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Exoskeletons for Human Performance Augmentation (EHPA): A Program Summary

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1. Introduction

Exoskeletons have been part of popular culture for many decades [1]. In Starship Troopers, Heinlein envisions troops leaping from building to building, being dropped from orbit and fighting with almost total invulnerability. While this vision makes for good fiction and provides fuel for the creative engine, as engineers we are usually bound by the laws of physics and thermodynamics. We view exoskeletons as the centerpiece of a soldier centric platform. Exoskeletons will enhance a warrior's capabilities, allowing him to be more lethal and survivable. Current limits of human portage will be greatly extended and the exoskeletons will provide power for communications, intelligence, surveillance, and reconnaissance supportive hardware. The exoskeleton program aims to create experimental prototypes that will address, and possibly advance, a number of critical technologies. These technologies are small scale power converters and actuation systems, controls, sensing of human motion and haptic interfaces.

Technology is applied to nearly every facet of warfighting to ensure that our forces are more capable and better equipped than potential adversaries. Technology is applied to nearly every facet of warfighting to ensure that our forces are more capable and better equipped than our adversaries. Technology enables superior capabilities for our armored vehicles, aircraft, missiles, submarines and surfaces ships. However, ground forces are generally equipped as they have always been with provisions and a personal weapon. Modern American ground forces also include other mission enhancing equipment such as body armor, Kevlar Helmets, night vision scopes and communications equipment, and a host of other modern advantages. Nonetheless, direct fire fights which can often results in high attrition rates. The adversary is often fighting on ground of his choosing, can blend back into the local population, and whose logistical supply comes from the local population.

The EHPA program is attempting to increase the capabilities of ground soldiers beyond that of a human. Body armor capable of stopping a 7.62 [mm] assault rifle bullet weighs about 6 lbs per square foot. If a soldier was to cover most of his body with this armor, it would weigh well in excess of 150 lbs. A soldier might be well protected under these conditions, but not mobile enough to be operationally effective. A recent study conducted by W. Brower at Fort Belvior, Virginia, shows that the portage loads for future *Objective Force Warrior* soldiers will weigh between 120 to 190 lbs per man, depending on specialty. The heaviest load is to be born by the anti-tank specialist at 188 lbs. It is the role of the objective force to impede the progress of an adversary's army, before our heavy forces can be amassed. Therefore, reducing the portage requirement for these soldiers, would be tantamount to reducing their weaponry and thus fighting capability, consequently undermining their mission.

Currently, foot soldiers are faced with considerable mental and physical stresses in combat situations. Major causes of physical stresses are the heavy loads most solider carry, as much as 120 to 160 pounds (55 to 73 [kg]) [2] [3]. These loads may have to be carried at a fairly rapid pace, e.g., running about 5 miles (8 [km]) in 2 hours, which the special operations and U.S. Marine Corps reconnaissance soldiers must do. Vehicles are an obvious way to augment human mobility and load carrying ability but they are not stealthy or maneuverable. Dismounted soldiers are still necessary, particularly in

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an urban environment [4]. The operative question then is as follows: can we build a machine to augment human performance and allow a soldier with enhanced mobility, strength, and endurance to go where a dismounted soldier goes?

Previous efforts (e.g., [5][6]) in the development of exoskeleton technology were attempted before a number of critical technology areas were ready for integration. While visionary, work performed by Mosher at General Electric relied on component technology which was not nearly as capable as what is available today. For instance, servo-hydraulic actuators were believed not to have the necessary fidelity and might even pose a danger to the user. These early exoskeletons were envisioned as machines for construction, whose power source would be off-board. A celebrated proposal known as Pitman [7], most closely copied the vision for exoskeleton forces as envisioned by Robert Heinlein in *Starship Troopers* [1]. However, the proposal made little reference as to how the augmentation was actually going to be achieved and where the power would come from. Recent technology developments (e.g., [9]~[15]) such as control architecture, digital controllers and informatics, knowledge of human kinematics may allow researchers to create a machine that is information intensive and operate based on a person's natural motion. It is the goal of the EHPA program to generate untethered machines that will carry their own fuel, power converters and actuation systems on-board.

