Design of a non-invasive Hip Exoskeleton (Team 19F03 - HipA)
Preliminary Proposal

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1.0: BACKGROUND

1.1: Introduction

The team will develop a lightweight and cost effective exoskeleton by making adjustments and improvements on the existing hip exoskeletons. The purpose of making this exoskeleton from the existing design is to ensure affordability, comfort and efficiency when functioning. Exoskeletons are used in different sectors such as healthcare, sports, military and rehabilitation facilities. They are used to assist individuals with hip issues to walk and maintain a stable posture. The device comprises of a system with motors that collaborate with the signal produced by the electronic device to provide adequate support to the hip joints of the user. The system also comprises of several actuators that can help the user to walk efficiently. The previous design of the exoskeleton is robotic and costly because of the components used in the manufacturing. The new designs will be cost effective, highly flexible to accommodate different ages and sizes of the users. It also has systems that allow ease of wearing and removing.

1.2: Project Description

"Design and build the mechanical aspect of a non-invasive hip exoskeleton for the NAU Biomechatronics Lab. The design must be comfortable for the user, have the degrees of freedom necessary to allow proper movement of the hip joint, and be as lightweight as possible."

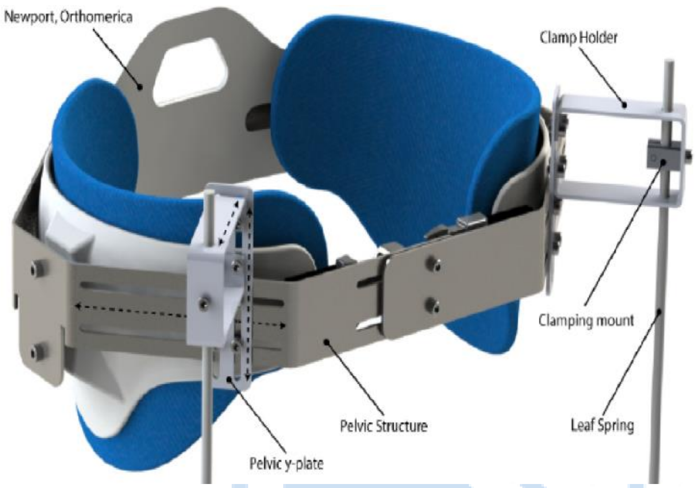
The project involves the design, prototyping and development plan for a hip exoskeleton device. The exoskeleton in this case is an electro-mechanical technology for assisting children with Cerebral Palsy and neuromuscular disorder. The exoskeleton will be used to assist the disabled children to walk again and also enable to correct their posture from the hip area. The movement aspect of the device is accomplished by using motors to support hip joint.

1.3: Original System

The re-engineered design is the pelvic exoskeleton. The device system is used as assistive technology to people with neuromuscular disorder.. The original design is limited by the aspect of flexibility, cost and comfortability. The biggest challenge faced by the present system is weight. Some of the existing designs are not strong enough to withstand the weight of some users; in addition, low-quality built design and implementation, mismatched user, product requirements and functionalities. The problems with the present system hinders the ability of the exoskeletons to meet the requirements of the customers.

1.3.1: Original System Structure

The structure of the original system is designed to be used by all individuals regardless of the age differences. The structure of the present system ranges from mechanical and electromechanical hip exoskeleton. The pelvic hip exoskeleton comprises mainly three subsystems which include electronic systems, mechanical systems and the electromechanical system. The mechanical and electromechanical systems provides the necessary movement to the hip joints enabling the user to walk effectively. The combination of these systems in an exoskeleton ensure that the user can move the joints effectively.



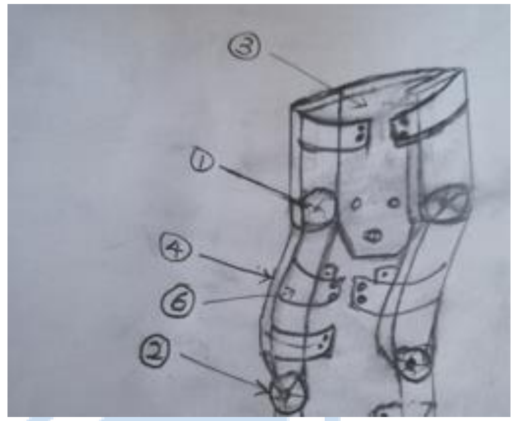


Figure 1: Pelvic design **figure 2: Pelvic drawing**

1.3.2: Original System Operation

The original exoskeleton operates in two different ways. The first means of operation involves the interaction of the sensors with the human body. When the hip joints move, the signal is acquired by the sensors on the pelvic structure, and converted to electrical signals. These signals are transferred to the motors to activate the necessary movement. The second phase of operation is the conversion of the electrical energy to mechanical energy by the motors. The motors on the hip and the needs convert the electrical signal from the sensor to mechanical energy, which triggers the movement of the joints on the hip and the knees based on the user requirement.

