Emerging Technologies

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ABOUT THIS REPORT

This report, the fifth in the *Super Soldier* series, covers findings of the Center for a New American Security's study on dismounted soldier survivability. This report is in response to a study conducted for the Army Research Laboratory to identify future concepts and technologies to improve soldier survivability and effectiveness over the next 20 to 30 years in order to identify high-payoff science and technology investment areas. While the primary audience for this report is the Army science and technology community, the report's findings and recommendations may be of interest to a broader group of stakeholders, including across the Army, the Joint Force, and the wider defense community. The full series can be found at www.cnas.org/super-soldiers.

Views expressed in this report are of the authors alone. CNAS does not take institutional positions.

EXECUTIVE SUMMARY

Changing the Survivability Paradigm

In World War II, being an infantryman was the third deadliest job in the American military, behind bombardiers and submariners. In the years since, technology has enabled the creation of stealth bombers and submarines, yet the infantry remains a deadly job. Eighty percent of all American casualties since World War II have been in the infantry, a community that makes up just 4 percent of the force.[1] One factor that has slowed improvements in infantry soldier survivability is the fundamental weight-carrying capacity of a human. Modern technology can improve survivability in aircraft and submarines because the platforms themselves can be redesigned to accommodate enhanced survivability measures. Bombers and submarines have grown in size without sacrificing mobility. The B-2 bomber, for example, is more than twice as heavy as the World War II era B-29 Superfortress and has a cruising speed more than 2.5 times as fast. For people, however, the load-carrying capacity is fixed. More weight impedes mobility.

Emerging technologies could potentially change this dynamic by:

- Reducing the weight of soldier equipment, increasing mobility;
- Increasing or augmenting soldier strength, allowing them to carry more weight without sacrificing mobility;
- Off-loading soldier weight; or
- Findings ways to improve soldier survivability and performance without adding additional weight.

This study, conducted by the Center for a New American Security for the U.S. Army, examined five disruptive technology areas that have the potential to address one or more of these approaches:

- Novel materials
- Exosuits and exoskeletons
- Robotics
- Lightweight operational energy
- Human performance enhancement

For each of these technology areas, trends and limitations were considered, as well as recommendations for how the Army could capitalize on the most promising opportunities. This report examines the first four disruptive technology areas and includes recommendations for investments to capitalize on the opportunities presented by these technologies. The next report in the *Super Soldier* series, "Human Performance Enhancement," will cover the technology and ethics of human physical and cognitive enhancement to improve warfighter survivability.

Key Findings

- Prospects for dramatically better armor materials are low in the near term, although there are some long-term opportunities for better materials.

- Rigid exoskeleton and soft exosuit proof-of-concept prototypes have already been built and demonstrated in laboratory settings but require further maturation before operational fielding.

- In the near term, joint-specific exoskeletons and exosuits could assist movement and reduce energy expenditure by 5 to 10 percent, improving mobility, reducing fatigue, and increasing survivability.

- In the longer term, rigid exoskeletons are the only technology that has the potential to truly break the "Iron Triangle" that currently limits simultaneous improvements in lethality, mobility, and protection. Exoskeletons could radically transform dismounted soldier effectiveness. Power is a limiting factor, but hybrid gas-electric power solutions may enable suits with operationally relevant endurance for combat applications.

- Robotic teammates can carry soldier gear, conduct rapid resupply, and provide extended situational awareness and lethality for soldiers.
- Robotic teammates also could directly protect soldiers from ballistic and blast threats by using shields or other devices. The increased standoff between the shield and the soldier allows for high-deflection materials, opening up new opportunities in protection materials.
- Autonomy is improving in robotic systems, driven by advances in computer processing, but power is likely to be a limiting factor for the foreseeable future. Robotic systems will still be useful, but their endurance will be limited by power, similar to other dismounted soldier equipment.
- Energy is likely to be a long-term weight burden for dismounted soldiers and a limiting factor for some technologies that can improve protection, such as robotics and exoskeletons.
- Robotic mules to carry batteries or rapid resupply are potential logistical solutions, but are only ways to get more batteries to the field. They manage, but don't solve, the power problem.
- Hybrid-electric power solutions may be promising for large physical systems like robotic teammates or exoskeletons that require the ability to run quietly for short durations.
- There are significant opportunities, and fairly well-demonstrated abilities, to use energy organic to or generated on the battlefield to help power devices, such as solar power or energy capture devices.
- In the long term, radioisotope batteries coupled with thermophotovoltaic cells may be a potentially valuable solution. These may not generate enough energy for power-hungry applications such as exoskeletons and robotic teammates, however.

Recommendations

The Army should:

- Pursue a hedging strategy in armor materials, investing in basic research in the most promising areas such as synthetic diamond or two-dimensional polymers, while continuing to modestly improve current materials.
- Establish an exosuit and exoskeleton development program consisting of prototyping, experimentation, concept development, and research tied to operational performance metrics. The goal of such a program should be to mature exosuit and exoskeleton technologies and concepts, with the aim of transitioning to a lower-body exoskeleton/exosuit acquisition program in 5 years and a full-body exoskeleton acquisition program in 10 years.
- Continue its investments in robotic teammates, such as the Squad Mission Equipment Transport (SMET) program, and autonomous cargo resupply systems in order to reduce soldier load and improve mobility and effectiveness.
- Conduct research into new materials that could provide passive protection from ballistic and blast threats if used onboard air or ground robotic teammates.
- Continue to pursue robotic teammates to extend soldier lethality, situational awareness, and survivability.
- Capture the gains of commercially available energy solutions, such as electric car batteries or structural carbon-fiber power sources, where possible.
- Invest in research that can be quickly integrated for military purposes, such as biobatteries, energy capture, and hybrid electric engines for robotic mules.
- Anticipate that energy will remain a limited resource that the Army has to manage, similar to ammunition or water, for the foreseeable future.

NOVEL MATERIALS

A critical factor in soldier protection is the fundamental building block of body armor: the underlying materials. Progress on better materials has been incremental to date and current trends point to similarly slow progress in the near term. In the longer term, there are promising possibilities in material science that may provide leap-ahead advances in body armor, even if these breakthroughs seem unlikely today.

Current Body Armor Materials

Existing body armor is a system of hard and soft protection. Hard plates are made of ceramics or ceramic polymers, most notably boron carbide and silicon carbide ceramic. While successive generations of hard armor have provided higher quality protection, the plates are heavy. Soft armor is constructed of Kevlar fiber, which is both flexible and strong – five times stronger than steel on an equal-weight basis.[2]

There are three significant properties for materials used in body armor: hardness, toughness, and strength. *Hardness* refers to how much a material resists penetration from an outside force. Diamond is hard, while aluminum is soft. *Toughness* refers to the amount of energy a material can absorb before fracturing. Steel and titanium alloys are tough, whereas ceramics are fragile. *Strength* refers to the amount of force required to change the shape of a material; steel is a strong metal.