The five-year Exoskeletons for Human Performance Augmentation program, supported by DARPA, is developing devices and machines to increase the speed, strength, and endurance of soldiers in combat environments. Contractors are developing and demonstrating technologies leading to self-powered, controlled and wearable exoskeletal devices and machines. During the first segment of the program, contractors are developing innovative power generation and actuation technologies. The next technical hurdles will be human/machine interfaces and control algorithms. Successful contractors will then design an integrated exoskeletal device and demonstrate its utility in military applications.

The program defines exoskeletal devices as being mechanical, load-bearing anthropomorphic structures attached to and "worn" by humans. The use of exoskeleton technology in combat could increase the capabilities of the ground-based warfighter and radically alter today's military doctrine. DARPA believes that the technology will extend the mission range of the soldier and increase the lethality and survivability of ground troops during short-range missions and special operations.

There are three critical technological areas that must be advanced in order to create these systems.

1. **Energy, Power, and Actuation:** Highly efficient actuators that can utilize a high density, man-portable energy source in both a safe and quiet manner are being developed. Such field actuation systems will use a minimal amount of fuel or energy per cycle. Methods of transforming high energy density sources into useful actuation power for these machines are also being developed. Energy sources are being integrated with compact, man-portable power generators and new types of actuators to allow for missions initially estimated to be 4 to 24 hours. Mesoscopic and/or microscopic components may be considered for management of fuel consumption or as integral elements of small power and/or actuation systems.
2. **Controls and Haptic Interfaces:** Control approaches that enable direct and seamless human and machine interaction will be devised. Distributed sensors and actuators, MEMS, and other novel components will be employed in the control system to enable this man-machine interface. Novel sensing concepts such as the utilization of neuro-mechanical responses and soft tissue interfaces are also being considered. Controllers that provide robustness and stability under a wide range of human activity are also considered crucial to the system. In particular, to retain solider agility, controller fidelity must be adequate and system bandwidth must be beyond human response bandwidths, 30~50 [Hz].
3. **Design and Integration:** The developed system must be ergonomic and consider a variety of human factors. To the greatest extent possible human agility must be maintained and even enhanced. In addition to being load-bearing, the exoskeletal structure may need to be multifunctional to arrive at an integrated and well-packaged machine architecture.

Fig. 1 Solotrek first test article

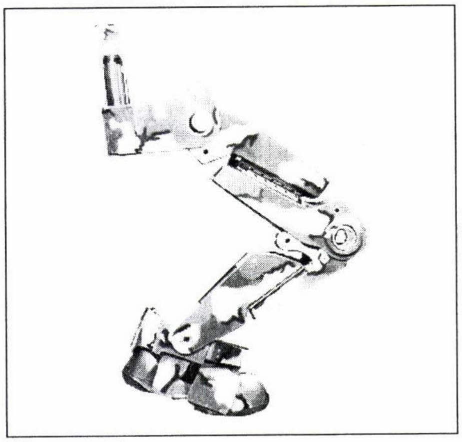

Fig. 2 Sarcos lower limb architecture

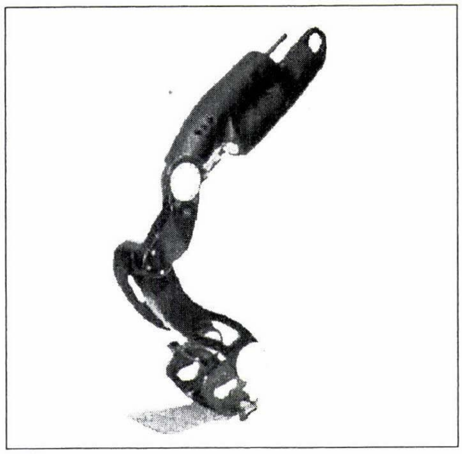

Fig. 3 University of California Berkeley lower limb architecture

2. Exoskeleton Projects

2.1 Exoskeleton Systems

A number of contractors are participating in the EHPA program. Four of the program's contractors are conducting research and development that may ultimately lead to fully integrated exoskeleton systems. These projects all face similar technological challenges in power generation, haptic interfaces, control algorithm development, and actuation systems that must all be integrated into a machine with an anthropomorphic architecture.

