DESIGN AND IMPLEMENTATION OF MECHANIZED EXOSKELETONS IN THE ARMED FORCES

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Abstract *- Mechanized exoskeletons are a relatively new technology being developed that combines human intellect and machine power achieving higher performance than either could produce alone. A large government backing from the military allows this technology to improve.*

Our research entails the current state of mechanized exoskeletons and the futures of these suits already in the experimental stages. The paper incorporates the mechanical aspects of the current generations of mechanized exoskeletons and the future advancements in this field. The feat of engineering a power source needs addressing along with the mechanical aspects of the machine. Further investigation details the system of sensors and processors integrated with the moving mechanical parts that allow the exoskeleton to function with the body flawlessly.

This breakthrough technology promises better performance, general well being, and overall efficiency for soldiers. The employment of the mechanized exoskeleton is no longer just a dream but is now a reality that has limitless possibilities.

Key Words- Armed Forces, Current Development, Key Problems, Mechanized Exoskeleton, Power Supply

A CALL TO ACTION

"Four men with rifles guard a thick, rusted steel door. Bam! A huge fist pounds against it--from inside. Bam! More blows dent the steel. The hinges strain. The guards cower, inching backward. Whatever's trying to break out is big. And angry.

The door flies open, and a metallic giant bursts through. It looks like a robot but, hidden inside, famed weapons designer Tony Stark maneuvers the mechanical beast. Bullets bounce off the suit, barely denting his armor. He levels the guards with one swat. Outside, he stares down the enemy camp around him, switches on the flamethrowers in his arms, and roasts the joint" [1].

Tony Stark is a single man taking on an entire terrorist organization in the movie Iron Man. In the film and comics this is capable through the use of his suit giving him advanced strength, skills, and protection. While these are grossly exaggerated advantages to a realistic suit the basic concepts of why the military would like to employ mechanized exoskeletons are instilled through the watching of this film.

The wars overseas have shown that improvements in technology give an advantage to the modernized country. This advantage comes in the form of more efficient and safer combatants. With the introduction of mechanized exoskeletons into the military the efficiency will increase due to increased stamina, strength, and communication. In terms of safety the exoskeleton will act as a natural shell to help deflect bullets, and the added benefits of strength and stamina will help to prevent injuries from stress and strain. What was once purely a superhero dream is becoming a reality.

The first known instance of a mechanized exoskeleton came from a horrifying event in 1983. During a malfunctioned parachute night jump for the Airborne Rangers, Monty Reed struck the ground rendering him paralyzed in both legs. Taking an idea from science fiction folklore Monty envisioned LIFESUIT a powered armor that would allow him to walk again. Stemming from this research the military adopted the technology to further their own advancements. [2]

To acquire more perspectives on the suit the government would fund institutions to progress their research through the Defense Advanced Research Projects Agency (DARPA). Current models of these suits are facing some various mechanical and electrical flaws. Two of the major drawbacks in the models are there is not a sufficient power supply for the unit and replicating the ergonomic movements of the human body with mechanical parts.

A WORK IN PROGRESS

The mechanized exoskeleton is in its developmental stages and is still being run through multiple tests to ensure that the suit will be adequate for use in situations that soldiers may encounter. A multitude of developers are involved with the designing of such suits. Three keystone developers imperative to the production include Sarcos, UC Berkley, and Cyberdyne.

Sarcos

Steve Jameson, the founder of Sarcos and the "Willy Wonka of robotics", is responsible for creating the XOS exoskeleton suit. Applying for DARPA money in 2000 Jameson started constructing the XOS. "The first suit, built in 2002, didn't even have power. The Sarcos team constructed it to prove that the exoskeleton would be able to move like we do. Jameson had one of the engineers strap in and try things like kicking a soccer ball, running, climbing into the tight cab of a bulldozer. This helped them determine that they had the right range of motion and the joints in the right places" [1]. Early steps in determining the range of motion of the suit were essential steps in the realization of an anatomically possible suit. With any hindrance of movement advantages of later incarnations would be nullified.

