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ENGINEERING THE WINTER SOLDIER: A STUDY OF AN ADVANCED BIONIC ARM

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ABSTRACT

The Winter Solider, better known as James Buchanan “Bucky” Barnes, possesses a highly advanced prosthetic arm that provides enhanced levels of strength, endurance, and toughness to the biologically enhanced solider. This paper covers some of the engineering aspects behind his advanced prosthetic. First, the origin of the Winter Solider is discussed with a review of the abilities of his prosthetic arm. These abilities are used to assess the essential characteristics of the arm. An assessment of the anatomical damage suffered by Barnes is presented with this dictating the functionality needed for his prosthetic arm. Some basic assumptions are then made to estimate the material composition of his arm, and thus help identify the real materials that could be used to actually make his arm. This analysis process indicates that early versions of the arm were most likely made from a ferroalloy with a depleted uranium/titanium alloy and tungsten carbides being highly suitable. This is followed by an engineering assessment that breaks down the core aspects of the arm (mechanical structure, actuators, sensors, a power source, and a control system) with discussion on past, present, and future engineering solutions of these core aspects.

PROLOGUE

James Buchanan Barnes died a war hero after bravely defending the world against the Hydra onslaught during World War II, or so everyone thought! Found by Hydra operatives with a severed left arm after a near fatal fall, Barnes was revived in Moscow suffering from brain damage-induced amnesia. Hydra scientists fitted him with a bionic arm and set about programming his mind, creating what would later become one of the most feared assassins in the world – the Winter Solider. After his latest successful mission, he checks in with his Hydra controllers. The Winter Solider is due yet another technical upgrade to what has become his most powerful weapon – his bionic arm!

INTRODUCTION

James Buchanan “Bucky” Barnes is the infamous sometime hero, sometime villain in the Marvel Cinematic Universe (MCU). Better known by his alias, the Winter Soldier, he is a biologically-enhanced super-solider exhibiting augmented speed, strength, and fighting skills on a par with Steve Rogers (Captain America). To date, the Winter Solider has appeared in a number of MCU films such as *Captain America: The First Avenger* [1], *Captain America: The Winter Soldier* [2], *Captain America: Civil War* [3], *Avengers: Infinity War* [4] and *Avengers: Endgame* [5]; and in the 2021 Disney+ series *The Falcon and in the Winter Soldier* [6].

Bucky Barnes first appeared in Marvel Comics in *Captain America Comics #1* (1941) [7], while first gaining the title of the Winter Soldier in *Captain America #1*, which was published in January 2005 [8]. In this series, Barnes is depicted as having been frozen for several decades after his apparent death during World War II. He was unfrozen and then refrozen by Hydra for use in periodic assassination missions. In Marvel lore, Bucky Barnes sustained a significant injury to his left arm during World War II, which led him to been fitted with a bionic arm. The arm, which was upgraded over time, gives him superhuman strength and improved human performance characteristics.

While there are numerous origin stories in the Marvel source material, this paper will focus on the Winter Solider that features in the MCU. In the comic book *Captain America #1* [8], it is revealed that Bucky Barnes did not die in World War II but was recovered after an aircraft explosion by General Vasily Karpov and the crew of a Russia submarine. He was recovered in a cold-preserved state, as discussed in Suris-Valls et al. [9], with a severed left arm. After being revived in Moscow, he was found to be suffering from serious brain damage and amnesia. During this time, he was fitted with an advanced bionic arm, which was periodically upgraded with advancements in technology.

The Winter Soldier's origin story in the MCU slightly differs. After months of battling Red Skull, Armin Zola, and Hydra across Europe, the Howling Commandos board a Schnellzug EB912 train on a mission to capture Zola in *Captain America: The First Avenger*. After neutralizing a number of armed guards, Captain America and Bucky are fired upon by a soldier with a Arnimhilation 99L Assault Weapon that blows a hole in the side of the train and knocks Captain America off his feet. After Barnes picks up Captain’s shield, another shot from the solider hits the shield, launching Barnes out of the train. After taking out the solider, Rogers sees Barnes hanging onto a rail on the side of the train. Before Rogers can reach him, Barnes loses his grip and falls to his apparent icy death.

However, earlier in the film, Armin Zola experimented on Barnes, enhancing his physiology in the process. It is these enhancements that help Barnes to survive the fall. His almost lifeless body, minus a severed left arm, is discovered by a Soviet solider on a riverbank. He is imprisoned by Hydra’s Soviet wing for many years until he is acquired by Zola and Hydra. Barnes then enters the Winter Solider program under Zola and Barnes becomes the first Winter Solider, gaining his advanced bionic arm in the process.

It's reasonable to assume that Barnes' original arm was constructed using the most advanced technology of the day, with additional enhancements and improvements added as technology progressed. To investigate the construction, integration, control, and improvement of such a bionic arm, this paper assesses the biological damage sustained by Barnes by looking at the effect of his bionic replacements on his physiology, the bionic arm itself; its functions, materials, construction, and operation, and finally, its integration into his neurological and nervous system to allow him to control the arm.

While advanced materials and technologies currently exist that could allow for the production and integration of advanced neurologically-controlled bionic and prosthetic arms, many of the features of the Winter Soldier bionic arm are purely fictional. However, an assessment of how the most realistic features could be replicated is presented here.

CAPABILITIES OF THE WINTER SOLDIER

The Winter Solider possesses a range of enhanced abilities thanks to the combination of his enhanced physiology and advanced bionic arm. Some of his advanced physiological abilities include enhanced strength, durability, speed, agility, stamina, reflexes, healing factor, and longevity.

These enhanced skills make him a formidable solider while also allowing him to survive the fall from the train in *Captain America: The First Avenger*. In addition, the physiological changes to his body from the Hydra treatments help facilitate the integration of his advanced bionic arm.

Figure 1: The Winter Soldier in action in *Captain America: The Winter Soldier* [2].

CAPABILITIES OF WINTER SOLDIER'S ARM

Barnes' advanced prosthesis exhibits a range of additional functionalities such as superhuman strength and stamina, while the arm itself is durable and resistant to wear. For example, in *Captain America: The Winter Soldier* Barnes use the arm to decelerate as he moves backwards across a road (Figure 1). In addition, later versions of the arm include holographic functionality, allowing it to appear like a human arm [10]; EMP discharge that shuts down Nick Fury's Life Model Decoy (LMD) when he attempts to use it on Iron Man [11]; auto-reloading of weapons and increased combat reaction times [12]; a flamethrower with additional electrical discharge [13]; biosecurity features, including biometric fingerprints [14], and most interestingly, the ability to control the arm remotely [15].

ANATOMICAL DAMAGE TO THE WINTER SOLDIER

Bucky Barnes was just one of many captured prisoners of war who were experimented on by Armin Zola, who sought to replicate the super-solider serum used to create Captain America. Initial experiments by Zola sufficiently enhanced Barnes' physiology so that he could survive the fall. However, this work was further advanced by Zola in the Winter Solider program, resulting in Barnes' enhanced physiology. While the initial experiments helped him to survive the fall, Barnes still suffered a serious physical injury. As shown in *Captain America: The Winter Soldier* (Figure 2), Barnes suffered significant muscle and bone loss.