There are tradeoffs between hardness and toughness; diamonds, while extremely hard, are fragile. Similarly, there are tradeoffs between strength and toughness. A tough material might be able to absorb a large amount of energy before fracturing but might deform while doing so, which would not be acceptable for body armor.[3] The ideal body armor material would possess high degrees of all three qualities. The underlying material needs to be hard enough to deflect rounds without shattering; it must resist complete deformation while also having the ability to diffuse energy and deform modestly, as the process of deformation results in energy absorption from the ballistic impact. While difficult to find naturally or in a single material, there are ways to achieve the advantages of each property through the use of composites.

Potential Leap-Ahead Materials

Diamond

Diamond has a few qualities that make it an appealing material for future body armor. First, it is incredibly hard. By some estimates, diamond is up to 10 times harder than steel. Additionally, diamond is lighter than many existing body armor materials – an added advantage.[4]

There are significant limitations on the utility of diamond. First and foremost, it is costly. One potential solution is through the growing synthetic diamond market. Synthetic diamonds are currently 30 to 40 percent less expensive than natural diamonds, and can be produced over the course of months instead of years.[5]

Additionally, the quality that makes diamonds appealing – hardness – also serves as a limiting factor with respect to toughness. While diamond can blunt ballistic impact, it is also highly likely to shatter. Further, diamond's hardness can make it restrictive to soldier movement in larger sheets. More promising uses for diamond may be in smaller pieces as components of a larger system or as elements of a composite material, where it can lend hardness without tradeoffs in toughness or strength.

Two-Dimensional Polymers

Polymers are complex molecules made up of simpler, repeated molecular building blocks. Currently, soft body armors are made up of aramids, polyesters, and polyethylenes;[6] however, to date, fibers composed of these materials have proven "insufficient to thwart armor-piercing pistol ammunition," despite offering a high degree of strength.[7] While many polymers exist one-dimensionally in a thread-like structure, two-dimensional synthetic polymers exist in a plane at the molecular level in a sheet-like structure.[8] Two-dimensional polymers, therefore, can be stacked in layers of interlocking sheets, providing high levels of strength.

One promising two-dimensional synthetic polymer is graphene. Graphene boasts a number of valuable properties. It is light, tough, and 200 times stronger than steel while remaining flexible.[9] Structurally, graphene is a single layer of pure carbon arranged in a hexagonal honeycomb lattice.[10] It is the lightest, strongest, and thinnest compound known, with 1 square meter weighing approximately .77 milligrams.[11]

The production of graphene requires a labor-intensive chemical vapor disposition process. This complex process in turn makes high-quality graphene expensive.[12] Therefore, much of the research on graphene's properties has been conducted theoretically, through simulation and extrapolation. In 2014, Rice University and the University of Massachusetts made significant strides by testing graphene with microbullets. The findings were promising: The material was strong and tough, though it did crack radially. This indicates that graphene would best be used as reinforcement within a larger composite system; the scientific team suggested its use in combination with ceramic. Given the incredibly thin and light qualities graphene provides, it would not add undue weight to existing ceramics; 1 million layers of graphene would total 1 millimeter of added thickness.[13]

Commercial uses for graphene may drive further development and potential military application. Graphene is one of the most electrically conductive materials, making it appealing for electronics and cell phone technology. However, battlefield considerations may make this quality a liability; soldiers must be insulated from the conduction of both heat and electricity.

Summary: Novel Materials

While prospects are dim for dramatic near-term improvements in armor materials, there are possible avenues for better materials in the long term. *The Army should pursue a hedging strategy in armor materials, investing in basic research in the most promising areas such as synthetic diamond or two-dimensional polymers, while continuing to modestly improve current materials.* This would allow the Army to position itself to capitalize on any scientific breakthroughs if they occur.

EXOSUITS AND EXOSKELETONS

Exosuits and exoskeletons are one area of research being explored to augment soldier weight-carrying ability, increase ballistic protection, and facilitate the ease and duration of motion. Long envisioned in the realm of science fiction, both exosuits and exoskeletons are advancing technologically and could provide a mid- or long-term option to advance soldier performance and protection. Soft exosuits are the most likely mid-term option, while rigid exoskeletons are a longer-term possibility. As Army researchers Dr. James Zheng and Dr. Shawn Walsh explain, exosuits and exoskeletons are envisioned as able to "overcome human limitations and upgrade the desired functionality and capabilities in such a manner as to allow the soldier significant advances in applied strength, endurance, and protection."[14]

Exosuits and exoskeletons are different applications of the same basic concept, providing mechanical assistance to increase load-bearing capacity, either through transferring load or easing fatigue. Rigid exoskeletons generally refer to a technology that augments human strength while transmitting load-bearing weight. Exoskeletons are already being developed and used for medical applications providing movement assistance. Military exoskeleton prototypes currently range from a full-body suit to a helmet-augmenting shoulder support. Exosuits, by contrast, are not load-bearing but rather aid specific joints to ease routine movement and ideally cause less fatigue, thereby increasing endurance and saving energy. Exosuit prototypes consist of soft suits that strap directly onto the wearer. This provides advantages for military use in the ease with which they can be combined with protective body armor and their ability to fit many body types. Though many exosuits are also powered, they are flexible and lighter than rigid exoskeletons, reducing power requirements.

There are no operable exosuits or exoskeletons suitable for military use in the short term, due largely to the state of the technology and current inability to meet power requirements for battlefield use. However, over the mid- to long term there is no other technology or combination of technologies that has the same potential to directly improve soldier load-carrying capacity and mobility. Current exosuit prototypes have demonstrated the proof-of-concept of reduced metabolic expenditure and merit further exploration and investment for future military applicability. Rigid exoskeletons have been demonstrated in medical applications, providing assistance for individuals with mobility disorders. However, military exoskeletons for dismounted activities will have unique requirements.

Rigid Exoskeletons

The rigid exoskeleton is a hardened external shell worn outside of the body, providing load-bearing assistance to movements. One of the most prominent military prototypes is the Tactical Assault Light Operator Suit (TALOS), conceived and led by SOCOM and being developed collaboratively by the military, private industry, and academia. The Army Research Laboratory is exploring the use of localized passive exoskeletons, such as to support the weight of a more advanced protective helmet.[15] The Army also began testing Lockheed Martin's ONYX lower body exoskeleton in 2018.[16]

The SOCOM TALOS project is explicitly aimed at improving survivability. Admiral William McRaven, then commander of SOCOM, established the TALOS project after a special operator was killed in a raid, leading to a desire to protect the 'first through the door' via an Iron Man-esque protective suit.[17] Despite the use of exoskeletons in medical applications, the needs of a military exoskeleton are different enough that TALOS lacks a non-military parallel and thus will need to be developed almost entirely by DoD. While exoskeletons may be broadly applicable across many parts of the military, SOCOM's current vision for TALOS is for a very specific use case: shielding troops from gunfire when they are conducting high-threat urban operations. Due to its tailored use, this specific exoskeleton system might enable an earlier adoption compared to a multi-mission system. However, significant power issues remain the primary obstacle to achieving an operationally viable suit.[18] The batteries required for sufficient power over a reasonable operational time period of at least several hours are currently too heavy. Internal combustion engines have been explored as an alternate power source, but are too noisy to be used on missions that require low signature. There are also concerns over potential power failures and the implications for the safety of the soldier inside the suit. Other obstacles to execution include control issues and human interfaces. This requires a different control paradigm than current medical exoskeletons, which are designed to aid a paralyzed or weakened person in walking. Military exoskeletons, by contrast, are intended to allow able-bodied individuals to move further and faster, carrying heavier weight. This makes the military control problem more difficult, as the suit should not unduly hamper normal movements.

