EXPLORATION INTO THE FIELD OF EXOSUITS

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What is an Exosuit?

In order to effectively begin this discussion, one must first answer the underlying question, "What is an exosuit?" The word begins with the prefix "exo" which means "outside" or "external". Therefore, the literal translation would be an external suit. However, the phrase exosuit clearly carries more meaning than just a suit that is worn externally. Further investigation lists the term exosuit as synonymous with other terms including powered exoskeleton, power armor, and exoframe…but what does it all mean? In *Between Iron Man and Aqua Man*, a paper written by Andrew Herr and Lieutenant Scott Cheney-Peters, they define an exosuit as "wearable technology that conforms to the human figure, enables relatively natural human movement and augments human abilities." The part of this definition that alludes to the truly exciting incentive behind exosuit technology is the ability to enhance the human creature beyond its natural state. Running faster, lifting more, the ability to safely explore hazardous environments, and much more are all possibilities with exosuit technology. As a young engineering student, the investigation of the topic of exosuits has been exhilarating for my imagination as the possible applications for exosuit technology is quite expansive and could transform the world in which we live. The purpose of this paper is to provide a summary of my findings throughout the course of my research project, *Exploration into the Field of Exosuits*.

History of Exosuits

The concept of exosuits originally dates back to 1868 with the publication of Edward S Ellis' novel *The Steam Man of the Prairies*. For almost a century following Ellis' novel, the primary appearances of exosuits would remain science fiction in a variety of media formats. Then, in 1961 the Pentagon invited proposals for wearable robots for efforts to create the next generation super soldier. In 1966, General Electric (GE) developed the Hardiman which served as the first concrete exosuit design and effectively demonstrated the feasibility of future applications of a powered exosuit. Throughout the late 1900's and early 2000's various companies have developed their own exosuits models expanding on preceding designs. The Defense Advanced Research Projects Agency (DARPA) and the United States Army have continued to fund research for this type of technology through initiatives such as the Exoskeletons for Human Performance Augmentation and Future Soldier 2030.

Media Influence and Appearances

As with many technologies, media has played a significant role in stimulating interest in exosuit technology. The purpose of this section is to highlight a few of the iconic depictions of exosuit technology that have fed interest into the field from a variety of media types.

Literature

Predating all of the other media in this section is one of the most common forms of written word, the novel. As mentioned in the History of Exosuits, the first account of exosuit type technology appeared with Edward S Ellis' 1868 novel, *The Steam Man of the Prairies*. Ellis' novel was reproduced a number of times and three sequels were written by Harry Enton due to public demand. The original story tracked the adventures of a Yankee, an Irishman, and a teenage boy who used his creation, the Steam Man, to carry their carriage. The Steam Man was described in text as being "ten feet in height" and possessing the general appearance of a steampunk giant. Another early novel that makes reference to exosuit technology is the 1959 novel, *Starship Troopers*, written by Robert A.

Heinlein. The military science fiction novel follows Juan Rico's military career in a war between humans and "the Bugs". Throughout the novel, the soldiers for mankind are equipped with variations of powered armor. These two examples of exosuit technology in literature helped lay the groundwork for other media references as well as real world development attempts.

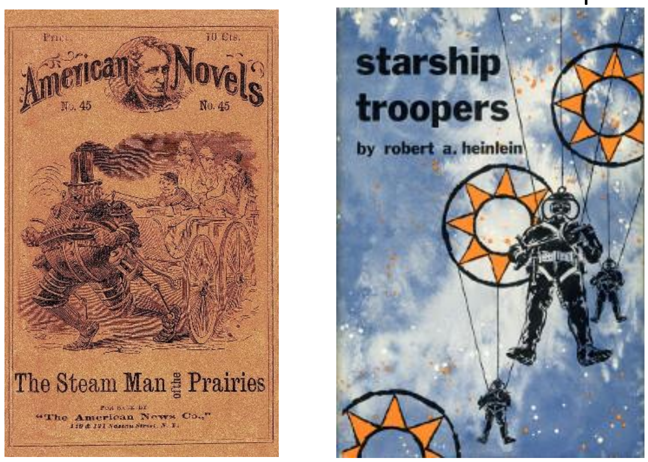

Figure 1: Original covers for *The Steam Man of the Prairies* (left) and *Starship Troopers* (right)