Once movement was deemed possible it was necessary for Sarcos to develop a multitude of sensors that allow for proper interaction with the human pilot. Sensors are essential to an interactive experience between man and machine. Ideally the sensors will be part of a computerized system that feels what the user is doing and initiates the machine to do the work without the user straining.

The next logical step for Jameson was to add the power his original suit forwent. Originally the use of hydraulics was determined to be plausible answer to their strength and movement needs. Upon further review hydraulics could not perform to the quicker tasks that were required along with the power. To solve what one man quoted as the designs "downfall" the team at Sarcos began to inquire upon electric actuators into the XOS. Ultimately Jameson reinvented the hydraulic system to become the only feasible option to power the suit.

Of course the machine cannot reach its true value being plugged into a wall as the current model is. Focusing on the performance of the machine, Sarcos left the problem of power source as their last issue of importance. While there are currently issues with a source of power, Jameson is still certain of a free range device.

Although the suit has not reached the initial potential that was envisioned it was the closest powered exoskeleton to that goal. " As a result, it is the only full exoskeleton the military has moved into the next development stage; Sarcos is now working under a two-year, $10-million Army grant" [1].

UC Berkeley

While Sarcos is currently working on a full body exoskeleton, UC Berkeley has made and now is improving upon a lower extremity suit funded by DARPA. Under the lead of Mechanical Engineering Professor Kazerooni, UC Berkeley has created the first prototype, the BLEEX 1. "BLEEX 1 consists of a pair of hydraulically powered leg braces, more than 40 electronic sensors, a control computer, and an internal-combustion engine providing power from an attached backpack" [3]. By combining these mechanical and electrical components, the suit allows the user to carry 120 pounds while still having the agility of a person not wearing the suit. Although a seemingly complicated device, the suit does not require any "special training to use it" [4].

Albeit, Berkeley is well on its way to meeting the military's expectations of the mechanical exoskeleton there are still design flaws that need to be addressed for the new suit Berkeley is working on, the BLEEX 2. One of the major issues with designing the new suit is creating a hybrid system to power the suit. The original suit ran off of an internal-combustion engine which held a quart of gas producing only fifteen minutes of quality use. To offset the lack of time the suit can operate, UC Berkeley has made the suit easy to take off for when the suit runs out of fuel. This is only a temporary and initial solution to the problem. A long term remedy would be the implementation of a hybrid engine would reduce the weight and noise while increasing the duration of use [3].

In addition to creating a more efficient motor, the system for balancing could be improved. The current model handles the lifting while the pilot provides the balance for the system. The system seems almost unstable due to the sensitivity of the sensors.

Ultimately UC Berkeley wants to enhance the power source, include a balancing system that increases safety measures, and provide a fuller range of motion to the pilot.

Cyberdyne

Another key player in mechanized exoskeletons is Cyberdyne, a Tokyo, Japan based company. This company is creating a suit that was initially "designed to aid people who have degenerated muscles or those paralyzed by brain or spinal injuries" [5]. Cyberdyne's suit is called the HAL-5, short for Human Assisted Limb. This is the fifth generation of suits since Cyberdyne started making them over 10 years ago. Their previous 4 suits have been designed to incorporate the enhancement of the performance of lower extremities. The HAL-5 integrates the upper body and allows the user to lift up to double that of an average human. Lightweight materials have decreased the weight of the suit to increase the machine's stamina. Along with lightweight materials, Cyberdyne implemented the use of Nickel-Metal Hydride and Lithium battery packs in cooperation with several electric motors to allow two hours and forty minutes of full usability. Another improvement that eliminates bulk was the switch from a back pack that contained the control computer and Wi-Fi communication systems to small pouches found on the belt. Two control systems work side by side to control the limbs of the HAL-5. The first system takes in bio-information from the impulses that are sent from the brain to the muscle fibers. When these are picked up by sensors that are attached to the user's skin in various locations they send feedback to the computing systems. The second system allows the hardware to move with the wearer of the suit. This system actually stores data from when the person puts on the suit. [5]. Cyberdyne represents a lower tier design of what DARPA is expecting from Sarcos and UC Berkeley. A ready for market HAL-5 could be a source of inspiration for the US players to use as a template for an increased ability variant of a military grade powered exoskeleton.