The current TALOS prototype models are battery-powered hydraulic rigid exoskeletons with a bulletproof outer shell. If developed as currently envisaged, the suit will increase protection by expanding the area of coverage of hard armor relative to current body armor.[19] Additionally, the intent is for the suit to monitor the wearer through advanced medical technology, allowing for a supervisor to note potential risks such as dehydration or low blood sugar. Moreover, the suit could release wound-clotting foam should a breach of the suit occur.[20] Exoskeletons are *themselves* load-bearing, so rather than simply improving the ability to carry the current burden, soldiers could carry more weight while also increasing their mobility. The ability of exoskeletons to dramatically increase load-bearing capacity makes it the only technology with long-term potential to increase protection *and* improve dismounted soldier mobility. In the short term, the 2018 goal for a SOCOM TALOS prototype is aimed at providing proof of concept, which will then hopefully garner further interest and investment, pushing the program past the rudimentary stage.

A soldier demonstrates the Lockheed Martin ONYX lower body exoskeleton. Exoskeletons can assist warfighters in carrying heavy loads over uneven terrain with reduced energy expenditure, allowing greater mobility, reduced fatigue, and improved mission performance. (Source: Lockheed Martin)

Private sector exoskeletons are beginning to expand into industrial applications. Lockheed Martin's unpowered FORTIS suit has reached operability for industrial uses, decreasing user fatigue by enabling heavy tools or loads to feel weightless. Additionally, US Bionics has been pioneering exoskeletons that could prove widely applicable to a variety of applications and potentially be evolved for military use. US Bionics has developed joint-specific partial suits for the back (backX), shoulder (shoulderX), and knee (legX), as well as a full suit (MAX) that combines all three. The suit is intended for industrial applications to aid movement under load and prevent injuries. The suits currently have sufficient power for a full day of work: 8 to 10 hours of use. The price is also fairly manageable, at $3,000 apiece for backX and shoulderX and $5,000 each for legX.[21] In developing these powered joint-specific suits, US Bionics is tackling some of the most difficult challenges associated with exoskeleton technology, including power, control, and human-machine interfaces.

The current state of technology still does not have sufficient power to manage the intense load-carrying capacity that the SOCOM TALOS suit concept requires, covering a user in hard armor. Further research and development is needed before full-body exoskeletons will be feasible for infantry combat away from a reliable power source. Still, these advances represent a major step forward in the necessary technology for dismounted soldier exoskeletons.

Exoskeletons with more modest goals, such as lower-body exoskeletons that are designed simply to increase mobility, reduce energy expenditure, and reduce musculoskeletal injuries, may show more promise in the near term. In 2018, the Army began testing Lockheed Martin's ONYX exoskeleton, which focuses on augmenting the knee joints when carrying heavy loads over uneven terrain. By focusing on joint-specific augmentation, ONYX uses less power than a full body exoskeleton. The current design is able to achieve 8 to 16 hours of operation over realistic terrain.[22] Army officials have said that if the tests are successful, the device could be fielded as early as 2021.[23] ONYX is intended to be a modular system and could later be augmented with hip and ankle actuation and load bearing to transfer to the ground. While a full-body suit along the lines of TALOS may be several years away, joint-specific augmentation may be more feasible in the near term and could deliver meaningful advantages to warfighters in improved mobility and mission performance.

Soft Exosuits

Soft exosuits are another near-term option. Exosuits assist movement, but without the load-bearing skeletal structure of an exoskeleton. The Institute of Electrical and Electronics Engineers (IEEE) describes soft exosuits as "devices that use textiles to interface to the body, and apply joint torques via tensile forces over the outside of the body in parallel with the muscles, utilizing the bone structure to support compressive loads."[24] Thus, while exoskeletons act like an external musculoskeletal system, exosuits merely augment muscles and rely on the user's bones to carry the weight. Leading exosuit prototypes target movement in specific joints. Textile actuators across targeted muscle groups assist movement in order to ease the effort required. The goal of an exosuit is to provide assistance that does not interfere with natural movement so as to be unnoticeable by the wearer, while also preventing any injury from unnatural movement. In this sense, the experience of wearing an exosuit might be akin to stepping on a moving walkway, where the increase in speed and ease of movement does not interfere with one's natural gait and is primarily noticed when stepping back off of the walkway.

Dr. Courtney Webster adjusts the fit of a soft exosuit developed at Harvard's Wyss Institute through the DARPA Warrior Web program. Soft exosuits augment movement, acting as artificial muscles and tendons, but are not load-bearing like exoskeletons. (Source: David McNally/ Army Research Laboratory)

Lightweight and relatively energy-efficient, exosuits are close to achieving net efficiency gains. Initial experiments in soft exosuits have shown they can reduce the metabolic cost of walking by approximately 6 to 10 percent.[25] However, the initial efficiency gains did not offset the weight of the suit itself, which added a 12 to 16 percent metabolic penalty to the user, causing a slight net metabolic penalty. It should be noted, however, that this is with an initial proof-of-concept prototype suit. Exosuit technology is extremely new. Improvements in suit design that increased the suit's performance benefits and/or reduced the suit's weight could result in suits that have a net metabolic savings for the user.[26] One study showed exosuits decrease the power needed to complete physical tasks. While carrying 30 percent of their body mass, subjects showed a 14 percent reduction in metabolic power required to walk while wearing the powered exosuit compared to the unpowered suit.[27] The improvements generated by the use of an exosuit then could be translated into increased mobility or added protection. Thus, there is reason to believe suits can achieve overall net metabolic gain for the battlefield.

Current prototypes weigh 5.5 kilograms, which includes batteries for up to 4 hours of endurance. With an additional 4 to 5 kg of batteries (resulting in a suit that weighs approximately 9 to 10 kg total), an exosuit based on today's technology could achieve several hours of use. This endurance is possible because the energy draw to power the suit is very modest, only 50 to 100 watts on average. If coupled with robotic teammates to carry extra batteries or drones for rapid on-demand resupply, this could tip the scales in terms of energy consumption to make this a viable concept.

In testing exosuit prototypes, there has been a significant variance in the efficacy from person to person. Some may see gains of 15 to 20 percent – after accounting for the metabolic cost of the suit itself – while others may not experience any reduced metabolic cost at all.[28] There is not yet a clear understanding of why this variability exists and whether more tailored suits or training on how to use the suit could improve performance. Additionally, while prototypes have been shown to reduce metabolic expenditure, there is not yet a good understanding about how this increased ease of movement translates to operationally relevant performance metrics, such as weight carried or time to move a certain distance. Exosuits have the potential to increase physical endurance, but further research is needed into how to maximize their utility across different people and tie their effects to operational gains.[29]

Exosuits have several comparative advantages that make them a more likely mid-term option than exoskeletons. First, the soft nature of the suit allows for variability in the size and shape of the operator, making mass procurement or use across different body sizes easier. Exosuit prototypes are fairly lightweight, and their weight will likely decrease with advances in material and battery technology, making their transport as part of the current military load more feasible than a heavier exoskeleton. Finally, their power requirements are substantially less than a load-bearing exoskeleton.

