UNSW

BIOM1010
Engineering in Medicine and Biology

Exoskeleton
Week 12 Final Report

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Abstract

With reference to the marking criteria and guidelines of “BIOM1010 Major Assignment”, this report will focus on the exoskeleton in its background, designs, applications, benefits, limitations and potential use in society. The report is sectioned into the following:

- the background will outline the general purpose of exoskeletons and how it improves on the anatomy and physiology of the human body;
- the design section will analyse the general designs in terms of function, materials and features.
- applications will discuss general applications of exoskeletons in industry, medicine and military, and the benefits and limitations as a result; and
- future developments will discuss with foresight where exoskeleton industry and research is directed, major researchers and developers of exoskeletons, and their progress with pioneering exoskeleton technology.

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1. Introduction

The concept of exoskeleton has its roots in the animal kingdom where animals utilise hard-shelled bodies to provide structure and protection for the body. One of the first human uses for an exoskeleton was patented in 1890 by Nicholas Yagn [1] *(refer to Appendix A)*. Named the *"Apparatus for facilitating walking, running, and jumping"*, utilises gas stored in a bag to facilitate certain actions. The purpose of the apparatus was to reduce the energy required by humans to walk, run and jump thus increasing endurance. The next major example of exoskeleton research and development occurred during the 1960s. General Electric collaborated with the US military in attempting to build a new kind of exoskeleton powered by hydraulics and electricity [2] *(refer to Appendix B)*. The Hardiman, as it was called, had the sole intent of increasing the strength of a human by *"a factor of 25"* for moving cargo and heavy equipment.

Exoskeletons are orthotic machines with design varying on the application. However, all exoskeletons work in tandem with the user's movement. In industry, exoskeletons protect the anatomy and physiology of workers by reducing stress and load on the body. In medicine, the major application of exoskeletons are in rehabilitation for patients with stroke; and returning gait function for patients with spinal cord injury. As a result, exoskeletons will see a variety of design iterations depending on the specific application of the design.

In the medical field, the exoskeleton utilizes the force provided by motors and supportive joints to provide a risk-free rehabilitation for patients who suffered from a stroke and Spinal Cord Injuries. The rehabilitation gives the patients a multitude of different pieces of training such as weight shift training and strength training, with the final goal of providing an early recovery for the patients that enables them to reintegrate into their normal lives.

The field of exoskeletons is primarily research orientated as there is still lots of potential for improvement in the current technology of exoskeletons where trends in future development are leaning towards software and a new type of exoskeleton, that is the soft exoskeleton. Many exoskeleton companies such as ReWalk, Ekso and Cyberdyne are contributing to this industry to set the standard of exoskeleton design.

2. Background

The interface between the human body and exoskeleton is purely mechanical. Therefore the exoskeleton follows the anatomy and physiology of the human body. Where the exoskeleton is made of a rigid frame that acts as the orthosis to the body. The exoskeleton also has a controller located on the back of the user. The aim of the exoskeleton is to provide treatment for or to replace the function of the following anatomy and physiology tabulated in table 1 (refer below).

Table 1 - Anatomy & Physiology Concerning Exoskeletons

Anatomy	***Physiology***
Bone	Structure within the body
Ligament (connective tissue between bones)	Allows bones in a joint to retain structure throughout the motion
Tendon (connective tissue between bone and muscle)	Allows muscles to apply a force to the bone, creating motion
Muscle	Contracts to create a force
Nerves	Sends signals to the muscles to determine the strength of muscle contraction

Exoskeletons in medicine have major applications in strokes and spinal cord injuries.

Stroke occurs when the brain receives an insufficient supply of blood and oxygen, causing the death of brain cells. Stroke is Australia's leading cause of disability and it is estimated that 709,000 Australians, about 2.4 % of the population will be expected to have suffered from stroke by 2032 [3]. Many stroke survivors can lose their motor function after a stroke, specifically gait control. Physiotherapy must be undertaken to regain strength and gait function; therefore patients can wear clinical exoskeletons that assist the patient to move correctly. Robot-assisted gait training has been proven to be more effective than without the exoskeleton in order to recover gait function after a stroke [4]. Therefore

The spinal cord is a nerve in the spine that connects the brain to other parts of the body. Spinal cord injury can result in partial or complete loss of sensation, strength or function below where the injury occurred [5]. Worldwide, an estimated 250,000 - 500,000 people suffer from spinal cord injury [6]. Spinal cord patients may bounded by wheelchairs, therefore exoskeletons provide an alternative solution by moving the user’s body for them to mimic gait function.