Figure 2: Close up of the upper shoulder section of the arm [2].

Damage to muscles near the top of the left arm resulted in damage to the trapezius, pectoralis major, pectoralis minor, subclavius, serratus anterior, rotator cuff, deltoid, latissimus dorsi, triceps brachia, and brachioradialis as indicated in Figure 3. These muscles would have to be replaced with biomechanical replacements, providing enhanced performance characteristics when compared to normal human muscle performance.

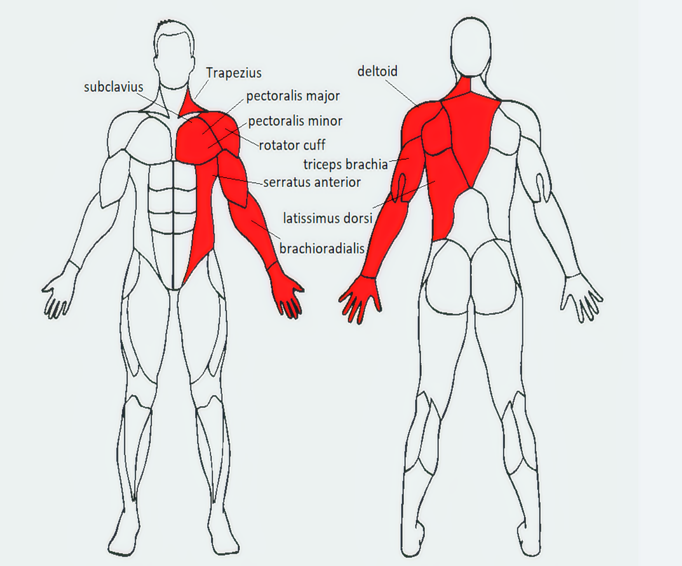

Figure 3: Estimated muscle damage sustained by Bucky Barnes [16].

Similarly, Barnes would have lost numerous bones in his left arm (Figure 4) including the clavicle, scapula, humerus, radius, ulna, and all of the bones of the hand (*ossa capri*, *ossa metacarpi* and *ossa digitorum manus* bones). In the bionic arm, these bones would also have to be replaced with high strength, high hardness artificial bones or similar underlining structures to act as support for the hardware, to properly connect the arm to the human body, and provide protection to the biological elements against the high stress use of the arm.

Such severe damage necessities significant replacement of damaged bodily components. These lost muscles, bones, and nerves must be replaced, either with anatomic replacements or similar structural frameworks. Assuming replacement with anatomic variants, a range of advanced biomedical replacements are necessary. While the clavicle and scapula, along with the pectoralis, deltoids and trapezius muscle will all have suffered some form of damage (Figure 5) due to the high weight and forces applied via the prosthetic arm, they will all require whole or partial replacement or reinforcement.

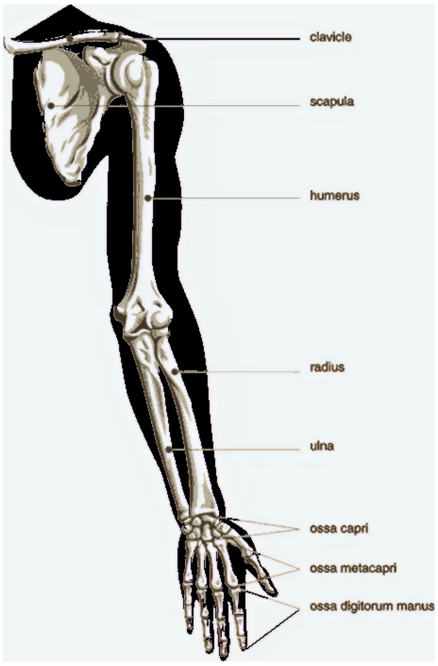

Figure 4: Estimated muscles damage sustained by Bucky Barnes [17].

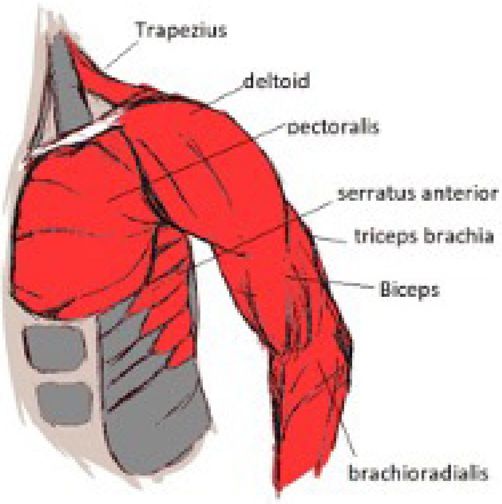

Figure 5: Muscles in need of replacement/replication post injury [18].

THINKING MATERIALS

Due to its inherent abilities, in particular its extreme material strength and durability, the materials used to fabricate the Winter Solider arm are very important. As shown in the MCU, the arm gives the Winter Soldier superhuman strength, while also being highly durable. The arm itself is super-strong, with an articulated surface that can be removed for repair if required as shown in *Captain America: The Winter Soldier* (Figure 6). Due to the relatively small thickness of this armour, the arm must be extremely tough and durable. This seems to be case given the number of times that the arm has deflected or stopped small and medium calibre gunfire. These characteristics support an exoskeleton design for the arm, with external support structures. These characteristics will be used to estimate the material properties and to identify suitable materials.

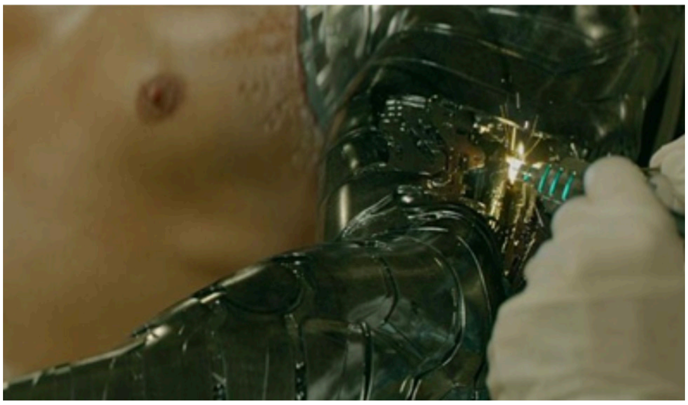

Figure 6: Close-up view of the external and internal structure of the arm while under repair [2].

The material used to construct the arm has been an active source of discussion on fan sites, with many ideas on the materials used [18]. In the Marvel universe, many fictional materials exist such as adamantium (grafted to Wolverine's skeleton), carbonadium (as used in Doctor Octopus's tentacles or Deadpool's Katanas), uru (Thor's hammers Mjölnir and Stormbreaker), and vibranium – the material that can be found in Captain America's shield, the Vision's body, and the most recent iteration of the Winter Soldier's arm as featured in the Disney+ series *The Falcon and the Winter Soldier*.