Promising military exosuit prototypes have come from the Defense Advanced Research Projects Agency's (DARPA) Warrior Web program. Initially developed with a focus on the infantry soldier, Warrior Web aims to "increase mobility and decrease the likelihood of injuries."[30] Unlike SOCOM's TALOS, which is a full-body suit with enhanced protection, Warrior Web has designed mobility-improving exosuits that are intended to complement, but not replace, existing soldier body armor. Warrior Web has led to several proof-of-concept prototypes, including from Harvard's Wyss Institute, Arizona State University, and Ekso Bionics.[31] However, operationalizing an exosuit will require further testing and refinement. Current testing has focused primarily on walking over level ground, with some progressing to running. An operationally viable suit will need to be able to assist mobility and reduce energy expenditure in a range of environments, including walking on uneven or steep terrain and in urban environments.

A soldier walks on a treadmill wearing an exosuit developed through the Warrior Web program while researchers at the U.S. Army Research Laboratory measure the soldier's energy expenditure. Exosuits could yield gains of 15 to 20 percent in reducing soldiers' energy expenditure while moving. (Source: Ron Carty/ U.S. Army)

The goal of Warrior Web was to achieve breakthroughs that demonstrate feasibility for further development, rather than to bring exosuits to full maturity.[32] Suit prototypes have demonstrated their potential. Unfortunately, there is not presently any DoD stakeholder moving forward with soft exosuit development following DARPA's initial proof-of-concept demonstration.

Exosuits have some applicability for non-military applications, but DoD will have unique requirements that will necessitate military-specific research and development. Commercial and industrial interests in exosuits appear to be initially focused on increasing load-bearing ability for jobs requiring heavy lifting. This does not necessarily equal the chief interest from a dismounted soldier perspective: increasing load carriage, endurance, and speed when moving long distances under heavy loads across uneven ground or in urban environments. Industrial solutions will likely assist in the advancement of relevant sub-components, such as power, actuation, sensors, human-machine interface, control, etc. This could potentially accelerate the timeline to making exosuits a feasible option for improved soldier outcomes. However, if the Army wants to capitalize on the advances made by DARPA's Warrior Web and develop an operationally viable exosuit, it will need to take ownership over the issue by creating a developmental program with sufficient resources.

Key Technology Development Areas

Although prototypes of both exoskeletons and exosuits have progressed in the past several years, there are some key challenges to be overcome before they can be a feasible solution for military use. Key technology areas for further development include power and control.

Power

While exoskeletons evoke the image of Iron Man, a more realistic portrayal of the limitations of exoskeletons today came in the 2014 futuristic film *Edge of Tomorrow,* when Tom Cruise's character's exoskeleton runs out of batteries and has to be abandoned in a farm field. Presently, the battery technology that exists faces weight issues – in order to provide full-day power, the weight of the batteries needed offsets the current gains provided. These limitations are most severe for rigid exoskeletons, which require significantly more power to operate than exosuits, as they are load-bearing and much heavier. Exosuits are much closer to providing net gains; they are much lighter and thus have lesser battery requirements. Significant improvements in battery technology could provide a critical turning point in the feasibility of both powered exosuits and exoskeletons, but current trends are not progressing at a fast enough rate to enable dismounted combat applications in the next 5 to 10 years. Walsh and Zheng argue that for research going forward, "the need for an efficient, compact power source is arguably the most critical technology gap; advances in sensors, actuators, lightweight structural materials, computer control algorithms, and device design are all fairly mature to make practical advances in powered exoskeletons conceivable."[33] Without such power advances, the weight of the batteries eats up the entire load-carrying capacity of the suits, although the lighter profile of exosuits makes their power requirements much lower.

A small gas-powered engine on an exoskeleton could extend its operational endurance significantly. However, running even a small gasoline engine would significantly increase the noise of the suit, reducing its operational utility. In some settings, the noise of an engine may not be a problem. However, soldiers will need the ability to exercise noise discipline and operate in a relatively stealthy manner, such as when infiltrating to a target. This makes existing gas-powered engine designs not operationally practical without noise reduction. Stealth is not generally an important consideration for small commercial engines, so this is an area that will likely require military investment to mature the technology. There are promising prospects for quieter engines, however. For example, Liquid Piston has developed a novel rotary engine design with reduced noise. Their intended mature commercial design would be a 3-pound engine that generates 3.7 kW of power. The engine would be quieter than comparable piston engines because of reduced vibrations due to the rotary design.[34]

Even a quieter engine may not be sufficiently stealthy for operational use in some settings, such as infiltrating to a target, suggesting that a hybrid gas-electric power system may be the optimal solution. This would allow longer endurance when operating the engine, with the ability to turn off the engine and operate in a quiet battery-only mode for some period of time, possibly on the order of 45 to 120 minutes. Regenerative braking, like that used on electric vehicles, could also mitigate power demands by re-harvesting some of the kinetic energy of the suit to power batteries. Some advancements in technology are required, particularly in reduced noise engines and regenerative braking for exoskeletons. However, there are no fundamental limits that preclude a hybrid power solution that is capable of limited duration stealth when needed.

Control

One particular area requiring further research is the type of control or sensing mechanisms to be used with both exosuits and exoskeletons. The focus of much of the current research and design is confined to movements such as walking and running on level ground. In operational use, the military user must have the ability to perform the full range of combat movement, to include agile shifts in position, loading and firing a weapon, and running with a full pack. Army researchers Walsh and Zheng note there are challenges in ensuring an exosuit does "not become a liability to the soldier wherein it impedes his or her ability to perform critical functions or has significant potential to injure or incapacitate the soldier," particularly with regards to the movement of the head and neck.[35] The ability of a suit to assist the soldier without inhibiting natural movement is critical, and will have to be developed in conjunction with all of the other required elements of soldier protection, such as body armor and weaponry.

Summary: Exosuits and Exoskeletons

Exosuits and exoskeletons are the single most promising technological innovation for improving soldier survivability. The Army today has the ability to equip soldiers with higher levels of ballistic protection covering more of their bodies. The limiting factor is the fundamental weight-carrying capacity of the human body. Improved physical fitness training, nutrition, and even performance-enhancing drugs can improve soldier strength, but cannot fundamentally change this paradigm. Exoskeletons can substantially augment soldier strength, radically improving dismounted soldier effectiveness and survivability. Even modest improvements could have significant advantages in mobility, endurance, reduced fatigue, improved situational awareness, and increased survivability.

