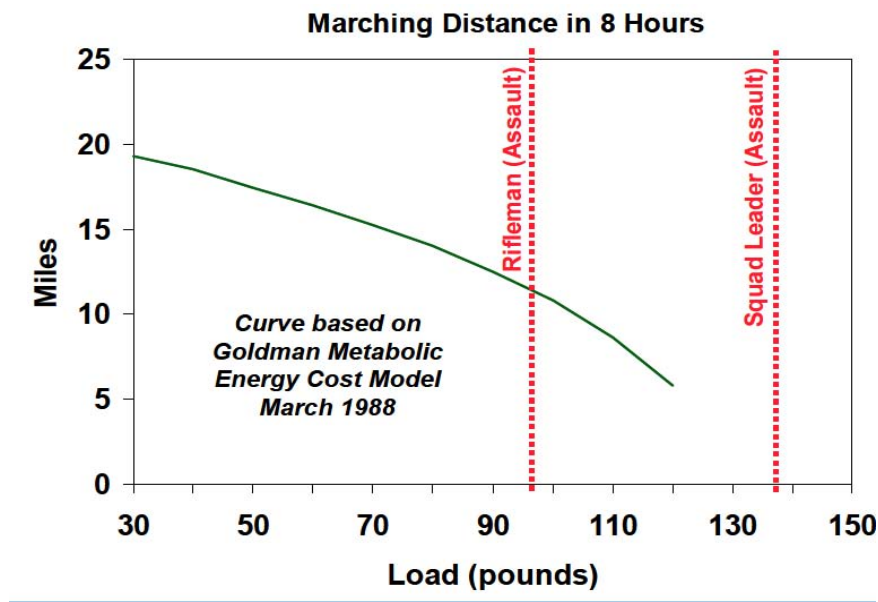


Figure 2. The Figure shows the results of an Army study developed from the Goldman Metabolic Energy Cost Model indicating that as weight increases a soldiers ability to march a given distance over 8 hours is decreased. This study was done on dirt with a 1% grade. (Source NRAC Lightening the Load Study, September 2007)

Load Description	Recommended Load*	Current Rifleman's Load**
Assault Load (In the Fight) Conduct combat operations indefinitely with minimal degradation in combat effectiveness	50 lb 30% of body wt based on Avg Marine (169 lb)	97 lb 57% of body wt
Approach March Load (Getting to the Fight) Conduct 20-mile march within 8 hours maintaining 90% combat effectiveness	76 lb 45%	123 lb 73%
Existence Load Limited movement within confines of transportation platforms and limited marching from landing zone into secure area	127 lb 75%	167 lb 99%

* MIL-STD-1472F

** Information received from MCCDC, Quantico

Chart 2 Marine Rifleman Loads

Figure 3. The Figure shows the comparison between recommended weights for various load types based on the average weight of male Marine and those actually carried in combat. (Source NRAC Lightening the Load Study, September 2007)

Weight Category	Actual	Objective
Total Static Weight (lbs)	8.408	8.408
Total Approach March Load (Approach march load + assault load + static load)	124.97	76.100
Total Existence Load (Existence load + approach march + assault + static loads)	166.936	126.800
Individual Assault Loads		
Assault Load Rifleman	97.334	50.700
Assault Load Automatic Rifleman	117.565	50.700
Assault Load Asst Automatic Rifleman	114.234	50.700
Assault Load Fire Team Leader	132.499	50.700
Assault Load Squad Leader	134.729	50.700
Assault Load Corpsman	97.814	50.700
Assault Load Machine Gun Team Leader	119.284	50.700
Assault Load Machine Gunner	125.314	50.700
Assault Load Asst Machine Gunner	150.734	50.700
Assault Load SMAW Gunner	125.334	50.700
Assault Load Asst SMAW Gunner	110.43	50.700
Assault Load Javelin Gunner	145.134	50.700
Assault Load Asst Javelin Gunner	167.334	50.700