FICTIONAL MARVEL MATERIALS

To identify the real-world materials that could be used to make the bionic arm, I applied an assessment procedure to ascertain the characteristics and performance of the arm when subject to certain stresses or situations. I consider both real-world and fictional materials.

Let us take a look at fictional materials first. Adamantium can be ruled out as it is almost completely indestructible, unlike the materials used to make the arm in the MCU. Carbonadium is the next fictional contender but can also be ruled out due to its highly radioactive nature, and the associated dangers that it poses to living cells [19]. As no particular radiation related safety precautions were taken by any of the scientists or engineers working on the arm in the MCU, it can be assumed that the arm is not made from carbonadium. While uru exists in the MCU and appears to pose humans no risk when exposed to it, its history as an alien material, arising from metal ore from the Universe's first moon [20] and its purported uniqueness to Nidavellir (as seen in *Avengers: Infinity War*) mean that it can be excluded. Vibranium is the final potential fictional material that could be used for the arm. Indeed, the Winter Soldier receives a vibranium arm in Avengers: Infinity War [4].

POTENTIAL MATERIALS FOR A REAL ARM

Now I'll take a look at real material options for the arm. While there are a number of real materials that could be suitable such as titanium alloys, aluminium alloys, and steel alloys, the high strength and durability of the arm does not match the properties of these materials, especially not the materials that were available during the period from the mid 1940's and to the end of the Cold War (1980s). Therefore, to identify real-world materials that match these characteristics, an initial assessment based on density is considered.

To estimate the density of the material in the arm, initial mass data was collected for Bucky Barnes and the Winter Solider [22], with an additional data set for the actor Sebastian Stan who plays Bucky Barnes [23]. This data can be seen in

Table 1, which was used to estimate the mass and density of the bionic arm. Density is a measure of the amount of matter in a given volume, describing how tightly packed the atoms of a substance are in a given volume.

Table 1: Estimated mass data of the actor Sebastian Stan, Bucky Barnes, and the Winter Soldier [22,23].

	Sebastian Stan	Bucky Barnes	Winter Soldier
Height (m)	1.83	1.70	1.75
Mass (kg)	78.02	68.04	117.92

Data from a paper by DeLeva [24] gives the average mass of each limb segment as a percentage of a person's total body mass (Table 2). It should be noted that the values for limb segments are statistical averages and individuals will exhibit some specific differences.

Table 2: Average mass of limb segments as a percentage of body mas [24].

Limb	Women (%)	Men (%)
Upper arm	2.55	2.71
Forearm	1.38	1.62
Hand	0.56	0.61
Thigh	14.78	14.16
Leg	4.81	4.33
Foot	1.29	1.37

Using the mass for Sebastian Stan (Table 1) and an estimated left arm mass of 4.94% (upper arm, forearm, and hand from Table 2) of the average mass of a male gives a left arm mass of 3.85 kg. Accounting for the estimated mass of the Winter Soldier of 117.93 kg, a mass difference of 39.93 kg exists between the Sebastian Stan and the proposed mass of the Winter Solider. Assuming similar bodily composition for Sebastian Stan and the Winter Soldier, it is estimated that the bionic arm weighs approximately 43.77 kg.

An average volume for the left arm can be estimated using biomedical data from a biomedical study of military personal conducted by the US Air Force in 1996 entitled "Weight, Volume and Center of Mass of Segments of the Human Body" by Charles E Clauser *et al.* at Air Force Systems Command, Wright Patterson Air Force Base in Ohio [25]. This military-focused study looked at US Air Force male cadavers that were undergoing dissection and analysis to measure mass, volume, and the center of mass of segments of the human body. Using this research, the average arm volume of a military solider is estimated to be 0.002324 m^3 (2324 cc) based on the average measurement of 3 male specimens aged 30, 30, and 68 to cover the full range of average serving ages. This average consists of the average measurement in cubic centimetres of the left upper arm, left forearm, and left hand of the three and subjects (Table 3).

Table 3: Estimated volume of the left upper am, left forearm, and left hand in m^3 and cubic centimetres (cc) [22,23].

	Upper arm	Forearm	Hand
m^3	0.00127	0.00069	0.00037
cc	1265	690.2	368.4

An estimated arm mass of 43.77 kg, combined with an estimated arm volume of 0.002324 m^3 give an arm density of 18,837.23 kg/m^3 (43.77kg / 0.002324 m^3). Hence, to replicate the arm in the real world, a material with a similar density is needed for the arm. This calculation assumes a solid arm without any internal cavity, motors or additional elements. This could result in the actual density of the main arm material being significantly underestimated. Using this density as a rough guide, various metals and alloys with a density within 10% of the density of the Winter Soldier's arm are presented in Table 4.

Table 4: Material densities of elements in the calculated range for the arm of the Winter Soldier [26].

Element	Density (kg/m^3)
Rhenium	20,800
Neptunium	20,200
Plutonium	19,816
Tungsten	19,600
Gold	19,320
Uranium	18,900
Tantalum	16,400

Density is linked in part to material strength or resistance to deformation or change. In most cases, the higher the density, the stronger the material. The main measures of material strength are tensile strength (resistance to tension), compressive strength (resistance to compression), yield strength (resistance to permanent deformation) and impact strength (resistance to fracture on impact). As the Winter Soldier's arm is bulletproof to some extent, it must exhibit high impact resistance and thus is not brittle. Based on the estimated density of the arm, the mostly likely materials are plutonium, tungsten, gold, and uranium.

Comparing these materials, plutonium is radioactive and is about as hard and brittle as grey cast iron (used in engine blocks). If it is alloyed with other metals, it can be made more ductile or soft. Gold is considered the most malleable of all metals as it can be drawn into wire by way of its high ductility, making it unsuitable for impact or tension. That leaves tungsten and uranium as potential metals. Tungsten is a hard metal, but is often brittle and difficult to work with, while uranium is a weakly radioactive metal equal in hardness to tungsten, but with similar levels of brittleness. Both of these materials can be made less brittle via alloying or advanced processing techniques. Historically, tungsten and uranium have been used in kinetic energy penetrators (KEPs) (Figure 7), more commonly known as armour piecing projectiles or rounds.

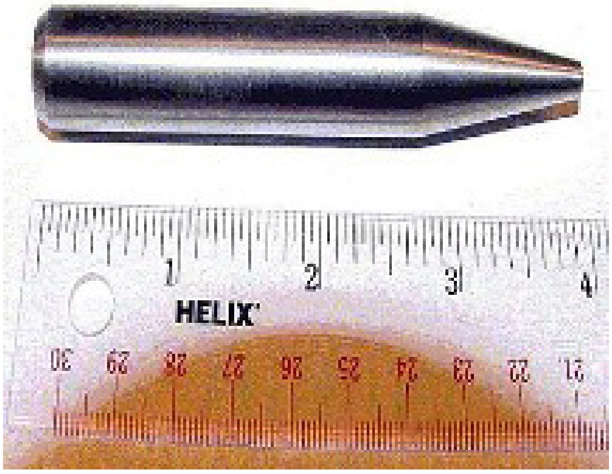

Figure 7: Tungsten kinetic energy penetrator (KEP) round [27].