DoD has taken some initial steps with exoskeleton and exosuit technology. With its TALOS program, SOCOM is building a rigid exoskeleton prototype, but the levels of funding allocated are likely insufficient given its ambitious goals. Additionally, the Army may have different requirements from SOCOM. The Army's ongoing tests of the Lockheed ONYX lower body exoskeleton are an important positive step toward improving exoskeleton technology, but more could be done. *The Army should establish and fully fund an exosuit and exoskeleton development program consisting of prototyping, experimentation, concept development, and research tied to operational performance metrics. The goal of such a program should be to mature exosuit and exoskeleton technologies and concepts, with the aim of transitioning to a lower-body exoskeleton/exosuit acquisition program in 5 years and a full-body exoskeleton acquisition program in 10 years.*

ROBOTICS

Robotics have seen tremendous advancement in recent years and are already used to enhance soldier survivability on the battlefield. Unmanned aerial vehicles provide valuable overhead reconnaissance and surveillance. Small hand-launched drones like the RQ-11 Raven give squads an organic capability to see over the next hilltop or around the corner, identifying threats ahead of time. Ground robots such as the Packbot have been used in counter-IED roles, providing valuable standoff for troops. Robots can continue to improve soldier survivability in a number of ways. They can off-load weight, improving soldier mobility, and they also can provide additional situational awareness, lethality, and protection for dismounted troops without adding weight.

Robot Mules and Rapid Resupply

Robots can be used to reduce soldier weight by off-loading to the robot part or all of a soldier's approach load. These can come in form of robot "mule" teammates that are integrated with the squad or rapid resupply robotic systems. The Legged Squad Support System (LS3, the joint DARPA-Marine extension of the DARPA Biodynetics Big Dog program) can carry up to 400 pounds of equipment.[36] LS3 has already been tested alongside ground troops and has demonstrated an ability to autonomously move over adverse terrain. Wheeled or tracked robotic systems could carry even more weight. The Army's Squad Mission Equipment Transport (SMET) is a tracked robotic system that can carry up to 2,000 pounds of equipment and has been demonstrated in a wide variety of environments.[37] Two SMET systems could carry the entire load of a platoon: water, ammunition, food, radios, batteries, chargers, and medical equipment.[38]

Noise is a concern for robotic teammates. The SMET system uses a diesel/JP8 engine, and in experiments the noise signature required troops to halt the SMET 1 kilometer from the objective, carrying their gear the rest of the way. Electric systems are quieter, but have shorter endurance.[39] Similar to exoskeletons, this suggests that hybrid gas-electric systems may provide optimum flexibility, allowing for extended endurance operations when noise is not a concern and for stealth operation on final approach.[40]

Rapid resupply drones also could reduce the need for extra batteries, water, ammunition, etc., lightening the approach load. Soldiers are limited in what they can carry, and dismounted soldiers depend on resupply for operations lasting more than a few days. Autonomous robotic systems can reduce the cost of logistics, potentially enabling more reliable rapid resupply. Unmanned (uninhabited) cargo helicopters have already been used in Afghanistan, and both the Army and Marine Corps are developing them for future conflicts. Advances in autonomy are evolving robotics beyond today's burdensome remote-piloting concept to one of autonomous operation, with oversight from humans. The Navy's Autonomous Aerial Cargo / Utility System can scout out unprepared landing sites in the field and land autonomously, under the supervision of ground troops who need no special training.[41] Autonomous helicopters can be significantly cheaper to operate compared to human-piloted ones, as a result of savings in pilot training costs. Consequently, the Army could field greater numbers of systems, building a network of autonomous drones to rapidly resupply troops on demand.[42] If this network was reliable in a contested environment, this could allow troops to operate with fewer supplies on their person, trusting resupply deliveries.

Robotic mule teammates and resupply drones could reduce some or all of the soldier's approach load, but neither of these solutions would reduce the fighting load. The soldier would still need to carry the same amount of fighting gear directly on his or her person. Nevertheless, these improvements could greatly increase soldier mobility and reduce fatigue, improving physical and cognitive performance. *The Army should continue its investments in robotic teammates, such as the Squad Mission Equipment Transport program, and autonomous cargo resupply systems in order to reduce soldier load and improve mobility and effectiveness.*

Distributed Situational Awareness, Protection, and Lethality

Robotic teammates also could increase soldier survivability by augmenting squads with increased situational awareness, protection, and lethality without increasing the weight soldiers carry. Robotic scouts could act as soldiers' eyes and ears ahead of, behind, and around formations, identifying potential threats and cueing them to soldiers before they are imminent. Robots could be the "point man" in a formation; in a movement to contact, the robot should be the one making the contact. Rather than the first person through the door being a soldier in a TALOS-type exoskeleton, it could be a robot designed to be expendable. Just as they are used today to increase soldier standoff from IEDs, robots could be used to increase soldier standoff from a range of possible threats.[43]

Swarms of autonomous, collaborative systems could provide a protective bubble around a squad as it moves through the environment, identifying and responding to threats to create time and space for soldier decision-making. Low-cost mini drones could scout out buildings and tunnels ahead of troops. Autonomous GPS-independent navigation has already been demonstrated using visual-aided inertial navigation.

If outfitted with weapons, robotic systems would also allow for extended lethality, under human control. In experiments, SMET systems were armed with M2 .50 caliber machine guns and M134 7.62mm miniguns. This can significantly increase the organic lethality available to light infantry troops, increasing their survivability on the battlefield.[44]

In addition to increasing soldier survivability through enhanced situational awareness and extended lethality, robotic teammates also could directly protect soldiers with distributed protection. Robotic teammates could provide passive and potentially even active protection for soldiers from ballistic and blast threats. Robotic teammates could provide mobile cover for ground troops, carrying shields to block bullets and shrapnel. The SMET concept includes designs with transparent ballistic shields to provide soldiers with mobile covered firing positions.[45] Robots could even autonomously respond to threats in the environment to rapidly position themselves between soldiers and likely threats, like Secret Service agents moving to protect a high-value asset.

Because backface deformation would not be a concern, shields carried on robotic systems could be made of more flexible high-deflection materials. This could open the door to new, lightweight, and/or transparent armor materials.[46] Some researchers have also suggested concepts for passive protection from blast pressure waves, such as sponge-like membranes that could collapse to absorb the pressure wave.[47] *The Army should conduct research into new materials that could provide passive protection from ballistic and blast threats if used onboard air or ground robotic teammates.* Active protection may even be possible, with robotic systems sensing and intercepting threats.

These capabilities are not far off, and while engineering challenges remain, robotic teammates like SMET have been demonstrated in experiments. An Army briefing to industry outlined a bold vision:

> a rifle company equipped with SMET vehicles could have an organic combined arms capability that is revolutionary, including: a "micro tank" with a [remote weapon system] and a coaxially-mounted Javelin; precision indirect fire from a 120mm mortar with a GPS-guided projectile; and a tethered UAV that could provide [intelligence, surveillance, and reconnaissance] and comms-relay for days. A light infantry company commander will have an unprecedented amount of organic combined arms combat power.

Because the SMET is relatively lightweight, this expansion of light infantry combat power has major strategic effects on rapid responses to crises. The briefing further elaborated:

> A single C-17 can deliver a dismounted combined arms company anywhere in the world. This combat unit will be able to fight and maneuver for three days, without any need for resupply. This unit will have a significant overmatch against dismounted opponents, and it will be able to hold its own against many heavier units.