Comics

From a young age I have been captivated by one of the most iconic superheroes to ever wear an exosuit, Iron Man. By no means would I describe myself as a comic enthusiast, but with the recent surge of Marvel movies in the past few years, I imagine that a much greater population has been familiarized with Tony Stark's character. Originally debuting in *Tales of Suspense #39* in 1963, Iron Man has stood the test of time. However, Iron Man is far from the only comic book character to ever wear exosuit technology. Notable heroes such as Batman, Spider Man, Dick Grayson, and Captain America as well as notorious villains such as Lex Luthor, Mr. Freeze, Loki, and Doctor Doom have all worn exosuits at some point. The powers that these comic based exosuits granted their uses ranges dramatically from extremely enhanced physical abilities to complete invulnerability. When beginning to investigate the real world applications of exosuits, I found it useful to remember that a healthy amount of imagination as shown in the comics can help keep research exciting and begin building the bridge for science fiction to become reality.

Figure 2: Original cover *Tales of Suspense #39* which debuted Iron Man's character

Television

The first televised appearance of exosuit technology occurred in 1979 with Sunrise's *Mobile Suit Gundam*. The series' plot is centered on the conflict between the Earth Federation and the Duchy of Zeon and features a piloted suit known as the RX-78-2 Gundam. Although originally cancelled after a year, *Mobile Suit Gundam* has been rebooted and expanded upon a number of times over the years. Jumping to the year 1986, James Cameron directed *Aliens* in which Sigourney Weaver's character, Ripley, uses the P-5000 Power Loader to wrestle with the alien queen. This appearance of extremely practical based exosuit technology has definitely earned a spot on the list of iconic exosuits of all time. Progressing further towards present day, a trend of fascination with exosuit technology can be seen as it has been featured in a number of films including the Iron Man franchise (2008, 2010, 2013), *G.I. Joe The Rise of Cobra (2009), Elysium* (2013), *Pacific Rim* (2013), and *Edge of Tomorrow* (2014). As a personal note, I find the large disparity (specifically in the size of the exosuit technology) to be quite fascinating as it illustrates the variety of forms that this technology may develop into to meet any particular task.

Figure 3: Original cover of the Anime Legends DVD compilation featuring *Mobile Suit Gundam*

Video Games

In addition to comics and television, exosuits have made a number of appearances in video games over the years. Some of the most iconic video games/franchises to feature exosuits include *Metroid* (1986-2016), *Fallout* (1997-2015), *HALO* (2001-2016), and *Call of Duty: Advanced Warfare* (2014). Each game has depicted a different version of exosuit technology, although each game's suits greatly increase combat proficiency, come in a wide number of variations, and have some form of extra ability system to increase the suit's base functions. Through my own moderate gaming experience (specifically with *Fallout* and *Call of Duty*), I can attest to the fascination that can arise from being able to seize control of these virtual exosuits. Similar to comics, the accessibility that video games can provide to exosuit technology can help to foster a curiosity into the field developing in the real world as well as spark imagination to challenge the current limits of current technology.

Companies with Exosuit Experience

Since the mid-1900s a number of companies have been experimenting, designing, and creating exosuits for a range of applications. The purpose of this section is to highlight a few of the companies that have served as leaders in the development and commercialization of exosuit technology over the years.

General Electric

Founding Year: 1892 (April 15th)
Years of Existence: 1892 – Present
Description: General Electric (GE), founded by Thomas Edison in Schenectady, New York in 1892, has grown into a multinational conglomerate of companies. GE offers products and services for a wide array of industries including aviation, power generation, grid solutions, transportation, city lighting, renewable energy and energy management, and healthcare. In Forbes' 2015 rankings, GE finished the year as the ninth most valuable brand with an estimated value of 37.5 billion dollars.
Exosuit Experience: Although not a technology giant by nature, in the mid-1960s GE responded to the Pentagon's invitation for wearable robotic designs (exosuits) with plans for an 18 foot tall device. By 1966, development began on GE's exosuit, the Hardiman. The Hardiman design operated on the concept of a master-slave system of two skeletons, one attached to the user and one amplifying the intended motions. GE also paved the way for the concept of force feedback, a safety feature where the user will still feel a percentage of the applied force in order to protect from exposure to excessive load. Although the Hardiman project never reached complete development and distribution goals, it can be seen as a success in its efforts to "demonstrate the potential of a powered exoskeleton". It can be stated that this early foray into exosuit technology has laid the groundwork for developments that have been made since.