Tungsten, alloyed with nickel and iron or cobalt, and depleted uranium, which is created during the enrichment of uranium for nuclear fuels, are often used as materials for KEPs. Similarly, they have found use in high-impact armour plating for tanks and other military operations. Alloys of these metals including staballoys (depleted uranium alloyed with titanium or molybdenenum) or ferrouranium (an alloy of iron and uranium) are both potentially suitable materials for the arm. Historically, uranium-doped steels were used in tools after World War I [28], while enriched uranium was first manufactured in the 1940's after both the US and USSR began their nuclear weapon programs. Due to the advanced nature of the technology, and the importance of the Winter Soldier program, I propose that post-World War II, the Winter Soldier's arm was produced from either tungsten carbide or depleted uranium alloys. Due to the inclusion of titanium in future iterations of the arm, a staballoy is a highly likely material.

It is important to note that during the events of *Avengers: Infinity War*, Barnes received a new arm made of vibranium that was produced by Shuri in Wakanda (Figure 8). However, due to the unknown properties of vibranium an assessment of this arm is not possible at present.

Figure 8: The Winters Soldier's vibranium arm that he received in *Avengers: Infinity War* [4].

Accounting for the inherent properties attributed to the arm, its density, its composition, and functional requirements, I propose that the earliest incarnations of the Winter Soldier's prosthetic arm used staballoys (depleted uranium alloyed with titanium or molybdenenum) or ferrouranium (an alloy of iron and uranium), owing to high proportions of this material available to the Soviet Union at the time. Later, the arm was replaced with a more advanced titanium alloy-based arm until Barnes received the vibranium arm.

BIOMECHANICAL ACTUATION

To properly control and move the arm, a series of human body parts must be replicated and replaced with technology such as bones, muscles, and nerves. Leal-Naranjo *et al.* conducted a study on the mechanical design of a prosthetic arm [29]. As part of the study, they created a block diagram describing the systems design for a prosthetic arm (Figure 9). This diagram sets out the main components required for an advanced controllable prosthetic arm.

Components required include a mechanical structure, actuators, sensors, a power source, and a control system. The mechanical structure takes the place of the bones, the actuators replicate muscles, and the sensors approximate nerves. The Winter Soldier's prosthetic arm will be reviewed under these core areas.

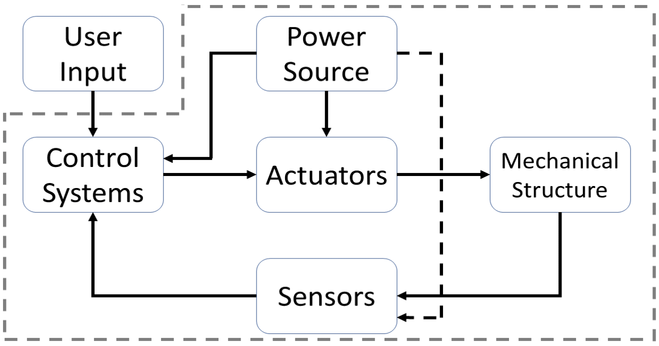

Figure 9: Illustration of the system design of a prosthetic arm [29].

MECHANICAL STRUCTURE

An underlying structure acts as the primary support for the arm. Bone replacements or structural framing networks can be used for this purpose. While the concept of full metal-based bone is currently fictional, mainly due to the impact such bones would have on the surrounding biological materials via displaced forces, the idea of adding metal elements to bone to increase strength is often used in healthcare

Internal fixation, the process of inserting a metal rod into the inter cavity of a bone, is used in many medical treatments. This process involves the insertion of a series of rods and nails into a bone, usually made from surgical grade stainless steel or titanium to provide internal support. Importantly, these metals are biocompatible, which means that they are non-toxic to biological cells. The internal bone marrow is removed, with the rod (also known as a nail) inserted into the marrow cavity in long bones such as the tibia, femur, humorous, or forearm. This rod is then fixed with screws into the surrounding bone, adding the required internal strengthening mechanism for the bone. These are considered as intramedullary devices – a device inserted into a marrow cavity. The process of inserting one of these intramedullary devices into a femur bone is shown in Figure 10.

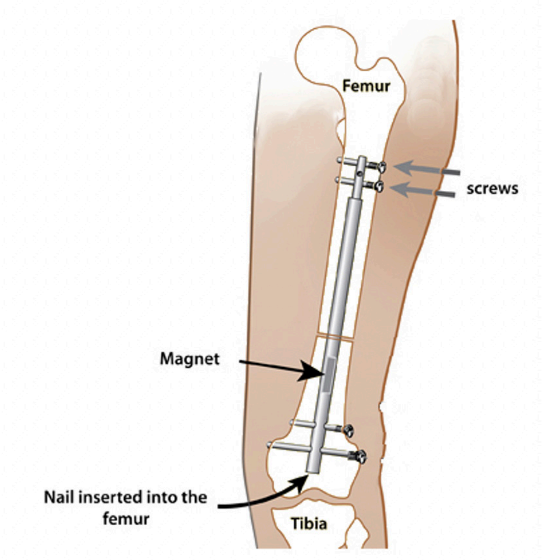

Figure 10: Illustration of the insertion of a intra-medullary device into a femur bone [30].

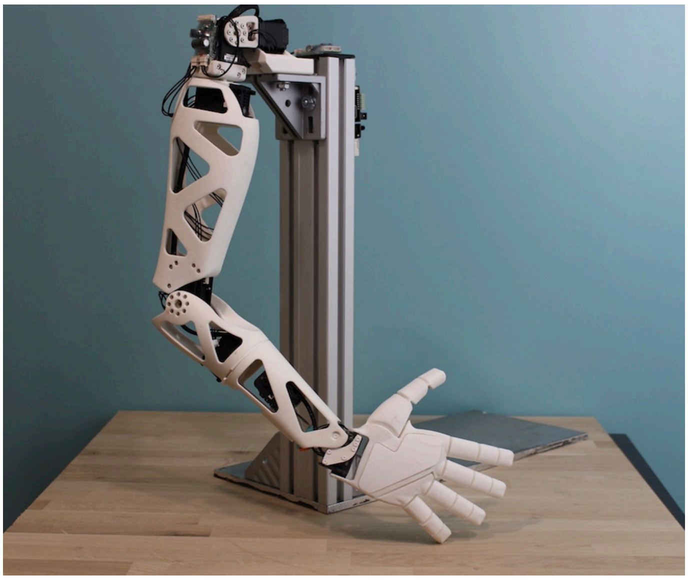

Figure 11: External structure of the "Reachy" arm - a human-like life-scale robotic arm [31].

If metallic bone replacements are infeasible, utilisation of an exoskeleton type support structure would be a viable alternative. Such a structure would provide overall support to the arm and allow integration of the motors and control mechanisms.