A continued program of experimentation and iterative technology development, in tandem with warfighters, could bring these capabilities to maturity. *The Army should continue to pursue robotic teammates to extend soldier lethality, situational awareness, and survivability.*

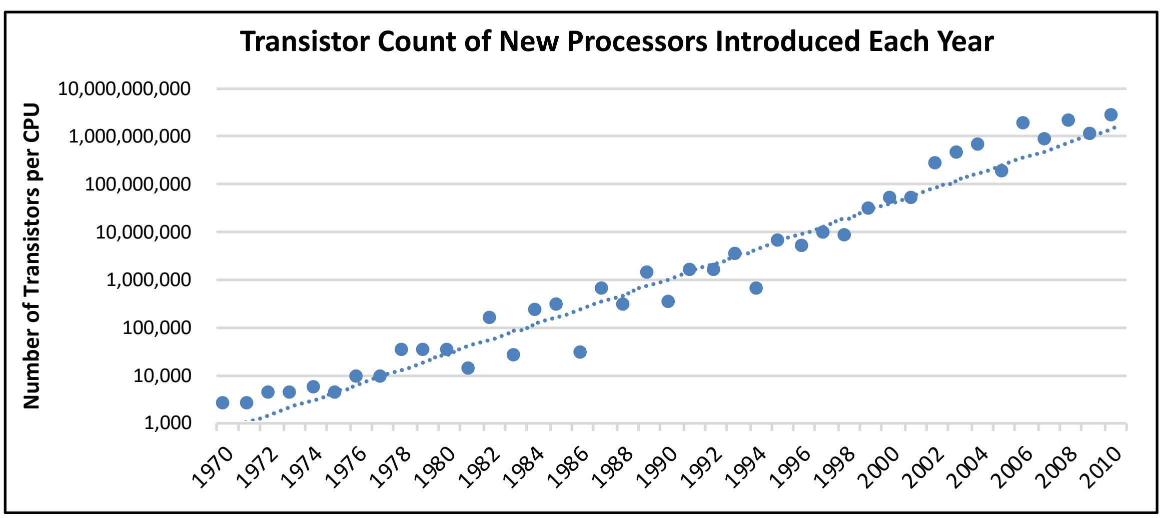
Technology Trends and Limitations

Autonomy

Aerial drones are capable of fully autonomous operation with today's technology. Commercial off-the-shelf drones can follow GPS-designated paths and can even track moving objects.[48] Commercially available drones also have begun to incorporate rudimentary collision avoidance capabilities.[49] Small aerial drones could autonomously follow a squad, maintaining a given distance from the formation. Researchers have also demonstrated autonomous indoor navigation in GPS-denied environments, allowing soldiers to send drones ahead to scout inside buildings.

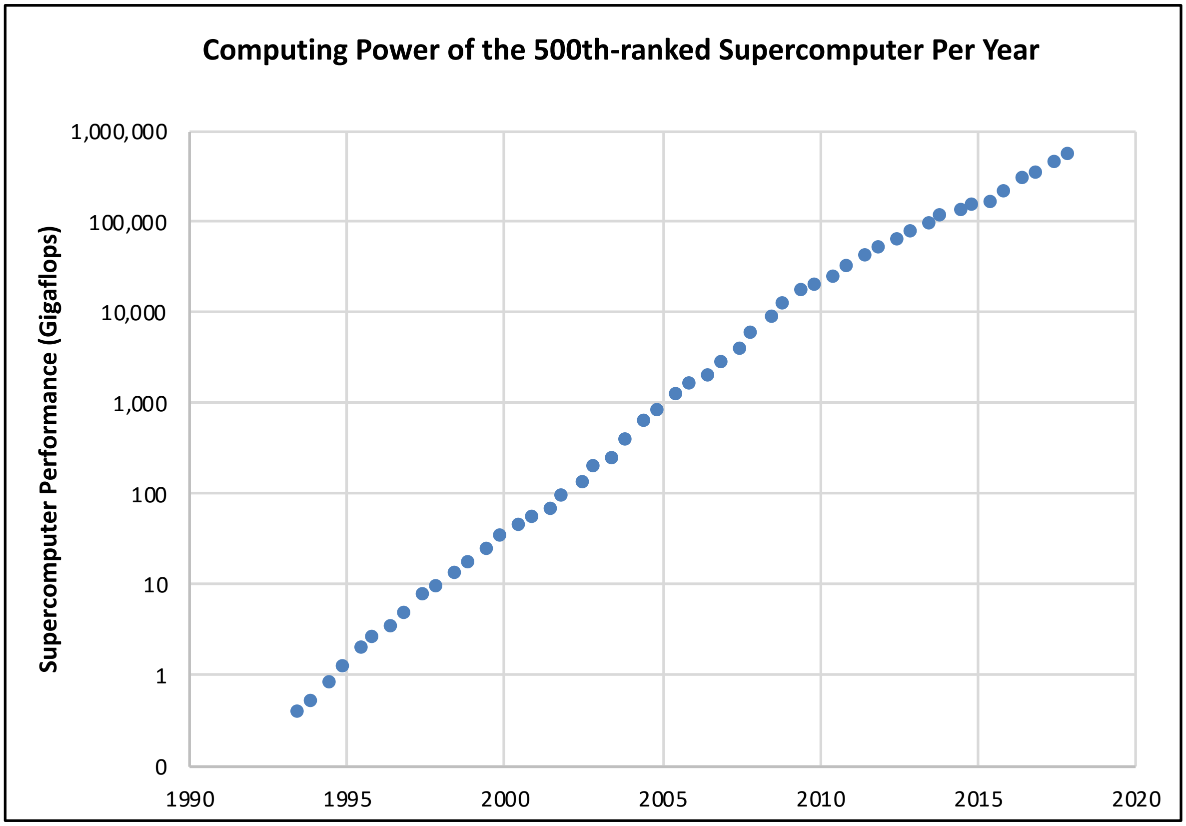
Autonomy is more challenging for ground robotics. Moving on the ground requires navigating more obstacles, including objects like potholes and foliage that are difficult for today's sensors. Autonomous cars have the benefit of navigating on roadways that have been thoroughly mapped; Army ground robots will have no such luxury. Teleoperated systems are possible today, and while simple "follow me" autonomous operation is feasible, the sensors required to do so reliably and safely are expensive. The autonomous applique kit for the SMET system costs more than the platform itself.[50]

For the past several decades, computing trends have favored more advanced processing power over time. Increased computer processing power enables improved sensing, understanding the environment, and autonomous decision-making. The number of transistors per central processing unit (CPU) of an integrated circuit has been increasing exponentially, according to "Moore's Law."



(Source: "Transistor Count," Open Access, OMICS International)

Experts predict that this pace of advance will slow in the next few years as transistors reach a fundamental atomic limit.[51] Indeed, this slowdown can already be seen in the world's top supercomputers. In recent years, the rate of increase of supercomputer power has slowed.



(Source: Top 500, www.top500.org)

However, even as computing growth slackens from its breakneck pace, we are still likely to see significant improvements in the coming decades. New artificial intelligence (AI) methods such as deep learning neural networks have shown startling advances, solving seemingly impossible AI problems such as object recognition and speech recognition.[52] Modifications in chip design, such as chips tailored to specific algorithms and functions, could optimize hardware, and software will continue to improve as well.[53] These advances are likely to enable ever-more sophisticated autonomous sensing and decision-making, even in complex and chaotic combat environments. If current trends continue, many problems in autonomy that seem insurmountable today are likely to be solvable – and potentially at a reasonable cost – in the coming years.