Exoskeleton application for these two health issues have the potential to significantly improve the patient’s quality of life by giving control back to the patient in an attempt to regain their lost function.

3. Design

3.1 Function

The exoskeleton can be decomposed into two general systems: control and mechanical system. The control system is the software

<u>Control System:</u>

The types of control systems can be sorted into three general approaches [7]:

- The model-based control system is where the control system and processing are based on a physical model of the body. The approach is split into two main models:
  - The dynamic model allows the exoskeleton to be controlled by the user physically moving the skeleton. By using advanced closed-loop feedback mechanisms, the skeleton appears to move with little or no resistance for the user, while overcoming external obstacles and forces.
  - The muscle model uses electromyography as its primary input combined with a working model of human muscle strength. However, EMG can be used without the model by using measured joint angles.
- The physical parameters-based control system: proportion-derivative controller, torque/force controller, and interaction force controllers can be combined into a full control circuit, and;
- The usage-based control system works by knowing the path the patient's limb must take, and actuates to correct the patient if they deviate from the desired path. One example is the ARMin III shoulder exoskeleton, where the patient interacts with a computer to play "games" that assist with rehabilitation and control. The system is also used in the ReWalk, outlined below.

<u>Mechanical System:</u>

The simplest and most effective way to actuate an exoskeleton is to use already well-established methods and techniques: high-torque servo motors, stepper motors, linear actuators, and hydraulic cylinders [8]. Although novel technologies can still be used such as pneumatic air muscles. However, the challenge in design is that the mechanical systems are partially constrained by, or must work with, the dynamics of the human body. For example, the shoulder is a complex system that cannot be modelled entirely accurately with a single mechanical joint. A simple abduction of the shoulder above the horizontal involves many different muscle groups and ligaments. Therefore, the mechanical systems of an exoskeleton must be designed and placed in positions appropriate to the movement they must assist. In many real-world cases, this problem is avoided by enhancing only a subset of possible shoulder motions, like on the Ekso Bionics EksoVest, which is designed to reduce worker fatigue in overhead work.

System Example:

Figure 1 - Rewalk Exoskeleton (Source: https://exoskeletonreport.com/product/rewalk/)

The ReWalk *(figure 1)* uses a combination of sensors and control systems that allow individuals with gait disability to mobilise. Sensors are placed near the lower chest as a control method. If the user leans forward, the walking program activates.

The device has a patient control system which allows the patient to select an operating mode such as sit, stand, or walk. From these commands, the device adjusts its algorithms and control methods in order to carry out the action. Note that this can be classified as a usage-based control system, as the device knows the intended path of the user's legs. Sensors all around the device assist with stability in response to external stimulus. While the device is not an *intuitive* or natural replacement for the user's legs, it allows independent mobility and therefore increases the quality of life.

3.2 Materials

<u>Frame:</u>

The material of the exoskeleton frame should have *"low density, high strength and toughness"* [9]. Exoskeletons are typically made of rigid materials such as steel, carbon fibre, or alloys due to their properties as listed in table 2.

Table 2 - Exoskeleton Materials

Material	***Property***
Steel	○ High Density $(8\ kg/dm^3)$ ○ Cheap $(\$1,091/t)$ ○ Rigid
Carbon Fibre	○ Rigid ○ High Specific Strength $(2457\ kN \cdot m/kg)$ ○ High Tensile Strength $(3.5\ GPa)$ ○ Corrosion Resistant ○ Biologically Inert ○ Expensive $(\$22,000/t)$ ○ Low Density ($1.75 - 2.06 kg/dm^3$)
Duralumin	○ Rigid ○ Lightweight $(2.79\ kg/dm^3)$ ○ Corrosion Resistant ○ Cheap $(\$2,000 - 3,000/t)$ ○ High Tensile Strength $(505\ MPa)$

Steel is cheaper but relatively heavy. A heavier exoskeleton requires more power and can be uncomfortable for the user.