Mick *et al.* [31] developed a biomimetic test arm platform called "Reachy", a human-like life-scale robotic arm with seven articulated joints to mimic the human arm. This arm was 3D printed, a process which is growing in popularity in several applications [32], and included off-the-shelf actuators, open-source architecture, and customisable design parameters. The underlying arm structure comprised of the three main segments of the human upper limb, from shoulder to hand, with a lattice link external frame (Figure 11). A similar arm structure would be a viable alternative to a metallic bone replacement for use in the arm of the Winter Soldier. This external support structure has a high probability of being the base structure in the arm, with its ability to support and protect the internal mechanisms needed to operate the arm such as artificial muscles, nerves, and control structures.

ACTUATORS

The bionic arm also needs "muscles" to operate, thus mechanical alternatives are needed. While electronic motors can provide the necessary motion, they do not have the strength or speed of the Winter Soldier's arm. As such, it is likely that a form of advanced muscle structure is used. Man-made devices that replicate muscle form and function have been in development for decades, inspired by science fiction designs such as those from Hesse [33] (Figure 12). These muscles are known as pneumatic artificial muscles (PAMs), first developed in the 1950s by Joseph L. McKibben under the name McKibben Artificial Muscles for artificial limbs. They were commercialised successfully by Bridgestone Rubber in the 1980s.

PAMs operate via contraction or extension by filling a pneumatic bladder or air sack to replicate real human muscles. A McKibben muscle consists of an inner rubber section containing air, and an outer woven shell of non-stretchable fibres (Figure 13). When relaxed, the air pressure in the muscle is the same as that outside the muscle, resulting in no change. When the muscle contracts, the air pressure increases causing the muscle to contract.

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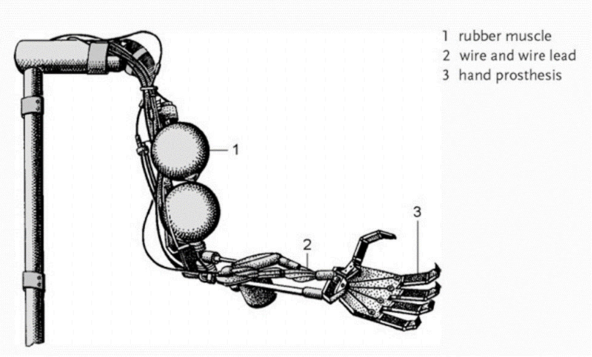

Figure 12: Arm prosthesis with segmented rubber muscles (after McKibben) [33].

PAMs are lightweight, which allows them to be easily integrated into artificial limbs, are very complaint which helps them to “give in” when tasked with delicate procedures, and their applied forces can be tailored via pressure and the state of inflation. These features allow them to provide power when needed, be gentle when required, and can be finely controlled due to their predictable response characteristics. Supporting power and air pressure is required, necessitating the use of electric values and some form of compressed air generator to provide air pressure. While most of these systems are pneumatically (gas) operated, they can also be hydraulically (liquid) operated with an incompressible fluid increasing system rigidity and reducing system compliance (the resistance of the system to variation). The most viable system for the Winter Soldier’s arm is therefore a series of PAMs acting as the muscles of the arm, similar to those illustrated in Figure 14. These devices would be controlled hydraulically (for increased pressure and power) with an advanced fluid pump in the arm to provide the necessary hydraulic pressure.

After the integration of actuator-based muscles, systems to allow Barnes to control how these “muscles” are required. It is essential that the arm has the appropriate control systems that allow Barnes to punch through concrete or pick up a pen, and to sense the forces associated with both actions. Sensing systems are therefore vital.

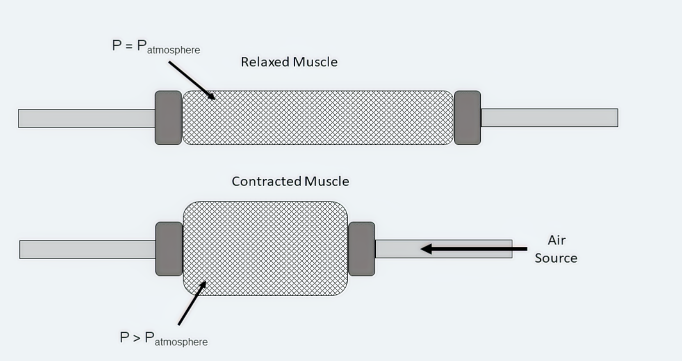

Figure 13: A McKibben muscle in a relaxed and contracted state [34].

Figure 14: Basic artificial muscle integration in a robotic arm structure [35].

SENSORS

While structural strength and muscular power are required for offensive capabilities, sensing and tactility are needed for non-offensive situations. The Winter Soldier’s arm needs to “feel” with his arm, whether it is sensing hot or cold, knowing when he is touching an object, or sensing how much force to use in everyday situations such as using a phone to text someone or to write a note on a piece of paper. Modern electronic sensing is well advanced with high quality, accurate sensors available from developments in the space, aerospace, scientific, and medical fields. A basic sensor assembly in the soldier's arm would need to measure the occurrence of a contact, the force experienced during contact, and temperature.

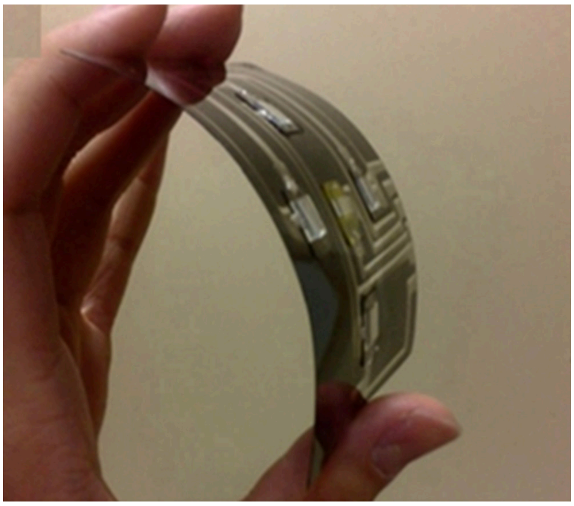

Figure 15: Flexible optoelectronic sensor [37].

Flexible contact sensors like those developed by Persichetti *et al.* [36] would be quite suitable for the arm. These optoelectronic-based sensors act as a flexible contact sensor for potential use in prosthetic hands. The sensors allow the user (via the controller system) to know when the finger is interacting with the environment around it. This type of sensor uses optoelectronics (where light carries the data signal) to measure when contact occurs. These sensors are available as thin flexible sheets made of semiconducting polymers (Figure 15), allowing them to be easily integrated into the hand.