PROBLEMS AND POSSIBILITIES

Power Supply

There are currently three feasible options that the suit can use for a viable power supply. Either electric power in the form of a tether or battery pack or a fuel driven engine will be used to supply power to the different mechanical and electronic systems of the suit.

Sarcos's suit operates not by battery or combustion engine, but by a power cord that is connected to a large source of constant electric power. Sarcos uses this system because the suit that they have produced requires great amounts of power to run all necessary processes. Although the suit is bound by a cord to a given range, the suit is not completely useless to the military. A suit such as this can be used for jobs around a military base where power is abundant. An exoskeleton that is powered in this manner is actually the most efficient because the suit receives a constant amount of power and not having to lessen energy output to conserve it. The primary application for the tethered exoskeleton would be lifting jobs, repair, and any other jobs that require continuous muscle endurance. The tethered mechanized exoskeleton is good for around the base jobs but to be more mobile a different type of power source has to be used.

A mobile power source such as an internal combustion engine has proven to be a more desirable option to the military. "Internal combustion engines utilize the high specific energy of gasoline…. to produce compact, lightweight power sources" [6]. Experiments were conducted to develop the lightest and most efficient internal combustion engine for the mechanized exoskeleton. The main method the experimenters used to compare different engine styles was the use of Ragone Plots. "Ragone plots are useful for evaluating the performance of a power unit for a wide range of operation times. They plot the power unit's specific power (power divided by total mass) versus the specific energy (energy divided by total mass)" [6]. By analyzing the Ragone plot one can evaluate the lightest engine based on the power output required for a given application. Based on the Ragone plots the ZDZ-80 HEPU faired the most efficient although being on the heavy side. With an efficiency of 8.1% and a power output of 2.3 kW hydraulic and 220 W electrical the ZDZ-80 weighs 27kg without fuel and only slightly more with fuel, the engine itself is only 2 kg while the other components make up the majority of weight. The engine is driven by "a single drive shaft to power an alternator for electric power generation, a cooling fan for air circulation and a gear pump for hydraulic power generation. This single shaft design elegantly avoids noisy and heavy belt drive mechanisms common in systems comprising many rotating shafts. A hydraulic solenoid valve regulates the hydraulic fluid pressure by directing the hydraulic flow from the gear pump to either an accumulator or to the hydraulic reservoir. The accumulator consists of an aluminum cylinder in which a free piston separates the hydraulic fluid from the pressurized nitrogen gas. A carbon fiber tank is attached to the gas side of the accumulator as reservoirs; the smaller the pressure fluctuation will be in the presence of hydraulic flow fluctuations. A pressure transducer measures the pressure of the hydraulic fluid the controller. A manifold is designed to house both the solenoid valve and filter. A novel liquid cooling scheme utilizes the returning hydraulic fluid itself to cool the engine. The hydraulic fluid from the robot actuators is divided into two paths. Approximately 38% of the hydraulic fluid is diverted to cool the engine cylinders. A heat exchanger removes the heat from this hydraulic fluid before it reaches the hydraulic reservoir and is mixed with the remaining 62% of the fluid" [6]. The power delivered by this engine runs the control computer and its sensors along with a cooling fan to keep the engine at an optimal temperature. The electrical power also helps to regulate hydraulic pressure throughout the lines in the suit in case of engine failure. The engine regenerates power by filtering off a small portion of the hydraulic fluid to cool the system. The filtered off fluid is then brought back into the engine to use one hundred percent of the fluid. This process saves weight and increases efficiency. By decreasing weight and using fluids for multiple purposes efficiency is achieved. These measures ensure the engine to meet DARPA's expectations for use. Internal combustion engines provide a plentiful power supply and can be used to support the system for long lengths of time. While meeting these needs the engine adds excessive weight to the already heavy machinery. To decrease this weight it is possible to refine the materials put into place to dampen the noise, which account for approximately half the weight, with future developments.