Power

Power, on the other hand, is likely to remain a limiting factor for robotic systems for some time. Larger systems, like SMET, can use internal combustion engines, although these are noisy. Smaller systems, such as small ground scout robots or aerial mini drones, are likely to use battery power. Batteries are improving, but at a much slower rate than computer processing power. One solution for smaller systems could be an SMET-like "mothership" that acts as a charging station, recharging the smaller robotic systems. Robotic systems will still be useful, but endurance will be a limiting factor and require a heavy burden in batteries or other power solutions.

Summary: Robotics

Robotic systems have tremendous potential to improve dismounted soldier survivability. Robotic teammates can carry soldier gear, conduct rapid resupply, and provide extended situational awareness and lethality for soldiers. Robotic teammates could also directly protect soldiers from ballistic and blast threats, by using shields or other devices. The increased standoff between the shield and the soldier allows for high-deflection materials, opening up new opportunities in protection materials. Autonomy is improving in robotic systems, driven by advances in computer processing, but power is likely to be a limiting factor for the forseeable future. Robotic systems will still be useful, but their endurance will be limited by power, similar to other dismounted soldier equipment.

LIGHTWEIGHT OPERATIONAL ENERGY

A significant limiting factor to reducing the soldier's load is the weight of energy required by battlefield technology, especially as new technologies often add to the weight carried. As SLA Marshall observed, technology has not decreased the soldier's load over time. The basic requirements of combat remain largely the same – weapon, ammunition, water – but the modern soldier carries enablers that add weight and require power, such as radios, laptops, GPS devices, and night vision. Further, emerging technologies that improve survivability, such as exoskeletons, robotic teammates, augmented reality capabilities, and microdrones, all require power.

Decreasing the energy component of the soldier's load could be achieved by increasing technology efficiency or decreasing the weight of the energy sources themselves. Eliminating the need to carry batteries, even for existing equipment, also would substantially decrease the soldier's load. At present, soldiers carry approximately 3 to 5 pounds of batteries for an 8-hour mission, but this could extend to 15 to 20 pounds for 72-hour missions without resupply.[54] A multi-day dismounted mission could require over 1,400 pounds of batteries for a company of 150 soldiers.[55]

Batteries Carried on a 72-Hour Mission

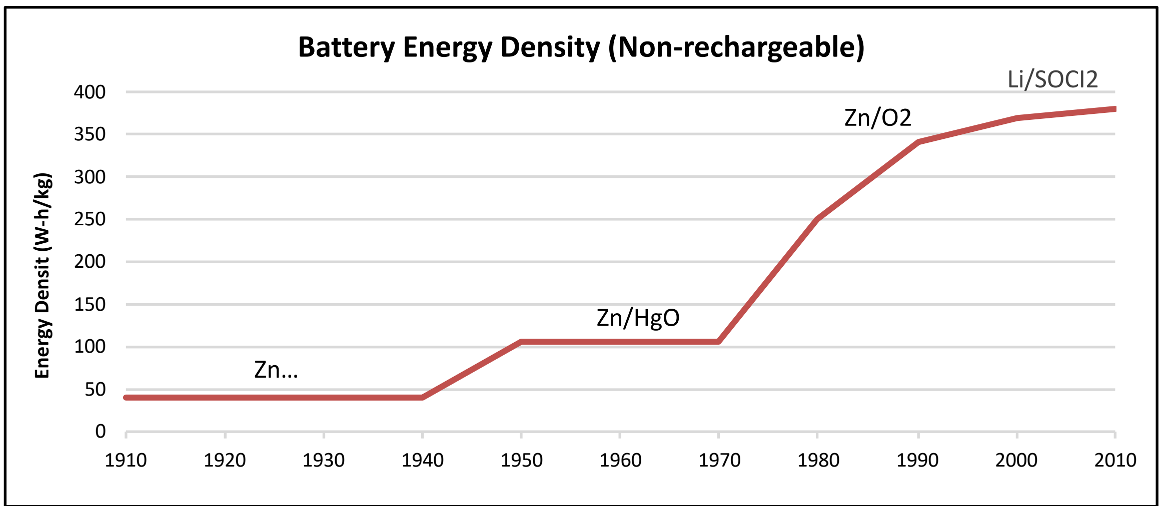
Energy is a significant fraction of the soldier's load. Soldiers can carry up to 16 pounds of batteries for a 72-hour mission. (Source: U.S. Army)

Options to Lighten Energy Load

There are a number of options to lighten the energy load soldiers carry, including longer-lasting batteries, novel power solutions, renewables, and energy capture.

Reliably extend battery life

Unlike the major advances in computing capabilities in recent decades, batteries do not appear to be on the cusp of major transformations. The technologies differ, as batteries face a physical limit to capability increases: The process of charging is a liquid material traveling from one pole to the other, which is then released over the battery's lifetime. Due to chemical constraints on improving this process, the rates of achievable gains do not keep pace with the high rates associated with Moore's Law for improved computing.[56] In fact, the observable decrease in battery size and the weight of everyday electronic devices comes from more efficient computing in the items themselves, rather than major advances in battery performance. This is welcome, but does not address the challenging weight and power issues plaguing the dismounted soldier.



Battery storage capacity has improved with each successive generation, but not by the orders of magnitude seen in computers. The pace of gains has diminished in recent years. (Source: Data from Chen-Xi Zu and Hong Li, "Thermodynamic analysis on energy densities of batteries," Energy and Environmental Science, 2011, 4, 2615.)

Battery development has made gains in recent years for non-military applications, such as the electric car industry, which has translated into improved batteries in the hands of warfighters. In the late 1990s, General Motors produced the EV1, the first mass-produced electric car. It used 600 kg lead-acid batteries that permitted a driving range of only 70 to 90 miles.[57] Today, Tesla's electric cars use lithium-ion batteries that are much more efficient. The top-line Model S has a range of over 300 miles, a threefold increase.[58] However, the difficulty of battery development and high efficiency of existing lithium-ion batteries means there are not substantial gains to be easily found. Those in the industry, such as Tesla's CEO Elon Musk, have lamented the slow pace of battery improvement. "We'll love it if someone comes up with a better chemistry," Musk has said.[59] But the hope for a reliable charge and durability over time without diminishing performance has not materialized. Musk has said he hears word of a new development every week, but that battery inventors "are big on promises and short on delivery."[60] Rechargeable batteries must stand up to complex challenges: quick charging, consistent power, high numbers of charge cycles without substantial battery degradation, and safe operation.[61] Today, the Army has switched to using lithium-ion batteries that are rechargeable and lighter, a significant improvement over 2003 when 90 percent of batteries used by soldiers were not rechargeable, resulting in many being discharged earlier.[62]