Force sensing is needed to ensure that the right amount of force is delivered for the desired action. For example, high force is needed for combat and lower force is needed for daily activities such as brushing one's teeth or opening a bottle. Force sensing is normally achieved using a sensor, with mechanical, hydraulic, or digital sensors being the primary sensors employed in current technologies. For use in a Winter Soldier arm, a digital force sensing system is required due to the size limitations of the arm. Digital force sensors commonly measure compressive, tension, or bending forces, and can be used to measure a range of physical force interactions. As the arm requires small, accurate, and tough sensors, it is likely some form of force sensing resistor (FSR) needs to be used. These FSR systems detect physical pressure applied to the sensor, allowing the measurement of physical pressure, squeezing actions, or weight.

FSRs are resistors that change their resistance (measured in ohms (Ω)) depending on how much pressure is applied. These sensors are low cost, and easy to use, and give an estimated value of the applied force. Their basic structure is two layers separated by a spacer (Figure 16). As one-layer presses into the other via the applied external force, more of the active dots or structure contact the upper layer, therefore reducing the resistance of the unit itself, and varying the electronic signal from the unit. These FSR units would give the fine force control needed for the arm's hand to be effective in combat, but also functional in daily life.

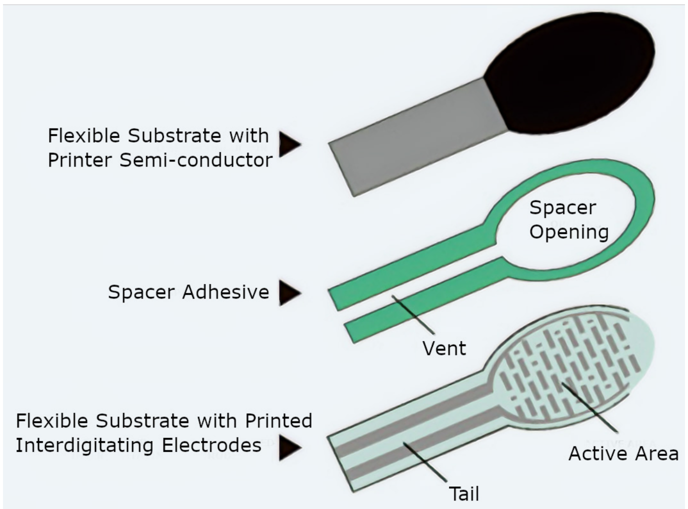

Figure 16: Operational principle of a force sensing resistor (FSR) [38].

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Figure 17: Sensor integration in the model of an artificial hand [39].

The final basic sensing function required is temperature sensing, which is used to measure the temperature of a surface and gather important environmental information for the user. Temperature sensing has been successfully used for centuries, making this one of the simplest sensing aspects to include in the arm and hand. A number of small highly accurate temperature sensors could be integrated into the arm and hand, giving fine temperature measurement to the system. A small temperature sensor, such as the SI7006-A10-IM1 sensor, gives an operational range of -40 °C to +125 °C in a square sensor of side 3 mm. Similar tiny temperature sensors are likely integrated into the arm, providing the same temperature measurement function in the upper parts of the arm. Polishchuk *et al.* [39] developed a sensor array from consumer components that includes the core sensing functionality required for an advanced prosthetic like the hand of the Winter Soldier's arm (Figure 17).

POWER SOURCE

After the selection of a support structure, actuator systems, and sensing functionality, these elements all require electrical power. It is not possible to estimate the power requirements of the arm without an idea of the type, specifications, and functionality of all the electronic components included. However, I will present an approximation of where the power source could be placed in the hand or arm.

It is safe to assume that due to the strength and performance of the arm, it has very high-power requirements. This would mean that the arm in the MCU is powered by some form of non-conventional power source, similar to the power source suggested by Tauber & Fitzgerald in their design of a digestive system for Vision [40]. I am going to assume that the vibranium arm utilizes a power supply based on vibranium. However, earlier versions must have had small high-power output power sources. While Tony Stark's arc reactor is the ideal power source for many superhero-related technologies, as discussed by Fitzgerald [41], it is unlikely that an equivalent arc reactor was developed by the Soviets who designed the first arm used by the Winter Soldier. A more viable power source would be a Tesseract-based power source, such as that developed by Armin Zola (Figure 18). Unfortunately, there is one major problem with using Tesseract-based power sources; the Tesseract doesn't exist!

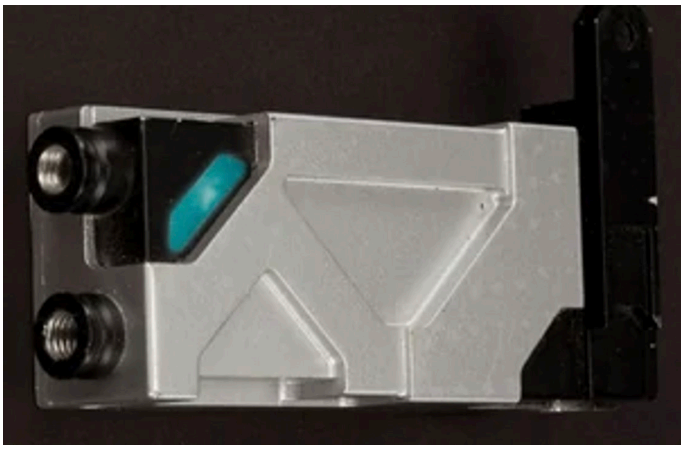

Figure 18: Tesseract battery as seen in *Captain America: The First Avenger* [1].

In realistic terms, a miniaturized nuclear-based power source is the only reasonable source that could meet the high power demands of the arm and that would have been available to the Soviet Union during the 1950s and 1960s. In modern times, most advanced prosthetics are powered by compact lithium-ion (Li-ion) battery packs, similar to those

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used in laptop computers. These batteries provide approximately 12 hours of continuous power for integrated sensing, control, and motor functionality. A great example of such a system is the OpenBionics Hero Hand [42], which uses a 7.5V 2600mAh Li-ion battery to give approximately 12 hours of battery life after 5 hours charge time. The batteries are integrated into the arm in a number of ways depending on size and design (Figure 19).

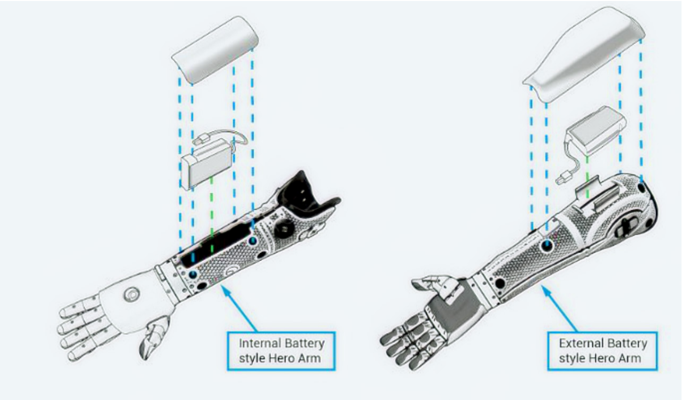

Figure 19: Illustration of battery placement in an OpenBionics Hero Hand [42].

CONTROL SYSTEM

An advanced prosthetic is useless without the ability to control the prosthetic. Due to the high performance of the Winter Soldier's arm, the arm is most likely using an advanced mind-controlled approach, as discussed by Fitzgerald [41].