Lithium ion batteries may be the complete package for producing powerful, lasting, quiet power supply such as the ones used for the HAL-5 and the Tesla Roadster. The motor in the Tesla Roadster produces torque from electricity and converts the cars kinetic energy upon stopping back into stored electrical energy. Using this system the entire car is propelled to 60 mph from a dead stop in under 4 seconds and can power the car for over 200 miles of use between recharges. The high number of small batteries wired together provides the means of storage [7]. With some simple reworking of a smaller motor with similar battery structure the same system can be used to power an entire suit. Such an motor would provide an equivalent power source as an internal combustion engine while using light weight, quieter components.

In addition to creating more efficient power supplies there are also features that can be implemented to reduce energy consumption. Like the kinetic energy conversion while stopping hybrid cars similar measures could be taken to convert the impact force of walking into stored electrical energy. Along with this conversion it is possible to redesign the gait of the exoskeleton to make use of the momentum of a natural stride. Doing so reduces the energy required for each step. Ultimately these two features along with advances in the power supply and engine of the suits will lead to an efficient, sustainable suit.

Sensory System

Without the suit moving in synchronization with the user the pilot would be able to feel the suit on him and be battling the suit in order to take every step. To combat this issue the exoskeleton must have a network of sensors and computers that is capable of self-recognizing the user's planned movements, transmitting this data, encoding said data to useful information, reading the information to think of how to react, and lastly relaying this reaction to the machine. All of this must be done in the blink of an eye to move in accordance with the pilot. With the primitive technology that was being used upon mechanized exoskeletons first concepts this was deemed impossible. Now with the current trends of increased processing speeds yearly the idea is attainable.

One solution to this is to incorporate force sensors throughout the suit such as those Sarcos implemented. A brief description of a pilot putting their XOS suit to use conveys how this system would react to a user performing a pull down on a weight machine. "The instant he starts to pull down that weighted bar, sensors in each of his hand–grips register changes in torque. Without the exoskeleton's help, the sensors would show that he was trying to pull down about 100 pounds in each hand. But the goal … is to get the … sensors as close to zero as possible" [1]. When one of the force sensors comes into contact with the resistance of a force the suit will respond by exerting the necessary power output into its actuators until the sensors decreases to zero and the user will feel next to no resistance towards his body. Essentially the suit is relied upon to accomplish all the work. "Those hand-grip sensors, along with similar ones in the suit's feet and back, feed measurements to a central processor hundreds and … several thousand times per second. The system runs these reading through a set of equations that governs the position and motion of the suit's arms, legs, and back. It recognizes that [the pilot] wants to bring his hands down and calculates what each artificial muscle in each of the joints needs to do to make the suit mirror him" [1]. With this system the suit actually instructs the mechanical components to hold the weight at the instant that the user planned to manage the weight himself. Placing the sensors in the hands, feet, and back strategically isolate the three main sources of force sensory in the human body. Any movement or shift in weight that the user will experience will be processed by the network of sensors allowing the suit to take action. To the pilot of the suit, it will appear as if he is going through motions supporting only himself.

Across the seas at Cyberdyne a more biological approach was taken to create harmonic motion between the pilot and the exoskeleton. This system begins with the electric sensors that contact the user's skin. "The first [system], the bio-centric system, monitors the electric currents known as electromyogram signals on the wearer's body. These signals flow along muscle fibers when a person intends to move. … [S]ensors attached to the wearer's skin near the shoulders, hips, knees, and elbows pick up the signals and feed them to the control computer, which then triggers the actuators to put the robotic arms and legs into action" [5]. This specific system works extremely well for the quick response necessary to the function. The instant the pilot thinks about moving, the sensors will pick up the electronic signal simultaneously and analyze the signal to initiate the actuators at approximately the same time as the human body can accomplish the same feat. In terms of uniformity it cannot be any more accurate than to use the same signals as the human body. But while this system has an advantage in quickness the force sensors have the advantage of outputting the exact power needed to apply a force.

A second system in Cyberdyne's HAL-5 furthers the harmony between man and machine with pre-programmed responses. "The job of the second control system is to let the wearer and suit move together more smoothly. It stores walking patterns – generated the first time the person tries out the suit – that are used to keep the suit's limbs always in sync with those of the wearer" [5]. No two persons will have the exact same way of walking making any "one size fits all" program of walking uncomfortable to virtually all users. With this system, although the suit is not running at full speed from first step, the suit will recognize the pilot's motions and know exactly how to respond to move the exoskeleton with the pilot as one. It will take a set amount of time for the computers to learn but overall will lead to a more effective usability.