Carbon fibre is the most attractive material for exoskeleton frames due to its high strength to weight ratio (specific strength), rigidity, resistance to corrosion and biological inertness. Therefore exoskeleton frames are biocompatible, small in size and light yet strong enough to support the weight of the user. However, carbon fibre is expensive to manufacture which increases patient costs [10].

Duralumin (aluminium-copper alloy) is cheaper, heavier and has a lower tensile strength than carbon fibre. By a simulation of applying an average human weight force of 800 N to the material. The resulting stress was 88.55 MPa [11]. Therefore, duralumin may be a more suitable exoskeleton material.

3.3 Distinguishing Features

Exoskeletons for gait assistance have distinguishing features that allow its comparison to wheelchairs which have long been the golden standard for mobility in individuals with gait disability [12] *(refer to table 3)*.

Table 3 - List of Features of Exoskeletons and Wheelchairs

Exoskeleton Design Features	***Wheelchair Design Features***
○ Use of sensors to activate movement ○ Walking process is automatic ○ Modes for walking, sitting, standing and changing positions ○ Joints in the exoskeleton to reflect joints in human anatomy ○ Requires battery backpack (ReWalk model lasts 4 hours continuously and 8 hours intermittently)	○ Manual wheelchairs are wheeled by hand or pushed (requires manpower) ○ Power wheelchairs are joystick controlled ○ Seat with independent wheels to each side ○ Power wheelchairs require a battery (80-96.5 km per charge)

Exoskeleton design features such as sensors, automated walking, joints, modes and battery supply; address gait disability by mimicking normal human walking. This differs significantly from the wheelchair's design features of utilising the wheel and a seat to overcome gait disability.

4. Applications & Benefits

4.1 Applications a Benefits

In the medical field, the exoskeleton is used as an assistive device aimed to help physiotherapists to conduct exercises for patients who suffered from a stroke and Spinal Cord Injuries. The aftermath of those conditions result in the long-term walking impairment of patients, these impairments can be mitigated through rehabilitation, if successful, the patient can better reintegrate into the community. The exoskeleton can help with the rehabilitation process by assisting with the patient's ambulation during the recovery process and provide earlier mobility and restored independence [13].

Detailed functions of the exoskeleton in the recovery process:

1. <u>Pre Gait Training:</u>
    a. <u>Weight shift & Balance:</u> The weight shift training prepares the patient for proper stepping through visual or auditory cues set by the physiotherapist to teach the patient to shift their weight laterally and find the midline orientation.
    b. <u>Stepping & Squatting:</u> Stepping is part of the strength retraining program which allows the patient to step in place using their own strength without the risk of falling or injury. This is achieved by using a smart assist force exerted by the exoskeleton which will finish the patient's step when the sensors detect a lack of force which may lead to overexertion of muscles if not cared for. Similarly, the squatting exercise utilizes the motors in the exoskeleton to prevent injury during the rehabilitation.
2. <u>Gait Correction:</u>
    The exoskeleton leads the patient into a predetermined path or trajectory through the use of motors. This forces the patients into a symmetrical gait pattern and performs repeatable smooth steps. Similar to the stepping training, the exoskeleton will provide the extra forces needed to finish the step to prevent injury. Furthermore, this correctional force can be dialled down to encourage the patient to use more of their own strength [14].

4.2 Limitations

Due to the limitations of our current technology, there are 2 distinct limitations of the exoskeleton that needs to be resolved in the future.

1. Limitation in Battery Life:

   Currently, the most used medical exoskeleton Rewalk developed by ReWalk robotics is powered by a main lithium-ion battery and a secondary lithium polymer battery which can provide a total of 2 hours and 15 minutes of continuous walking [15].

2. Limitation in Cost:

   A Rewalk unit costs between $69,000 and $85,000 US dollars [16], whereas the Median household income in the U.S. is only $59,055 [17]. The high cost of the exoskeleton technology made large-scale implementation difficult and push many people into seeking a more affordable alternative for their physiotherapy and recovery aid.