Figure 4 The Figure shows a more comprehensive table of the comparison between recommended weights for the assault load alone based on the average weight of male Marine and those actually carried in combat. (Source FMID Combat Load Report, April 2007)

Category	~ Individual Weight Savings
PPE – Advanced Materials (nanotechnology)	4 to 6 lb
Weapons and Ammo – Caseless Ammo and Lightweight Weapon	5 lb
Integrated Optics	3 to 7 lb
Overall Marine Systems Integration	2 lb
Advanced Batteries	1+ lb

Possible Savings of ~ 10 to 20 pounds per Marine(~300 per squad but would still be ~ 600 pounds overweight)

Chart 7 Reducing the Weight: S&T Forecast

Figure 5. The Figure shows the possible future weight savings for an individual Marine based on current S&T efforts. (Source: NRAC Lightening the Load Study, September 2007)

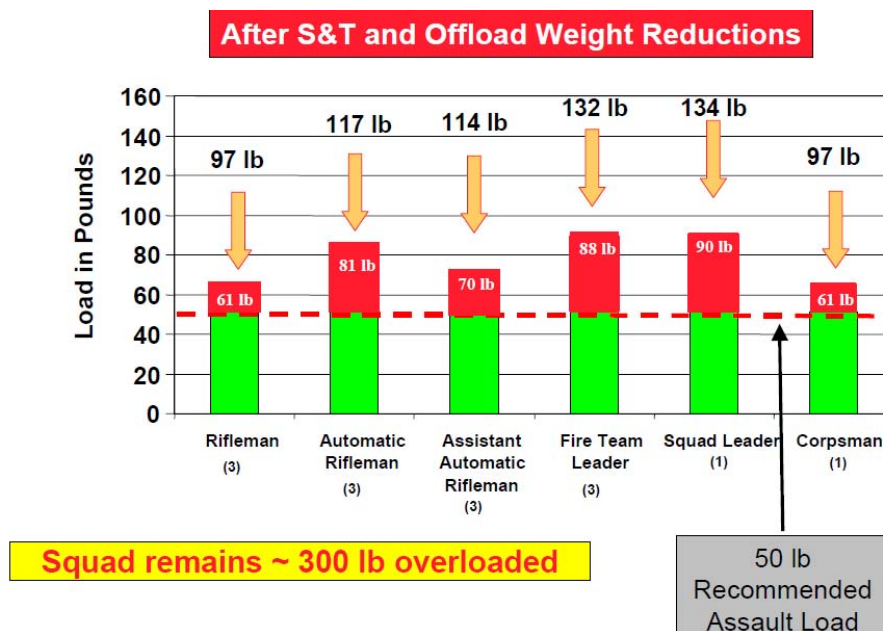


Figure 6 The Figure shows the possible future weight savings for an individual Marines by billet within a rifle squad based on current S&T efforts for an assault load. (Source: NRAC Lightening the Load Study, September 2007)



Figure 7 The Figure shows the evolution of military exoskeleton technology. From left to right: 1963 General Electric/Office of Naval Research HARDIMAN project, The Berkely Bionics/Locheed Martin HULC, and the SARCOS Labs/Raytheon XOS. HULC is a lower body exo design to support roughly a 10:1 ratio carrying capacity, is battery powered, and performs assisted walking and load transfer through the skeleton to the ground. XOS is a full body design for strength augmentation that currently supports roughly a 25:1 ratio and is powered from a tethered source. HULC supports an infantry-type mission and XOS is envisioned for rear area support for such tasks as heavy lifting, powered tools, and repetitive load tasks. (Source: Dollar and Herr article, HULC product card, U.S. Army Natick Labs)

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Endnotes

¹ Col J.F.C. Fuller, *The Foundations of the Science of War*, London, Hutchinson and Co (Publishers) Ltd, 1926 pg 102