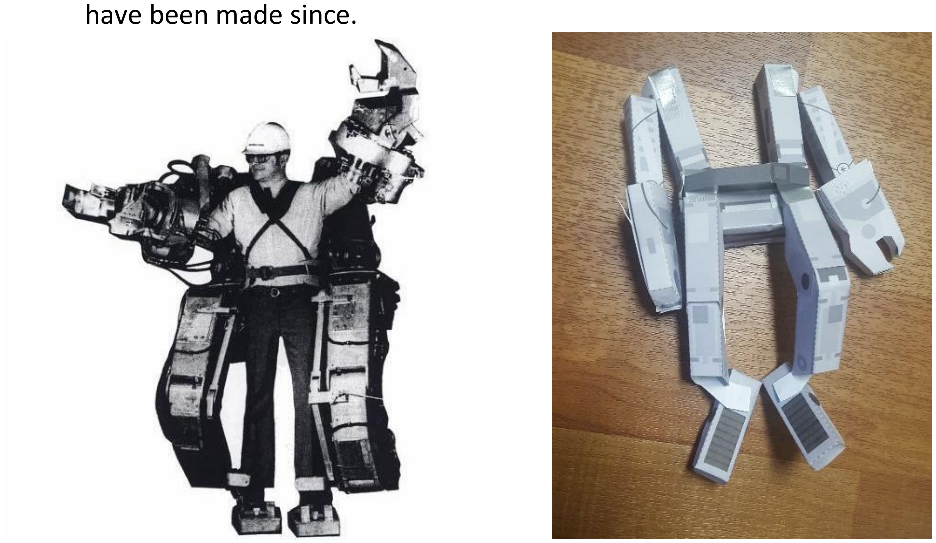

Figure 4: General Electric's Hardiman (left) and paper prototype Hardiman I made (right)

Personal Thoughts: General Electric's Hardiman served as my introduction to the master-slave and force feedback exosuit concepts which have been utilized in a number of later exosuit designs. The concepts seem remarkably practical, and I enjoyed delving into the history of the first major corporate design. As a side note, I do feel that large corporations (such as GE) are a wonderful sponsor for this type of research due to their expansive resources.

Lockheed Martin

Founding Year: 1995
Years of Existence: 1995 - Present
Description: Lockheed Martin formed from the merger of two aviation companies, Lockheed and Martin Marietta. Primarily providing products for the aerospace and defense industries, Lockheed Martin also develops for the energy, information technology, and space industries. In addition, Lockheed Martin has an impressive history of research and development as a government contractor producing some notable aircraft including the SR-71 Blackbird and the F-117 Nighthawk.
Exosuit Experience: Obtained from an exclusive licensing agreement with Ekso Bionics (previously Berkeley Bionics) in 2009, Lockheed Martin has provided research and development of an exosuit known as the Human Universal Load Carrier (HULC). Designed for the US Army Natick Soldier Research Development and Engineering Center (NSRDEC), HULC's primary design goal was to aid soldiers in carrying large loads over various terrains. HULC operates through the use of lower extremity hydraulics and has been reported to allow the user to carry 200 pound loads for an extended time. Since this initial endeavor into exosuit technology, Lockheed Martin has created another exosuit known as FORTIS which is intended for industrial applications. FORTIS's design redirects loads to the ground rather than the user in order to reduce fatigue and has received numerous awards since its development.


Figure 5: Lockheed Martin's HULC
Personal Thoughts: Growing up roughly fifteen minutes away from one of Lockheed Martin's facilities in Akron, Ohio, I found all of my research on their organization very interesting (even finding myself getting side tracked on non-exosuit topics a number of times). However, concerning their exosuit, HULC, I believe it provides an accurate summary of the currently available exosuit designs for military applications: reasonable power amplification for the user, functionally mobile design, and recognized limitations in power supply. That stated, defense contractors (such as Lockheed Martin) have an advantage over larger corporations in the future development of exosuit technology due to the focused nature of their corporation's products and services.