With the combination of currently developed technologies and the inevitable exponential increase in processing power and design a flawless sensory system can be built. Force sensors can be used to determine load outputs along with sensing any upset in balance to allow a user to prevent a fall and keep safety while using the suit. Hand in hand with force sensors the bio-centric sensors can detect initial movement and store more natural movement algorithms to replicate the pilot's innate actions. This multi-system control may be what is needed to utilize a full scale powered exoskeleton for a human pilot.

Replicating Anatomy

To be true to the definition of an exoskeleton these suits must act as a natural shell such as that on an animal. Mechanical parts must properly represent their natural counterparts. The sensors and computers talked about previously act as the brains and cognition for the suits while the power supplies and engines would function as the digestive system that fuels the human body. But these are only parts of the entire system of a complete organism. To function such as a human would the suits must incorporate joints and muscle to fully replicate a person's movements. Along with these one of the main purposes of an exoskeleton is protection.

"The exoskeleton should be analogous to the human limbs and trunk in the case of joint positions and distribution of degrees of freedom. As a result, it is important to investigate the atlas of the human limb and trunk during motions" [8]. The six fundamental joints that must be modeled are the condyloid, ball-and-socket, pivot, hinge, planar, and saddle joints. The condyloid joints, such as those in the fingers, are similar to a ball-and-socket joint that must give the fingers flexibility downwards but in only one direction and little side to side movement. The ball-and-socket would represent the shoulders joint which must be capable of 360 degree rotation in one hemisphere. The pivot joint would be a joint capable of complete rotation around an axis and no other direction. The hinge joint, like those for your elbow and knee, must be able to flex a large mass in one direction approximately 180 degrees. Your wrist would be a planar joint which must allow for a left to right swivel while still providing similar flex in another direction as the hinge joints. Lastly at the base of fingers are the saddle joints that in replication similar to the mix of the ball-and-socket joint in coordination with a hinge joint. All of these joints are easily machined and must be refined and fused along with one another on a large scale to create the complex structure and flexibility of most parts of the human body.

One problem with joints is the extended range of man made parts. "Especially under the abnormal state, the exoskeleton cannot hurt the operator due to its over-scaled joint motion spaces" [8]. In simple terms the machine can only move within the confines of the human range. You can't have forces larger than a human is even capable of bending your elbow back against itself. To counter this stop blocks are being mounted in the joints. Stop blocks can be used as either a soft or hard stop. A soft block would be programming the computer to only allow so much rotation in a joint; this is easy to program but under computer failure could become a safety issue. That is why along with these, hard stops are implemented in the actual machinery to fully limit a joints motion in specific directions protecting the pilot from unnecessary dangers.

Once the machine can move in the directions a human body is capable of the joints must be put into motion. "The actuations in exoskeletons should be allocated in the corresponding position to the representative muscle in human limb and trunk, in order to simulate the function of muscles during the process of the human operator moving" [8]. This means that when moving the forearm of a particular suit a pseudo bicep in the form of hydraulic actuator must contract when raised and extend with the forearm when lowered. Another actuator in place of the triceps must also be in place to supply the opposite force from the bicep. Hydraulic actuators are the most likely candidate to provide this force in the exoskeleton. "Hydraulic cylinders convert the energy produced from a hydraulic pump into a linear mechanical output so that they can perform useful work" [9]. Hydraulic cylinders create force by pumping hydraulic fluids into a sealed chamber containing a piston that moves up and down connected to a piston rod that exits the chamber.

Each exoskeleton must be built in the same specifications for factory production. The only problem with this is no two people have the exact same dimensions of their anatomy. Solving this problem would be the implementation of adjustable length limbs for the structure and mechanical muscles that can adjust accordingly with it.