The significant cost of research and difficulties in improving reliability limit major battery advancements. Intel has backed a battery technology called Prieto, a type of lithium-ion battery with interlocked poles. This change to the cathode and anode speeds charge times.[63] The energy storage capacity of other battery materials, such as silver-zinc, is higher, but these alternative materials remain costly without investment.[64] Most successes have not been based on huge breakthroughs, but on minor changes. Tesla's work with battery maker Panasonic has spurred incremental changes that have led to an approximately 50 percent reduction in cost but a 60 percent increase in energy capacity through slight changes to engineering, manufacturing, and chemistry.[65]

There are many potential alternatives to lithium-ion batteries on the horizon that could lead to incremental improvements. Lithium-air batteries decrease battery price and weight by one-fifth compared to lithium-ion, but the technology is still about 5 to 10 years from maturity.[66] The U.K. government has been looking at lithium-sulfur batteries, which have a higher energy density than lithium-ion, as another possibility to reduce the weight of batteries for dismounted troops.[67]

Novel power solutions

Advancements in nanotechnology may provide novel power options. Thermophotovoltaic systems convert heat to electrical energy. Combined with a radioisotope power source, which generates thermal energy, a radioisotope thermophotovoltaic system could enable small, ultra-long-lasting power sources.[68] As a benefit, this technology also has thermal-masking properties. While a radioisotope source would have tremendous endurance, on the order of years, it would also be relatively limited in power output.

Remote power

Another concept for reducing the soldier's energy load is to remotely power devices from a robotic teammate, which would be a source of energy for the squad. Wireless non-radiative power transfer using magnetic fields could provide low power (tens of watts) over short distances (meters).[69] The robotic teammate could use an engine or batteries as a source of power, depending on the need for noise discipline. The Army's SMET robot mule, for example, can produce over 2 kW of continuous power. Wireless non-radiative power transfer likely would be limited to relatively low-power devices, though, such as night vision goggles, not power-hungry technologies such as an exoskeleton.

Integrated power

Integrated power solutions also could potentially reduce weight by incorporating batteries directly into soldier equipment. New lithium-ion fibers can weave batteries into existing textiles or create new garments capable of charging devices.[70] The technology is still being tested for safety, but 1 square foot of the textile can provide 6.8 watt-hours of power, which can charge a mobile phone for 24 hours.

Similarly, breakthrough carbon-fiber composites with electric performance from embedded lithium-ion can operate as both structural elements and power sources for squad equipment, from rucksacks to robotic mules.[71] Technology prototypes have already been demonstrated for electric vehicles, enabling weight savings. Carbon-fiber is light relative to standard materials – a prototype car trunk lid was 5 kg instead of 13 kg – decreasing the overall weight of the vehicle, further reducing fuel costs for hybrids and increasing range. In a hybrid vehicle test, Volvo replaced the front rally bar with a carbon composite equivalent that also functioned as the battery. This resulted in a 50 percent weight reduction for the rally bar.[72] Transitioning to these composite materials could reduce vehicle weights by approximately 15 percent, which would decrease fuel costs, ease transport to theater, and increase range. This technology could be incorporated into military hardware.[73]

Solar power

Alternatively, rather than bring lighter power sources to the battlefield, soldiers could take better advantage of energy sources available on the battlefield. The Office of Naval Research has developed a Marine Austere Patrolling System (MAPS) consisting of a 9-by-14-inch solar panel and a 3-pound rechargeable battery. [74] This system incorporates multiple solar cells to capture solar energy along a wider spectrum, with the goal of breaking the 50 percent efficiency barrier.[75] Even with perfect efficiency, the amount of solar power captured per square foot and converted to electrical power is fixed, limiting the total amount of power that can be gained. Nevertheless, even modest reductions in the soldier's load from batteries could be very valuable. MAPS's success has been proven – after a four-day operational test, only those Marines with MAPS did not require battery resupply.[76] Further improvements in commercial solar technology could improve efficiency even further. A recent joint venture between Tesla and Panasonic to develop efficient and affordable solar cells[77] indicates the interest in the field.

Energy harvesting

Soldier movement itself is a potential source of power. Like a spring, each movement of a soldier's joints generates energy that can be captured. Canadian company Bionic Power has developed a system that can charge batteries or devices from the actions already taken by soldiers in the field. Their PowerWalk Kinetic Energy Harvester can capture 10 to 12 watts of power.[78] Currently weighing 2.5 pounds, and with a goal weight of under 2 pounds, the device can capture up to 20 watts at higher rates of speed or when loaded up with gear.[79]

Rucksacks can also be modified to capture the otherwise wasted energy of movement, such as the Energy Harvesting Assault Pack. Its springs and suspension help a generator capture the energy produced by the movement of marching, which can be used to charge devices.[80] The pack can be locked in place to stay stable when needed, but when it moves with the soldier, the static load is easier to support,[81] improving agility. With a 50-pound load, walking can generate 12 to 35 watts of energy depending on the pace, and running can generate up to 40 watts.[82] The pack was tested for ergonomics during the summer of 2015 at Fort Benning.[83] Packs used by airborne units in Afghanistan in 2012 generated enough energy ("tens of watts") per soldier to power field radios.[84] Similarly, using regenerative braking in robotic mules or exoskeletons would help recapture kinetic energy.

Biobatteries

Even more exotic energy sources are also emerging, including those turning sweat into energy. A biobattery is a battery powered by organic compounds. During exercise, sugar is converted to energy, which results in lactate, a process called glycolysis. A bandage-type biobattery skin patch can capture the lactate released and convert it to energy to power small devices, such as an iPod, GPS, or health monitoring device.[85] A soldier's sweat can be used to power wearable fitness trackers or potentially small devices like night vision. Biobattery advances also include temporary body tattoos. These 2mm-by-3mm applications also capture the lactate in sweat and can generate half the power needed for a watch.[86] Because glycolysis results from fatigue, those who are more physically fit produce less lactate in their sweat. This could limit the applicability of the technology for service members.

Summary: Lightweight Operational Energy

Radical improvements in energy storage and novel energy solutions are unlikely, but near-term improvements could yield modest but nevertheless valuable reductions in weight. *The Army should capture the gains of commercially available energy solutions, such as electric car batteries or structural carbon-fiber power sources, where possible. The Army should invest in research that can be quickly* *integrated for military purposes, such as biobatteries, energy capture, and hybrid electric engines for robotic mules.*

Far-off and revolutionary changes in battery technology appear to be unlikely. Overall, the state of the field does not look favorable for substantial disruptive innovation. *The Army should anticipate that energy will remain a limited resource that the Army has to manage, similar to ammunition or water, for the foreseeable future.*

CONCLUSION

Modern technology already has dramatically improved soldier survivability through the development of body armor, and other emerging technologies could yield similar game-changing advantages in the future. Of the four technology areas surveyed, the most promising to revolutionize dismounted ground combat troop survivability is exoskeletons, which could allow troops to carry heavier loads and increase protection without sacrificing mobility. Exoskeleton development is significantly under-resourced in the Department of Defense. The Army should invest in exoskeleton research, along with other emerging technologies such as robotic teammates, novel materials, and lightweight operational energy, in order to improve dismounted soldier survivability. The next report in the *Super Soldier* series, “Human Performance Enhancement,” will cover the technology and ethics of human physical and cognitive enhancement to improve warfighter survivability.

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