Raytheon

Founding Year: 1922 (July 7th)

Years of Existence: 1922 – Present

Description: Raytheon is an American technology company that specializes in defense and homeland security. Founded in 1922, Raytheon's first big development was a gas rectifier tube that allowed radios to be plugged into a traditional wall socket which paved the way for radios to become common household items. Over the years, Raytheon has contributed to a number of notable government operations including World War II efforts (developed magnetron tubes for radar defense) and the lunar landing (built variety of hardware for space vehicles).

Exosuit Experience: In 2007, Raytheon acquired Sarcos and continued designs on their exosuit design by the name XOS. The first model (XOS 1) and the updated model (XOS 2) have been demonstrated in action in 2008 and 2010 respectively. The suit is based on high-pressure hydraulic systems and was designed with the intent to aid soldiers in carrying large loads for extended durations. The XOS 2 has reported a strength amplification factor of 17:1 and makes it feasible for the user to carry 200 pound loads for an extended time. Raytheon plans to expand the XOS 2's functionality through the development of a fuel-carrying backpack (allowing for extended untethered functionality).

Figure 6: Raytheon's XOS2

Personal Thoughts: Similar to Lockheed Martin's HULC, Raytheon's XOS2 exhibits similar performance and limiting factors. I did not find this extraordinarily surprising as each design was funded by the US Defense Advanced Research Projects Agency's (DARPA) "Exoskeletons for Human Performance Augmentation" program. Given the military applications for each of these designs, I was moderately surprised that no form of defense mechanisms/shielding were prominently featured in the designs. When envisioning future soldiers using exosuit technology, I believe that this is a step that can not be ignored.

Cyberdyne

Founding Year: 2004 (June 24th)
Years of Existence: 2004 – Present
Description: Cyberdyne is a Japanese company, founded by Dr. Yoshiyuki Sankai, that seeks to provide its cutting edge exosuit technology to the public for a focus on healthy living. Cyberdyne's training staff provides support programs for a variety of medical applications (ranging from complete to limited assistance needs) in conjunction with its exosuit variations. Due to its technological advancement and beneficent corporate vision, Cyberdyne has received international recognition as a leader in medical technology and therapeutic measures.
Exosuit Experience: The core of Cyberdyne's exosuit developments rest in the HAL (Hybrid Assistive Limb) projects. HAL operates on the interesting principle of detecting desired user motion through bio-electric signals (BES) that can be detected through the skin. The exosuit then produces the intended motion in order to assist or guide the user. As HAL's main intended purpose is currently recovery and health maintenance (not overall enhancement), the exosuit is commercially available as segmented limb or joint supports (the first full body suit, HAL 5, was demoed in 2012). As of 2010, HAL had received enough interest that it began mass production at a rate of 500 units per year. Since its inception, significant research has gone into the HAL project, including three years of research by Dr. Sankai to accurately link brain impulses to leg movements, four years of research to determine the appropriate timing for conveying the signals to the suit's motor, and continuing research in expanding HAL's feasible application range to include whole body assistance and disaster recovery.

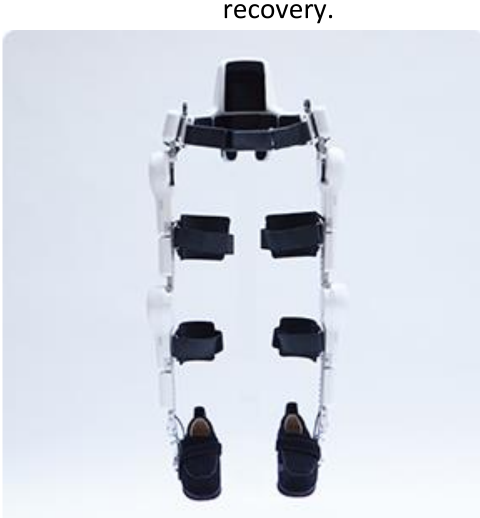


Figure 7: Cyberdyne's HAL for lower limb support (left) and HAL 5 (right)

Personal Thoughts: I am amazed by Cyberdyne's HAL 5 specifically its systems to sense movement through bio-electric signals. This approach sharply contrasts the master-slave hydraulic amplification seen in a number of other designs. My first reaction was excitement and hope that this approach to movement recognition would be researched further and incorporated into all exosuit designs. However, it must be noted that Cyberdyne's primary application for HAL (medical) allows for the increased technological sophistication (as opposed to military applications where practicality and cost play a huge role in feasibility). Regardless, I am quite interested to track what type of developments come from this technology in the next decade.