5. Future Developments

5.1 Focus on Software

Exoskeletons are a field of research with limited commercial viability. Future developments and research in exoskeletons are shifting towards software in control systems as gait and balance control, as well as power efficiency becomes a greater concern in design. This is because while machines can fairly well approximate the mechanical functions of the human body, they are much further away from being able to accurately replicate complex processes at which the human brain excels, such as walking. Shifting the focus of future development towards software will allow for more effective therapies and greater commercial viability.

For example, Ekso's flagship medical rehabilitation product is the lower-limb exoskeleton called the EksoGT. It is a newer device, gaining FDA approval in 2016. Ekso markets their product with a special emphasis on the software features available to the users' physicians. For the life of the product, Ekso will be focusing on software to better utilise the already released and purchased hardware.

5.2 Soft Exoskeletons

Future developments of exoskeletons will see a different category of exoskeletons that are "soft exoskeletons" which is an area undergoing active research. The advantages and disadvantages of soft exoskeletons are listed in the following table below:

Table 4 - Advantages & Disadvantages of Soft Exoskeletons

Advantages	***Disadvantages***
○ Light-weight ○ Comfortable ○ Unconstrained movement ○ Fewer mechanical components ○ Efficient Actuation ○ Easier to use ○ Potentially less expensive	○ No external frame ○ Motors and sensors are difficult to mount

The soft exoskeleton developed by Harvard Biodesign Lab attaches to the body and generates the forces required to help the body. It consists of wearable sensors which are compatible with the textile to ensure proper control of soft exoskeleton, the multi-actuator systems to provide flexibility which lead to adaptive human-machine interface to guarantee sync the movement of the user and the exoskeleton [18].

Soft exoskeletons have the potential to become the ideal standard for exoskeletons. From table 4, it is lighter and more comfortable than traditional exoskeletons as it abandons most of the rigid frame; it also provides an unconstrained movement across the usage, where it was previously limited by the frame; and because the material used is significantly less than the traditional exoskeleton, the soft exoskeleton has the potential of being affordable instead of the conventional one.

6. Conclusion

Since its inception, the powered human exoskeleton has been a superficially elegant and simple idea. With its key concepts and features being easy to grasp, it is immediately appealing to the general population. However, this report has shown that there is much depth to real-world design and application of the exoskeleton, and the engineering challenges are much greater than what they seem to be in pop-culture depictions. Seamless control systems are complex to design and implement, materials will always have disadvantages, and computational power has a limit. Even though currently available exoskeletons are slow and bulky at first glance, their ability to provide targeted physical therapy and greater quality of life is tangible. Moving into the future, many of the limiting aspects of exoskeletons such as batteries and computer processing are areas undergoing active research, especially in the case of battery technology. Soft exoskeletons may one day greatly reduce the physical footprint of the powered exoskeleton, and allow for a more general use as an enhancement device rather than a rehabilitative one. The powered human exoskeleton has already shown great potential in the field of biomedical engineering and its utility will only increase as time progresses.