1. **Millennium Jet Inc.** (Sunnyvale, CA): MJI is developing "SoloTrek XFV." Millennium Jet will develop a small, one-man vertical takeoff and landing vehicle that will operate on conventional aviation fuel. They have conducted initial free-hover and flight tests of their turbine-powered craft and will deliver a prototype for further evaluation and testing by the military. The vehicle is propelled by two ducted fans and will have a 120-nautical mile range and a top speed of 70 knots. Millennium Jet will demonstrate their test vehicle in 2003.
2. **Oak Ridge National Laboratories** (Oak Ridge, TN): ORNL is developing an "Exoskeleton for Soldier Performance Enhancement." The Oak Ridge team has focused their system development effort on the design of a full-body enhancement system that will use a sodium borohydride-fueled proton exchange membrane fuel cell to drive a system of distributed closed-loop, piezo-hydraulic actuators. Oak Ridge will demonstrate their system, which is expected to weigh approximately 90 pounds and be able to carry 250 to 300 pounds for 24 hours, in 2005.
3. **Sarcos Research Corporation** (Salt Lake City, UT): Sarcos is developing "Wearable Energetically Autonomous Robots." Their concept is a full-body exoskeleton. The system uses a unique combustion process to produce hot gas in discrete and highly controlled amounts. A distributed network of pneumatic type actuators then uses the hot gas to control movement. The Sarcos team plans to demonstrate a fully operational lower extremity prototype in 2003 and a full body prototype in 2005.
4. **University of California** (Berkeley, CA): UC-Berkeley is developing a "Lower Extremity Enhancer." Their effort is concentrating on the development of an exoskeleton to assist the lower extremities. The exoskeleton will use distributed, pneu-

matic actuators powered by a hydrogen peroxide monopropellant; this work is being performed by Vanderbilt University. In two years, the project will demonstrate a completely functional prototype to validate the generalized design architecture and controller methodology. In 2005, the University will demonstrate a fully integrated lower extremity enhancer powered by hydrogen peroxide. As designed, the system will weigh about 50 pounds and be capable of carrying a 150-pound load at speeds of eight miles per hour for 12 hours.

2.2 Exoskeleton Component Technologies

In addition to these full integration efforts, the EHPA program is also supporting several contractors developing innovative power-producing devices. If successful, these technologies would be available for integration into a future exoskeleton system and for a wide variety of other applications needing small power generation systems.

1. **Arthur D. Little (now TIAX, LLC)** (Cambridge, MA): ADL/TIAX is developing a "Chemo-Hydraulic Actuated Power System." They are modifying the methylacetylene propadiene (MAPP) gas-powered hydraulic system now used in commercially available nail guns to produce a MAPP-powered, self-contained, closed-loop hydraulic actuator that will possess high force, large stroke and high bandwidth.
2. **Honeywell** (Minneapolis, MN): Honeywell is developing a wearable, hydrocarbon fuel-based, free-piston engine. The engine, which will run on heavy fuels, will be capable of providing approximately 500 Watts of pneumatic power for exoskeleton systems. Preliminary estimates suggest efficiencies significantly higher than conventionally arranged internal combustion engines.

2.3 Major Milestones and Metrics

A Technology Advisory Board consisting of representatives from the services including Army, Marine Corps, Navy, Special Forces/Special Operations and other government agencies, provides a path for defining specific system requirements and identifying important soldier metrics. Major milestones and metrics have been identified for the program as a whole; these range from demonstration of key component technologies to complete systems.