As a closing note, I found Cyberdyne's emphasis on the use of technology to promote healthy living and recovery quite impressive. I noticed throughout my project that there exists fear among some people surrounding the concept of exosuit technology (I would say movies are mainly to blame there), and a company such as Cyberdyne (despite its ironic naming) is an excellent example of the good that can be accomplished with exosuits.

Nuytco Research Ltd.

Founding Year: 1979

Years of Existence: 1979 – Present

Description: Nuytco Research Ltd. is a small Canadian research organization that has received international recognition for is specialization in undersea technology. Nuytco produces a range of aquatic products from atmospheric dive suits to remotely operated vehicles. Nuytco's president and founder, Phil Nuytten, has over 40 years of design experience for aquatic diving products and has used this knowledge to inspire products that allow for longer and safer diving excursions.

Exosuit Experience: Nuytco has two atmospheric diving suit designs, the Newtsuit (developed in 1982) and the Exosuit (developed in 2012). Each operate for the purpose of allowing safe deep sea exploration (rated up to 1000 feet) where maintained human dexterity is required. While the Newtsuit is a time tested design, the Exosuit offers a number of upgrades and will serve as the future choice for deep sea exploration.

Fig. 8: Nuytco's Newtsuit (left) and Exosuit (right)

Personal Thoughts: I found the exosuit designs from Nuytco Research Ltd. very intriguing. When I began my research project, I investigated which industries might see a benefit from exosuit technology to determine a reasonable focus for the remainder of my project (I anticipated the military applications but this one caught me off guard). Nuytco's efforts were one of the unique applications that I came across and serves as an excellent example of my belief that exosuit technology can be a tool for humanity to challenge frontiers in a number of industries (or more aggressively, all industries that an effort is made in). For this reason I decided to include them in my final report as an inspiration to seek other unique applications for this technology.

Design Considerations/Issues

When analyzing exosuit technology, it is apparent that each major design is an intricate combination of a number of subsystems requiring knowledge in a number of fields. The purpose of this section is to highlight a few of the major design considerations that must be addressed while developing an exosuit.

Material Science for Exosuits

One of the first design considerations when developing an exosuit that must be addressed is quite simply, "What material is going to be used to make each component of the suit?" There is clearly no straightforward answer to this question, as what material is desired can be determined by a wide range of factors including strength, hardness, machinability, weight, cost, and more. This subsection will provide some basic analysis on commonly used materials as well as some currently being researched (for both construction and shielding).

When prototyping exosuit frames, the most common materials used include simple metals such as steel or aluminum as cost tends to stand out as the determining factor. It can be noted that each of these metals carries with it its own positive and negative. In general, steel is considerably stronger and harder than aluminum, but also weighs more meaning that when used in an exosuit, more power generation would be required simply to offset the suit carrying its own weight. On the other hand, the lighter aluminum will fail from fatigue much sooner than steel. Other common materials that are used include titanium and carbon fiber.

One of the largest causes of the variance in properties among materials, even within the same base metal, is the treatment process (annealing, hardening, tempering, carburizing, etc.) that the material has went through. I was first introduced to the concept of manipulating material properties in my Manufacturing Processes class and the concept was again discussed in my Solid Mechanics class. To give an example of this variance, consider the steel versus aluminum comparison made in the previous paragraph (focusing on the yield strength and tensile strength properties). The online Engineer's Handbook lists steel having a yield strength between 26 and 234 kips and a tensile strength between 47 and 260 kips. Aluminum is listed as having a yield strength between 5 and 72 kips and a tensile strength between 13 and 82 kips. This example highlights the difficulty that arises when trying to compare materials based on their mechanical properties. Given the overlap between the upper and lower bounds of steel and aluminum's properties, it is possible that there could be an instance where a sample of aluminum was stronger and lighter than a sample of steel.