² The Marine Corps Vision and Strategy 2025 indicated in the strategy section several key areas of focus, key among them are efforts on force optimization and modernization that address issues of right-sizing and weight to meet the objective force design for the future. **“Strategy statements:** Retain nation’s force in readiness capability. We will be: **Optimized** to conduct naval expeditionary operations while retaining the institutional agility, battlefield flexibility, and initiative to meet constantly changing conditions of war. **Modernized** with equipment and logistics that expand expeditionary capability and preserve our ability to operate from the sea.” Conway, Gen James T., *Marine Corps Vision and Strategy 2025*, HQMC, Washington, DC, 28 August 2008. Pg 14

³ For an enlightening and entertaining discussion on the increases in load associated with adding numerous “light weight” components to an expanded individual combat equipment suite see CWO4 Jeffrey L. Eby, *It Is Time for the Exoskeleton*, *Marine Corps Gazette*; Sep 2005, 76-79.

⁴ *Combat Load Report*, Marine Corps Combat Development Command, Materiel Requirements Division, 31 Dec 2003, pg 1

⁵ Gen Charles C. Krulak, *MCDP-1 Warfighting*, Headquarters United States Marine Corps, Washington, D. C., 20380, pg 72-73

⁶ *Ship-to-Objective Maneuver Concept of Operations (Draft)*, Marine Corps Combat Development Command, Quantico, VA 30 April 2003 pg 1-2

⁷ *Ship-to-Objective Maneuver Concept of Operations (Draft)*, pg 1-3

⁸ LtGen Paul K. Van Riper, *Ship-to-Objective Maneuver*, Commanding General, Marine Corps Combat Development Command, Quantico, VA 25 July, pg II-7-II-9.

⁹ Gen Michael W. Hagee, *Concept for Distributed Operations*, HQMC, Washington, DC, 25 April 2005.

¹⁰ Hagee, *Concept for Distributed Operations*, pg I

¹¹ Hagee, *Concept for Distributed Operations*, pg II & VI

¹² Gen James T. Conway, *A Concept for Enhanced Company Operations*, HQMC, Washington, DC, 28 August 2008, (*December 2008 Gazette*) pg 56.

¹³ Conway, *A Concept for Enhanced Company Operations*, pg 58

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- ¹⁴ Conway A Concept for Enhanced Company Operations, pg 59
- ¹⁵ Conway A Concept for Enhanced Company Operations, pg 61
- ¹⁶ Conway, Marine Corps Vision and Strategy 2025, pg 19
- ¹⁷ Marine Corps Warfighting Lab has conducted several ECO related Limited Objective Experiments(LOE) namely such programs as Combat Hunter, Company Level Operations Center, and Company Level Intelligence Center. For complete documents on these LOEs and equipping efforts see <https://www.mcwl.quantico.usmc.mil/xfiles.cfm> in X-Files and AAR sections, as well as results within the Experimentation Division.
<https://www.mcwl.quantico.usmc.mil/experimentDiv.cfm>.
- ¹⁸ One example of the many after actions and lessons learned regarding the incremental development of the ECO-enabled company is Enhanced Company Operations Lessons and Observations from OIF, 2008. This MCLL product reviewed results from three battalions deployed in OIF and covered topics such as logistics, patrolling, CLOC and CLIC operations, size of AO's, etc. Enhanced Company Operations Lessons and Observations from OIF, 2008, Marine Corps Center for Lessons Learned, Quantico, VA 5 Oct 2009.
- ¹⁹ Enhanced Company Operations Lessons and Observations from OIF, 2008, Marine Corps Center for Lessons Learned, Quantico, VA 5 Oct 2009. pg 2 & 9
- ²⁰ Flynn, LtGen George J., Evolving the MAGTF for the 21st Century, Commanding General, Marine Corps Combat Development Command Deputy Commandant for Combat Development and Integration, Quantico, VA 20 March 2009, pg 11
- ²¹ LtGen George J. Flynn, Evolving the MAGTF for the 21st Century, pg 7
- ²² Lightninging the Load January - September 2007 NRAC 07-02, Naval Research Advisory Committee 875 North Randolph Street Arlington, Virginia 22203-1993, pg ES-1
- ²³ Lightninging the Load, pg ES-1
- ²⁴ Richter, Mark. "Subject Matter Interview," December 8, 2009. Mr. Richter is the Marine Corps Systems Command Program Manager for PM Marine Expeditionary Rifle Squad. PM MERS is tasked to manage the integration of new equipment within the rifle squad and evaluate its cumulative effect on weight and performance. He is also the Director of Gruntworks Squad Integration Facility which focuses on human factors, ergonomics, and a systems engineering approach towards weight reduction and balanced loads. He was intimately involved in the NRAC study and provided the impetus for the selection of the rifle squad as the focus of the study.
- ²⁵ Lightninging the Load, pg 13
- ²⁶ Lightninging the Load, pg 15