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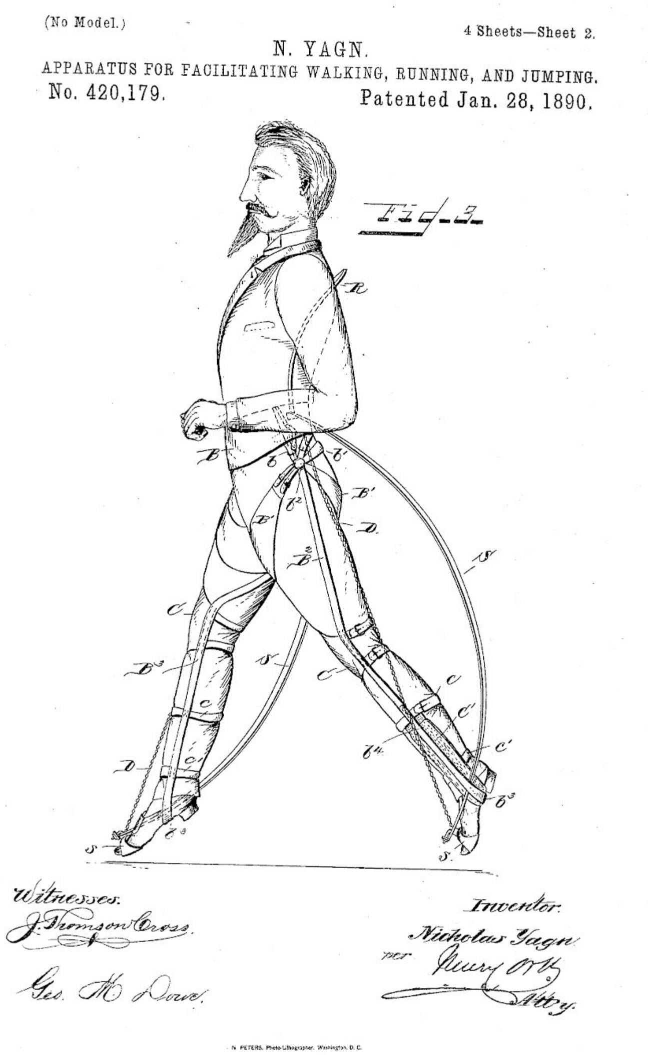
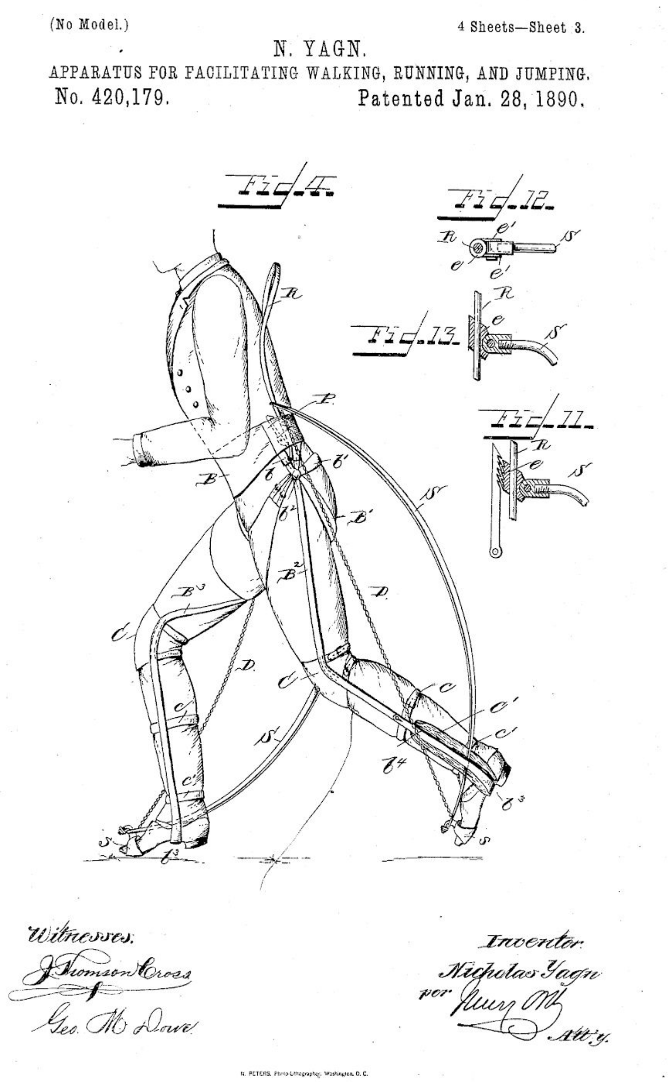
8. Appendix

Appendix A - Figures of Apparatus for Facilitating Walking, Running and Jumping





Source: https://patents.google.com/patent/US420179

Appendix B - Figure of Hardiman Exoskeleton

Source: https://www.ge.com/reports/post/78574114995/the-story-behind-the-real-iron-man-suit/

Appendix C - Figure of Ekso GT

Source: https://exoskeletonreport.com/wp-content/uploads/2016/08/ekso_gt-product-image.png