Properties of Steel

UNS Number	Processing Method	Yield Strength kpsi	Tensile Strength kpsi	Yield Strength MPa	Tensile Strength MPa	Elongation in 2 in. %	Reduction in Area %	Brinell Hardness H_b
G10100	Hot Rolled	26	47	179	324	28	50	95
G10100	Cold Drawn	44	53	303	365	20	40	105
G10150	Hot Rolled	27	50	186	345	28	50	101
G10150	Cold Drawn	47	56	324	386	18	40	111
G10180	Hot Rolled	32	58	220	400	25	50	116
G10180	Cold Drawn	54	64	372	441	15	40	126
G10350	Hot Rolled	39	72	269	496	18	40	143
G10350	Cold Drawn	67	80	462	551	12	35	163

Fig. 9: Example of what a common material property chart could look like

Other materials that may play a role in the design process of an exosuit (more so in shielding design considerations) include KEVLAR, the US Army's shear thickening fluid, dragon armor, carbon nanotubes, weak material combinations, and spider silk (notably these materials vary in their application readiness). Created by a DuPont chemist, KEVLAR is a well-known synthetic fiber that is commonly used as a protective component in combat helmets and vests. Although effective against slashing and blunt impacts, KEVLAR vests do not perform as well against stabbing impacts as it is possible for a sharp blade to slip between the KEVLAR weavings. In response to this, the Material Research Laboratory of the United States Army developed a military grade non-newtonian fluid made from silica and polyethylene glycol that they call a shear thickening fluid. When applying this shear thickening fluid to a standard KEVLAR vest, it virtually eliminates the possibility of penetration from a stabbing impact. Dragon armor is a plating based armor that uses overlapping ceramic and titanium composite disks to stop projectiles as well as dissipate energy away from the point of impact. Carbon nanotubes and spider silk are both still in the research and development stages, but each seeks to take advantage of common natural substances that have incredible strength and toughness properties. Finally, there are examples in nature of standalone weak materials that combine to make a stronger composite. For example, a toucan's beak consists of an outer shell made of keratin and in inner air pocketed bone structure. On their own, the keratin shell lacks stiffness and the bone structure is susceptible to shear fracture; however, when combined the outer shell and bone structure allow the beak to be strong, stiff, and functional.

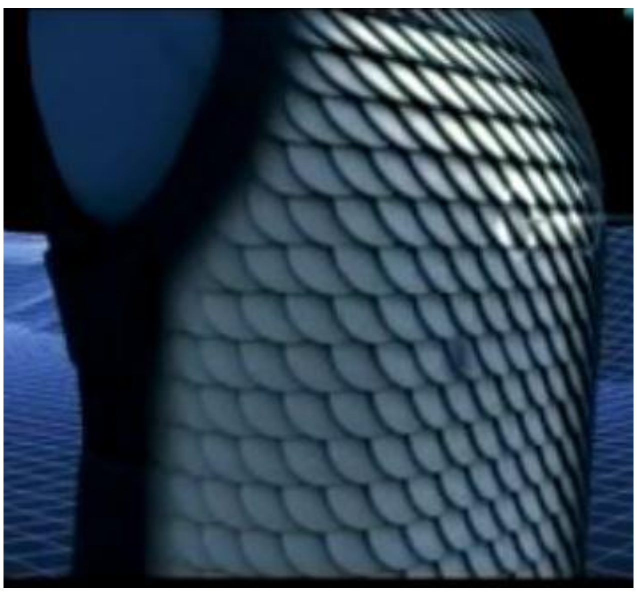

Fig. 10: Plating representation of dragon armor (left) and toucan's beak (right)

I found the topic of material sciences interesting when it was first introduced in my Manufacturing Processes class, but seeing the same concepts arise during the course of this research project helped me see how valuable a working understanding and appreciation of the field can be. Overall, it can be stated that if presented with the opportunity to design or analyze an exosuit design, the material chosen for fabrication or defense should be selected to meet the specific application parameters. The selection process should also be taken seriously as a faulty material could cause the failure of a perfectly sound design.

Actuators

Actuators can basically be defined as devices that function to convert energy into a format that is used to control a mechanism or system. A simple and common example of actuators can be seen in automatic door openers at most shopping facilities. After receiving an impulse from the sensor, the actuator functions to convert the electrical energy into the desired motion of an opening door. Actuators can be categorized by the source of the input energy or by the configuration of the motor (if present). Three common sources of input energy for actuators include an electric current, hydraulic pressure, or pneumatic pressure.