In the early days of prosthetics, the devices were basic hooks or very simple physical objects, giving extremely limited functionality to the user. As time progressed, more complex, but still basically physical driven, solutions were applied, with many requiring an articulated joint or movement to provide some form of mechanical input from the user. A classic example is the Bowden Cable Harness prosthetic control system (Figure 20). This system uses a cable connected to a body harness, which allows a hook to close when the user moves their arm, thus applying tension on the cable, and closing the "hand".

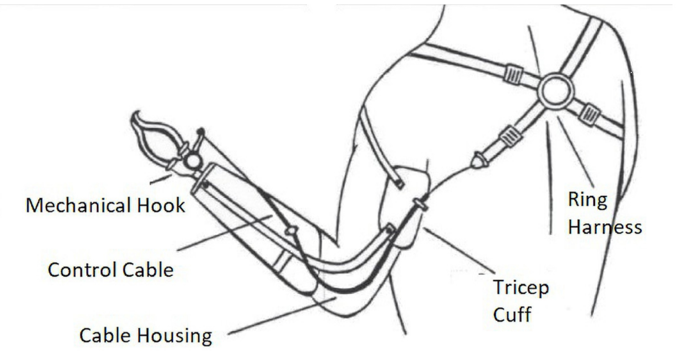

Figure 20: Bowden cable harness system [43].

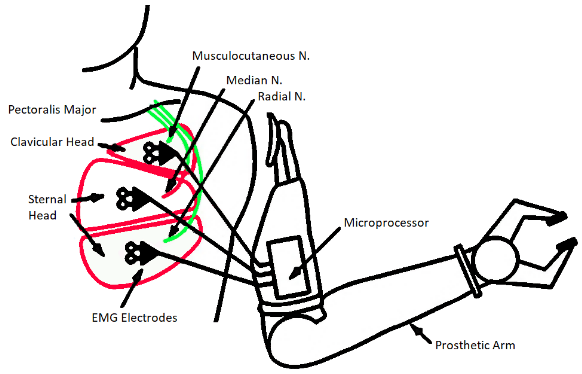

Figure 21: Electromyography based prosthetic control schematic [44].

More advanced prosthetic systems utilize muscle sensing systems, via a myoelectric process. Myoelectric is the term describing the electric properties of muscles, where a myoelectric prosthesis is a limb controlled by using the electrical signals generated naturally by the individual's own muscles. For a full arm system, the arm must use existing user muscles to control the limb. Research published by Scheme and Englehart [44] showed how a control system that sensed movement from the muscles of the upper chest (Figure 21) allows the myoelectric control of a prosthetic via an embedded microprocessor in the arm. This system uses electromyography (EMG) sensors to measure the muscle activity in the chest muscles, translating these signals into arm movement. These systems are growing in popularity, but to date cannot provide immediate full function control in an advanced manner similar to that of the Winter Soldier's arm.

An even more advanced version is the use of direct nerve control for advanced prosthetics. A study by Ortiz-Catalan [45] in the New England Medical Journal documented the case of 3 patients who have used mind-controlled prosthesis daily for several years via a neuromuscular prosthesis. These systems are connected directly to the users' nerves, muscles, and skeleton, and give the user the ability to not only control the arm but also to feel sensations via direct stimulation of the users' nerves. This system involves attaching the prosthetic to the user's upper arm bone, implanting a number of muscular and neural electrodes into the arm muscles, and a bidirectional communication system in the arm. This bidirectional communication system allows for direct communication between a prosthetic hand and the electrodes implanted in the nerves and muscles, adding "brain control" and simulated feeling for the user. Users of the device did not require any formal training as the device is operated via intuitive user intent. This integration of rapid natural responses and sensory feedback from the prosthetics would be necessary to support the immediate reaction time of the Winter Soldier arm.

This final control aspect completes the proposed arm assembly, and in theory will give a strong, durable, tough, highly functional arm, which has the dexterity required for human function, the responsiveness required for combat, and the sensing and control required for fine motor skills.

CONCLUSIONS

This paper presents some key background information on the origins of the Winter Solider, his creation and development over time, and discussed a series of technical engineering observations which allows a prediction of some of the functional characteristics of his iconic bionic arm.

An assessment of the anatomical damage suffered by the Winter Solider was discussed, with this setting out the basic engineering requirements for an arm equivalent in the real world. My analysis led to a series of informed assumptions supporting an estimate of the probable mass of the bionic arm, allowing for the calculation of estimated mass, volume, and therefore the material density of the arm. This density was used to identify viable materials that would provide the necessary strength and durability displayed by the arm in the comic books and MCU films. These calculations, added to the technical capacity of the era of the Winter Soldier, indicate that the earliest incarnations of the Winter Solider prosthetic most likely used staballoys (depleted uranium alloyed with titanium or molybdenum) or ferrouranium (an alloy of iron and uranium), owing to the high proportions of this material in the Soviet Union at the time of the Winter Soldier's inception. Later on, the materials in the arm were replaced with more advanced titanium-based alloys until the arm was eventually replaced with a vibranium arm, thanks to the innovation of Shuri from the fictional African nation of Wakanda.

A follow up engineering analysis of the main components of this arm, namely the mechanical structure, actuators, sensors, a power source, and a control system was supported by a discussion on viable options for each component including a number of advanced technologies currently used and proposed for future use in advanced prosthetic systems.

In conclusion, it is possible to create a functional arm demonstrating some of the functionality of the Winter Soldier's arm, but the high levels of performance shown in its durability, strength, and reaction speed are currently far beyond our current technologies. Further developments are ongoing with regards to all of the subsystems discussed here. One day we may have the technologies needed to duplicate the arm of the Winter Soldier. My hope is that this technology will be made available to amputees or those born with limb deformities rather than cryo-preserved assassins who are more than 100 years old.

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REFERENCES

1. Johnston, J., Captain America: The First Avenger (motion picture). 2011, Marvel Studios

2. Russo, J. and A. Russo, Captain America: The Winter Soldier (motion picture). 2014, Marvel Studios.

3. Russo, J. and A. Russo, Captain America: Civil War (motion picture). 2016, Marvel Studios.

4. Russo, J. and A. Russo, Avengers: Infinity War. 2018, Marvel Studios.

5. Russo, J. and A. Russo, Avengers: Endgame. 2019, Marvel Studios.

6. Spellman, M., The Falcon and in the Winter Soldier. 2021, Marvel Studios.

7. Kirby, J. and J. Simon, Captain America Comics. 1941, Timely Publications.

8. Brubaker, E., Captain America Vol. 1: Winter Soldier, Book One. 2006: Marvel Comics. 168

9. Suris-Valls, R., Mehmedbasic, M. and Voets, Ilja K.,

Marine fish antifreeze proteins: The key towards cyropreserving the Winter Solider, 2018, Superhero Science and Technology, Vol .1, No. 1

10. Captain America Vol 5, Marvel Comics

11. The Gamer [cited 2020 March 18th]; Available from: https://www.thegamer.com/marvel-winter-soldier-super-powers-hidden-weaknesses/

12. Zub *et al.*, Thunderbolts (2018) Vol. 3 #2. Marvel Comics.

13. Zub *et al.*, Thunderbolts (2018) Vol. 3 #1. Marvel Comics.

14. Kyle Higgins *et al.*, Winter Soldier (2018) #4, Marvel Comics

15. Zub *et al.*, Thunderbolts (2018) Vol. 3 #4. Marvel Comics.

16. Muscle Wiki, [cited 2020 March 18th]; Available from: https://musclewiki.com/.

17. GraphDiagram, [cited 2020 March 18th]; Available from: http://graphdiagram.com/skeletal-system-arm/.

18. Tumblr: Cptsassroger [cited 2020 March 18th]; Available from: https://cptsassrogers.tumblr.com/post/84882869377/inspired-by-therealsixs-meta-on-buckys-arm-by.