²⁷ Richter, Mark. "Subject Matter Interview," December 8, 2009. Mr Richter has been using the Gruntworks facility to test Marines' ability to conduct certain combat tasks in a fatigued and non-fatigued state with the assigned combat equipment. The results have not been published but the data to date has shown intuitive results that fatigue is a factor in task accomplishment.

²⁸ Lightening the Load, pg 13

²⁹ Lightening the Load, pg 14

³⁰ Lightening the Load, pg 21

³¹ FMID Combat Load Report, Fires and Maneuver Integration Division, Marine Corps Combat Development Command, Quantico, VA April 2007, pg 2

³² Richter, Mark. "Subject Matter Interview," December 8, 2009. Mr Richter provided similar observations based on field research in Iraq and Afghanistan to the Assistant Commandant of the Marine Corp, Gen Amos, in support of congressional testimony.

³³ Enhanced Company Operations Lessons and Observations from OIF, 2008, Marine Corps Center for Lessons Learned, Quantico, VA 5 Oct 2009.

³⁴ Lightening the Load, pg 18-19

³⁵ Lightening the Load, pg 22

³⁶ Aaron M. Dollar & Hugh Herr Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-Art (IEEE TRANSACTIONS ON ROBOTICS, VOL. 24, NO. 1, FEBRUARY 2008) pg 1

³⁷ Paraphrased from Merriam-Webster Online Dictionary, 2009 available at <http://www.merriam-webster.com/dictionary/anthropomorphic>, accessed 17 December 2009.

³⁸ Hugh Herr, Commentary Exoskeletons and orthoses: classification, design challenges and future directions, Published: 18 June 2009 Journal of Neuro-Engineering and Rehabilitation 2009, 6:21 doi:10.1186/1743-0003-6-21 pg 1

³⁹ Herr, pg 2 & 4

⁴⁰ Dollar & Herr, pg 3 & 4

⁴¹ David Audet, Personal Augmentation HULC & XOS Program Status, U.S. Army Natick Solider RD&E Center, Natick, MA 3 Nov 09, Mr Keith Maxwell Lockheed Martin, Subject Matter Expert Interview, 30 September 2009.

⁴² CAPABILITY DEVELOPMENT DOCUMENT (CDD) FOR EXOSKELETON, SUSTAINMENT VARIANT: Increment: 1 and 2 (Draft), Combined Arms Support Command (CASCOM), Materiel Systems Directorate (MSD), Fort Lee, Virginia 30 January 2009 pg i

⁴³ David Audet, Personal Augmentation HULC & XOS Program Status, U.S. Army Natick Solider RD&E Center, Natick, MA 3 Nov 09; Dr Frazier Smith SARCOS Labs, Subject Matter Expert Interview, 9 December 2009.

⁴⁴ David Audet, Personal Augmentation HULC & XOS Program Status, U.S. Army Natick Solider RD&E Center, Natick, MA 3 Nov 09, slides 10 & 25.

⁴⁵ Dollar & Herr, pg 6

⁴⁶ Marine Corps Mobile Electric Power Study, Marine Corps Systems Command, Quantico, VA 2005, pg i-v.