When considering the design of an exosuit, actuators often serve as the motion control systems for joints, operating in a very similar way that a human muscle would. Similar to the material science selection considerations, it would be important to know the anticipated loading that an actuator would be expected to endure before choosing which actuator type and size to use. In general, hydraulic actuators are more suitable for high force applications, pneumatic actuators are cheap and good for environments with large temperature ranges, and electric actuators provide high position precision. However, hydraulic and pneumatic actuators can leak fluid/air lowering efficiency while electric actuators tend to be more expensive and are not suited for extreme environments. Manufacturing information should be noted and followed when implementing actuation systems into an exosuit design.

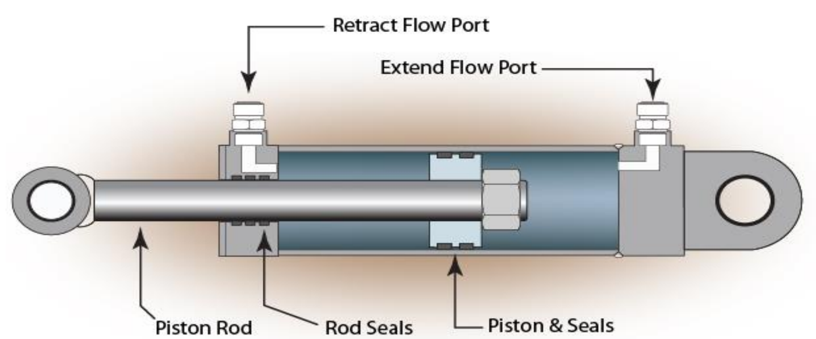

Fig. 11: Simple hydraulic linear actuator cutaway

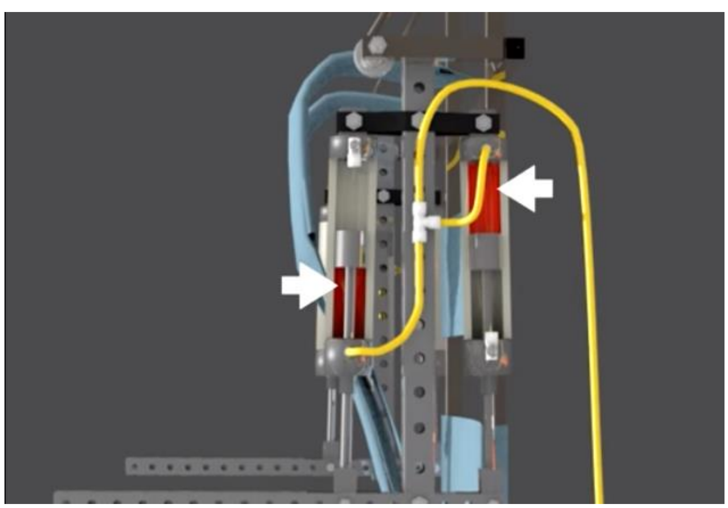

Fig. 12: Example of how two hydraulic actuators could be used to raise an arm support (from the Hacksmith's Elysium exoskeleton build project)

Stealth/Cloaking Technologies

One alternative to incorporating defensive minded material science into an exosuit design is instead including a stealth/cloaking system into the design. The basic concept behind stealth is to make the desired object unobservable by monitoring systems whereas cloaking seeks to make the desired object completely invisible. This is an important distinction as stealth is much simpler to achieve as it only requires countering the given monitoring system. For example, traditional radar operates by emitting radio waves, receiving reflected radio waves on the same or another transmitter, and calculating distance/position based on the time that the reflected wave took to be received. Therefore, most stealth aircraft implement two techniques to avoid detection, low radar cross sections (flat surfaces with sharp corners; based on the principle of deferring reflected radio waves away from the transmitters) and material coatings (based on the concept of absorbing radio waves). However, for the anticipated application of a combat based exosuit, a full cloaking system would be a more suitable threat deterrent.