Having all of the safety measures built into the structure of the exoskeleton the suits are missing one more safety feature of other exoskeletons, added protection. Adding revolutionary bullet proof technologies to strategically cover sensitive areas of the suit and the human body could add an almost invincibility factor to the pilot of a mechanized exoskeleton. Along these lines flame retardant materials could allow for timely protection in unfortunate situations.

Following the biological designs and uses of nature's exoskeletons the mechanized variations will give one facet of the added support to the soldier in need that the suits will supply.

BENEFITS TO THE MILITARY

The benefits mechanized exoskeletons contribute to the military are insurmountable. Not only will a soldier be able to look as if he or she was a superhero but also they will posses some similar physical characteristics. Acquiring strength and stamina, soldiers will be able to carry their gear with ease and still have additional energy after a long trek. Larger weapons can be wielded by soldiers on the ground to give an increased artillery advantage. Lifting and repetitive tasks will become simple and will require less involvement by others. Single persons could load missiles onto aircrafts and repair the heavy parts of vehicles taken out of service. Reducing the amount of people involved in a certain activity will increase productivity with the allowance of more troops to fulfill other projects. In the near future the suits will have communication apparatuses installed to make communicating safer and easier for the soldier and others around them [3]. Wi-Fi is already installed in the HAL-5 to control the suit, but it could also be transformed into a form of communication between soldiers in the exoskeletons and the home base allowing quick communication and the possibility of head up displays of important visuals such as maps. The suits will not only save lives because of their protective shell or soon to be added communication systems, but also because wounded soldiers will easily be taken off of the battlefield by a rescuer wearing an exoskeleton which will increase the likelihood of survival [4]. Adding strength, stamina, protection, and communication to military men and women will always have a positive impact in productivity as well as safety.

APPLICATIONS PAST THE MILITARY: SUSTAINABILITY

Many technological advancements are created to aid the United States Military. Over time these technologies tend to evolve into uses for other fields; this is no different for the use of mechanized exoskeletons. Foreseeable fields of usage are easy to imagine such as firefighting, construction, and any manual labor. Along with this the usage of this to aid people with muscular dystrophy.

Firefighters are constantly involved in dangerous environments requiring strength, agility, and stamina. Breaking down doors, lifting heavy objects, and creating alternative paths to safety in a burning building are essential to aid in the rescue of civilians. With an exoskeleton you could perceivably attach an ax to a limb that could be used in succession with the added strength of the suit to forcefully create these pathways to safety. Carrying others to safety is also in the job description of firefighters, often requiring multiple trips back and forth. With the suit doing the lifting this would no longer put as much strain of the pilot of the suit and allow for more stamina and strength in rescue. With the added carrying capacity the firefighters could also take on a larger load of oxygen for clean breathing inside the burning buildings.

With any type of manual labor, such as construction, repetitive motions involving great amounts of force are often in the job description. This overstrains the muscles of the workers and leads to a multitude of injuries on the job. With the use of a powered exoskeleton the strain on the muscles would be applied to the machine and injuries would inevitably be reduced. This allows for more production for the company. Also adding to the production would be the ability for one man to perform what would once require two or more people. Manual labor is also a staple of yard work for the weekend warrior dad. Much like you could rent out a Bobcat or a UHAUL van for the weekend a mechanized exoskeleton could be yours for the weekend, giving you the advantages of strength and safety.

Already being developed at the same time as the militaries' version of the exoskeleton is a version to aid in the daily movements of people suffering from muscular dystrophy. People with the condition have weakened muscles that dampen the use of their limbs. With the addition of the suit is possible for these people to regain complete usage of all of their limbs. To a paraplegic this could mean relearning how to walk.

As with most current technology the applications of mechanized exoskeletons branch out from their original intentions to previously unthought-of uses.

COMING FULL CIRCLE

With the implementation of each company's isolated research and development together an ideal mechanized exoskeleton is on the verge of creation. This technology will greatly benefit not just the military but eventually other applications. People suffering from muscular dystrophy and similar diseases will have the opportunity to regain function with their disabled limbs. Firefighters would get the advantage of added strength and protection to withstand fires while rescuing victims. The list of applications goes on and on and with the rate of advancements in technology it can only grow.

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