In FY2002 exoskeleton contractors are demonstrating key component technologies. The particular focus is on integrated, man-wearable power and actuation systems that utilize chemical fuel to directly and efficiently produce mechanical work. Important metrics include power conversion efficiency (3-10X better than existing technology), specific power, specific energy density.

In FY2003 contractors will be focused on developing man-machine interfaces that generate input relevant and appropriate command signals for machines from human neuro-motor responses. Important metrics will include response bandwidth, deadband, and signal-to-noise ratio.

In FY2004 contractors will begin field-testing a machine for augmenting a soldier's load-bearing capability during locomotion. Testing will be aimed at performance metrics to be outlined in more detail in 2QFY04 but will be carried out in terrain simulating environmental conditions in a combat area. Maneuverability and agility performance of an exoskeleton system-equipped soldier will be compared directly to that of soldiers wearing standard combat gear. Important metrics include metabolic energy consumption (L/O2/min, watts), measurement of human force amplification factors, and task performance characteristics such as time for task completion, number of repetitions, sustained performance and accuracy.

3. Conclusions

EHPA contractors are working steadily to achieve the program goals of enhanced physical performance speed, strength, and endurance for soldiers in combat. Preliminary results indicate that the power and actuation technologies being developed will be adequate for the system demonstrations planned for FY2004.

The successful development of exoskeleton systems opens up a broad range of applications for both military and non-military personnel. Military applications include munitions handling on ships and at airfields, field repair of heavy equipment, dismounted solders in urban terrain, among others. Other applications include fire fighting, search and rescue operations in harsh environments (earthquakes and other civil disasters), heavy lift operations in manufacturing, assist devices for the physically handicapped. The portable power technologies being developed in this program also have a variety of applications beyond that of exoskeletons

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References

[1] R. Heinlein: Startship Troopers. Putnam, New York, 1959.
[2] F. Vizard: "Future Soldier," Popular Science, pp.42–47, 2000.
[3] S.I. Erwin: "Lighter Load Is Cyber-Soldier Dream," National Defense, pp.11–13, 1999.
[4] R.F. Hahn II and B. Jezior: "Urban Warfare and the Urban Warfighter of 2025," Parameters, pp.74–87, 1999.
[5] S.J. Zaroodny: "Bumpusher—A Powered Aid to Locomotion," Army, Aberdeen Proving Ground, Ballistic Research Laboratories, Technical Note, no.1524, p.40, 1963.
[6] GE Company: "Exoskeletons prototype," final report on Phase I, Rep. S-67-1011, Schenectady, NY 1966.
[7] R.S. Mosher: "Handyman to Hardiman," SAE Rep. 67-0088.
[8] J.A. Moore: "Pitman A Powered Exoskeleton Suit for the Infantryman," Los Alamos National Laboratory, LA-10761-MS, UC-38, p.16, 1986.
[9] H. Kazerooni: "Human–Robot Interaction via the Transfer of Power and Information Signals," IEEE Trans. On System, Man and Cybernetics, vol.20, no.2, 1990.
[10] S.C. Jacobsen, I.D. McGammon, K.B. Biggers, and R.P. Phillips: "Design of tactile sensing systems for dextrous manipulators," IEEE Control Systems Magazine, vol.8, Issue: 1, pp.3–13, 1988.
[11] J.F. Jansen: "Apparatus and Methods for Human Extender"; Patent no.: US 6,272,924 B1.
[12] JPL: "Exoskeleton System for Neuromuscular Rehabilitation," NASA Tech Briefs, pp.62–63, 1999.
[13] S.vL. Henkel: "Building a Smart Prosthetic Leg," Sensors, pp.32–33, 2000.
[14] M. Mecham: "Ames Researchers 'Land' 757 With Nothing But Muscle," Aviation Week and Space Technology, p.51, 2001.
[15] M. Barinaga: "Turning Thoughts Into Actions," Science, vol.286, pp.888–890, 1999.

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