For complete cloaking the system must not only reflect light waves away from the observer or absorb the light waves (resulting in a silhouette), but must provide the observer with an undistorted view of what lies exactly behind the object. This concept has led to the development of two relatively new fields known as transformation optics and the creation/study of metamaterials (materials whose properties derive from constituent units versus their constituent atoms allowing for engineering manipulation; developing in conjunction with transformation optics as a tool to be used in transformation optics). One of the leading theories on how to achieve complete cloaking rests in the manipulation of refractive indexes to bend light around the object. For more information concerning the fields of transformation optics and metamaterials as well as cloaking efforts (including mathematical breakdowns), I would strongly recommend viewing Professor Sir John Pendry's lecture on the topic (https://www.youtube.com/watch?v=yP-ZCJ4BDcw).

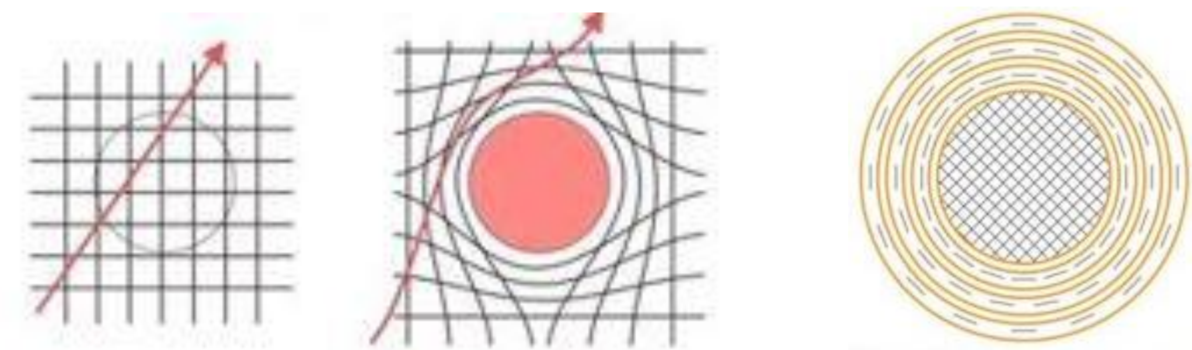

Fig. 13: Manipulating refractive index by bending light around an object (left) ad a proposed magnetic cloak layout (right)

Power Supplies for Exosuits

There is a high probability that a well-rounded exosuit design will require some form of power supply in order to function properly. Options for powering an exosuit are similar to powering other large machinery (such as a car) and include options such as an internal combustion engine (with a range of fuel options) and battery cells. One of the most useful metrics for comparing the efficiency of different power supplies is energy density, the amount of energy received per unit volume. For whichever power supply is chosen, the ultimate goal is for the power supply to possess a high energy density, be lightweight, long lasting, affordable, and based on application stable (e.g. nuclear power in a war application may be unwise).

Similar to the other design considerations, each power supply option comes with its own advantages and disadvantages making the anticipated application crucial information before the selection process can occur. If battery cells are being considered, the main distinction is if a primary or secondary cell style is appropriate for the application. Primary cells possess a higher energy density with better charge retention over extended durations than secondary cells but must be discarded after they are depleted. On the other hand, secondary cells can be recharged; although, this still limits the exosuits application as additional charging equipment would be required to be brought along. The internal combustion engine option will vary in output based on the fuel used but typically will produce a higher energy output then either of the battery cell types. However, an internal combustion engine will idle, meaning that fuel will be consumed even when the exosuit is not necessarily active. In addition, an internal combustion engine will raise additional considerations for noise moderation, vibration impacts, and safety. Current exosuit designs indicate that the power source question is the largest limitation in the exosuit designing process. There is not a clear cut great option for a power supply, and most exosuit research initially accepts a tethered power limitation in order to not hold up the remainder of the design. Therefore, the topic of power supply is an area that would require its own breakthroughs before exosuit technology could reach its maximum potential.

Application/Culture

Throughout my research project, I noticed that opinions on exosuit technology were split between individuals who thought the technology seemed exciting and those who seemed afraid of what consequences this next step in the technological era could bring. I clearly see exosuit technology as an advancement that has already shown potential to have valuable application across a number of industries, although acknowledging the concerns that have been raised are essential in the development of a product that will be generally accepted. I am optimistic that through this paper I have provided an effective summary of the topics I researched and that this can serve as an excellent starting point for others interested in learning more about the field of exosuits.

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