⁴⁷ David Audet, Personal Augmentation HULC & XOS Program Status, U.S. Army Natick Solider RD&E Center, Natick, MA 3 Nov 09, slides 10 & 25

⁴⁸ David Audet, Personal Augmentation HULC & XOS Program Status, U.S. Army Natick Solider RD&E Center, Natick, MA 3 Nov 09, slide 8; The Effects Of A Lower Body Exoskeleton Load Carriage Assistive Device On Oxygen Consumption And Kinematics During Walking With Loads;, U.S. Army Natick Soldier Center, Natick, MA 01760-5020, USA, 1 Nov 2006 pg 7

⁴⁹ David Audet, Personal Augmentation HULC & XOS Program Status, U.S. Army Natick Solider RD&E Center, Natick, MA 3 Nov 09, slide 18.

⁵⁰ Ship-to-Objective Maneuver Concept of Operations (Draft), Marine Corps Combat Development Command, Quantico, VA 30 April 2003. This STOM CONOPS used a defense planning scenario that conducted an assault by a notional 2015 MEB. The concept of maneuver required delivery of two reinforced battalions by air and two reinforced battalions by surface lift. The MV-22 and CH-53K where the primary assault aviation platforms, whereas the only future surface platform was the EFV. All other vehicles were legacy systems w/o the armored protection found in the current operating environment, so the scenario did not realize the deficiency that is proposed in the later MCCDC documents nor the impact to lift. Weight factors for Marines were also not calculated based on current configurations, but were likely based on legacy tables, numbers of seats available, and gross lift capacity of the aircraft which may or may not be an issue. Delivery of the vertical force was out to 110 nm and was conducted within 8 hours (during the hours of darkness). Planning factors for units ashore was that they would only carry 1 DOS. The scenario did account for some future C2 systems but not all. The MEB projected ashore a vertical TF consisting of 2,153 Marines, 25 LAVs, 16 EFSS, and 170 vehicles using 271 sorties (4 waves) from the flight decks of 3 amphibious ships and 6 MPF (F) ships. At the conclusion of the insertion, only 16% of the vertical lift assets were available for tasking and after one crew rest cycle, only 50% of the assets and half the spots were used to maintain a 24-hour operations capability (day and night ops). Thus three things are obvious from this scenario: 1. Movement of the entire force is not achievable on a constant basis but would be a function of surge operations; 2. Constant resupply would be required based on 1 DOS that would be a problem for the force if a weather event cancelled resupply; 3. It would take a minimum of two

days to reset the force to conduct a another surge operation to lift the forces allocated to the vertical element, even if the vehicles were not a factor.

⁵¹ A U.S. Army Study working with PM MERS at SYSCOM conducted a study of squad patrols in Iraq in the Summer of 2008. The study plotted 157 military heat stroke deaths during training and compared those conditions to the operating environment in Iraq. Units merely donning equipment were already operating in conditions beyond the “Heat Death Line”. USARIEM Technical Report T09-01, Thermal-Work Strain During Marine Rifle Squad Operations in Iraq (Summer 2008), U.S. Army Research Institute of Environmental Medicine, Natick, MA, November 2008 pg 24

⁵² HULC Product Card, Lockheed Martin, 2009 Although numbers vary with each generation, the current generation of HULC advertises a range of 1 hour walk at 3 mph per 4 lbs of batteries carrying a payload up to 200 lbs and can carry front and back loads. The max speed of 7 mph for long duration or 10 mph burst speed is likely configured with a lighter load. Most of the information at this time is competition sensitive and subject to change since these factors will likely be unacceptable for tactical use. Expect that numbers approximating 24 hour duration with an approach load and march times similar to USMC infantry standards would likely become the final requirements if this system were to enter the EFDS cycle.

⁵³ Statistics for MEB-A in Afghanistan produced in August 2009 showed that power generation requirements alone consumed 32% of bulk fuel requirements which for the whole force (Aviation, other, and power) consumed 88,749 gallons of fuel a day. Statistics for water and fuel truckloads provided by CLB-8 required 76 truckloads daily of for fuel and 330 truckloads daily for water. Jim Lasswell, Marine Power and Energy S&T Needs, Marine Corps Warfighting Lab, 22 Oct 09, slides 5 & 6.

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