19. Marvel Fandom Database, Carbonadium, [cited 2020 March 18th]; Available from: https://marvel.fandom.com/wiki/Carbonadium.

20. Marvel Fandom Database, Uru, [cited 2020 March 18th]; Available from: https://marvel.fandom.com/wiki/Uru.

21. Marvel Cinematic Universe Wiki, The Winter Soldiers Prosthetic Arm, [cited 2020 March 18th]; Available from: https://marvelcinematicuniverse.fandom.com/wiki/Winter_Soldier%27s_Prosthetic_Arm.

22. Marvel Cinematic Universe Wiki, The Winter Soldier, [cited 2020 March 18th]; Available from: https://marvelcinematicuniverse.fandom.com/wiki/Winter_Soldier.

23. BodySize.Org, Sebastian Stan, cited 2020 March 18th]; Available from: https://bodysize.org/en/sebastian-stan/.

24. De Leva, P., Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. J Biomech. 1996 Sep;29(9):1223-30. doi: 10.1016/0021-9290(95)00178-6. PMID: 8872282.

25. Clauser, C. E., J.T. McConville, and J. W. Young, Weight, Volume and Center of Mass of Segments of the Human Body, 1969, Aerospace Medical Research Labartaty, Aerospace Medical Devision, Air Force System Command, Wright Patterson Air Force Base, Ohio, Distributed by the Nationall Technical Information Service of the U.S Department of Commerce.

26. The Engineering Toolbox, Metal Densities, [cited 2020 March 18th]; Available from: https://www.engineeringtoolbox.com/material-properties-t_24.html.

27. DU penetrator from the A-10 30mm round, [cited 2020 March 18th]; Available from: http://www.deploymentlink.osd.mil/du_library/du_balkans/fig1.htm

28. Marshall Cavendish Corporation (2003). How It Works: Science and Technology. Marshall Cavendish. p. 2548. ISBN 0-7614-7314-9.)

29. Leal-Naranjo J.A., M. Ceccarelli, and C.R. Miguel Torres-San, Mechanical Design of a Prosthetic Human Arm and its Dynamic Simulation. In: Rodić A., Borangiu T. (eds) Advances in Robot Design and Intelligent Control. RAAD 2016. Advances in Intelligent Systems and Computing, vol 540. Springer, Cham. https://doi.org/10.1007/978-3-319-49058-8_52.

30. Lifebridge Health, Internal Fixation: Rods and Nails, [cited 2020 March 18th]; Available from:https://www.limblength.org/treatments/lengthening-deformity-correction-devices/internal-fixation-rods-and-nails/.

31. Mick, S. *et al.*, Reachy, a 3D-Printed Human-Like Robotic Arm as a Testbed for Human-Robot Control Strategies, 2019, Frontiers in Neurorobotics, Volume 13, pg: 65, doi: 10.3389/fnbot.2019.00065

32. Keaveney, S. *et al.*, Applications for advanced 3D imaging, modelling, and printing techniques for the biological sciences, in: 2016 22nd Int. Conf. Virtual Syst. Multimed., IEEE, Kuala Lumpur, Malaysia, 2016: pp. 1–8. doi:10.1109/VSMM.2016.7863157.

33. Hesse, S, Golems Enkel - Roboter zwischen Phantasie und Wirklichkeit, 1986, ISBN 10: 3332000330 ISBN 13: 9783332000337.

34. Popovic, M.B. *et al.*, Chapter 3 - Actuators, Biomecatronics, Academic Press, 2019, Pages 45-79, ISBN 9780128129395, https://doi.org/10.1016/B978-0-12-812939-5.00003-3.

35. Cyberneticzoo, [cited 2020 March 18th]; Available from: http://cyberneticzoo.com/bionics/1968-artificial-muscle-bioprosthesis-polish/.

36. Persichetti, F. Vecchi and M. C. Carrozza, Optoelectronic-Based Flexible Contact Sensor for Prosthetic Hand Application, 2007 IEEE 10th International Conference on Rehabilitation Robotics, Noordwijk, Netherlands, 2007, pp. 415-420, doi: 10.1109/ICORR.2007.4428458.

37. SPIE, The International Society for Optics and Photonics, An organic optoelectronic muscle contraction sensor for prosthetics, [cited 2020 March 18th]; Available from: https://spie.org/news/5812-an-organic-optoelectronic-muscle-contraction-sensor-for-prosthetics?SSO=1#fig1.

38. Adafruit, Force Sensitive Resistors, [cited 2020 March 18th]; Available from: https://learn.adafruit.com/force-sensitive-resistor-fsr/overview.

39. Polishchuk, A. *et al.*, Multisensory Smart Glove for Tactile Feedback in Prosthetic Hand, 2016, Procedia Engineering. 168. 1605-1608. 10.1016/j.proeng.2016.11.471.

40. Tauber, F., & B. W. Fitzgerald, How to build a synthetic digestive system for Marvel's Vision. Superhero Science and Technology, 2021. 2(2), pg: 1-20. doi: 10.24413/sst.2021.2.5636

41. Fitzgerald, B.W., How to Build an Iron Man Suit. 2019, the Netherlands: BW Science.

42. OpenBionics Hero Arm- User Guide, Openbionics, [cited 2020 March 18th]: Available from: https://openbionics.com/hero-arm-user-guide/.

43. Orthobullets, Rehab & Prosthetics, [cited 2020 March 18th]; Available from: https://www.orthobullets.com/basic-science/9072/rehab-and-prosthetics.

44. Scheme, E., and K. Englehart, Electromyogram pattern recognition for control of powered upper-limb prostheses: State of the art and challenges for clinical use. J Rehabil Res Dev., 2011. 48(6):643-60., doi:10.1682/JRRD.2010.09.0177.

45. Ortiz-Catalan, M., Mastinu, E., Sassu, P., Aszmann, O. and Brånemark, R. Self-Contained Neuromusculoskeletal Arm Prostheses. New England Journal Medicine 2020; 382:1732-1738, doi: 10.1056/NEJMoa1917537.