1.3.3 : Performance of the Original System

The performance of the original system is successful. The original comprises of various systems that function collaboratively to ensure efficiency and comfort of the user. The design of the original system is meant to assist the user's hip joints to move and also provide energy to the user to facilitate the movement of the thighs and the hips. However, the systems requires some adjustments to ensure comfort, minimize weight and efficiency.

1.3.4: Original System Deficiencies

The original system has two main deficiencies. One of the limitations of the original system is the huge weight which limits its use by young people and adults who cannot sustain the weight. The issue of weight limits the use of the system to people with a minimum of 110 pounds of weight. The other deficiency of the original system is the lack of support on the hip and the limbs, which hinders the comfort of the user.

2.0: REQUIREMENTS

There are different requirements that the team focused in order to develop a design that functions effectively and improve the design. These requirements include the customer and the engineering requirements. These requirements serves to fulfil the deficiencies that were identified in the existing devices.

2.1: Customer Requirements (CRs)

After examining the customer needs in the context of a hip exoskeleton, the team identified the customer requirements as indicated in table 1 below. The most important CR's are to provide flexible moving points and a lightweight device, because it will allow the children to be more stable when using the exoskeleton. The other customer requirement for the device is comfortability, and cost (see Table 1 for full customer requirements). The target users are children between 6 to 14 years old with walking problems and should therefore feel comfortable when using the device. Cost is one of the customer requirements it should meet the financial targets of the customers. Strength and durability are other aspects of the customer needs that the device targets should meet.

Table 1: Customer Requirements

CUSTOMER REQUIREMENT
• Lightweight Design
• The exoskeleton should be flexible to suit children from 6 to 14 years old
• Strong Device
• Non-invasive
• Simple

2.2: Engineering Requirements (CRs)

The team created the engineering requirements based on the customers requirements. The team examined the existing designs and their objectives. Specific acceptable tolerances were designated for each of the physical parameters and work was carried out to meet the customer expectations within the acceptable tolerances. The engineering requirements that should fulfil the customer requirements are shown in table 2 below.

Table 2: Engineering Requirements

Engineering Requirement	Description	weightning
Lightweight	Lightweight as possible	See Appendix B
Non-invisible	No contact between the metal bars and the human skin	See Appendix B
Strength	Material’s Modulus of Elasticity	See Appendix B
Flexibility	Adjustable from 12” – 18” on dimension from hip to knee	See Appendix B
Ease of wearing and removing	Must take less than 20-40 seconds to don/ doff	See Appendix B
Cost	Cost effective	See Appendix B
Torque	0-2 Nm out of the motor	See Appendix B

2.3: House of Quality

House of Quality (HoQ)										
Customer Requirement	**Weight**	**Engineering Requirement**	Weight	Flexibility	Ease of putting ON/OFF	Yield Strength	Cost	Non-invisible	Young Modulus	Torque
Light weight	7		9	5	9	9	5	8	5	9
Low Mobility	3		2	9	3	3	3	9	7	3
Adjustable size	9		5	3	1	3	6	6	1	1
Comfortable	8		7	4	1	7	8	3	5	2
Reliability	9		1	8	2	9	9	2	3	5
Durabiilty	9		3	3	1	1	1	5	9	8
Ease of Wearing	4		7	8	7	1	3	1	2	3
Range of Motions	9		6	9	3	2	1	3	1	1
Absolute Technical Importance (ATI)			**288**	**333**	**171**	**267**	**273**	**255**	**230**	**235**
Relative Technical Importance (RTI)			14%	16%	8%	13%	13%	12%	11%	11%
Target ER values			80N	18in	40 s	210Gpa	$2,500	-	215Gpa	7N.m
Tolerances of Ers			2	5	10	3	500	5	2	2
Testing Procedure (TP#)			6	4	5	3	8	1	2	7

3.0: DESIGN SPACE RESEARCH

3.1: Literature Review

3.1.1: Student 1 (Lahdan Alfihan)

Robotic exoskeletons are currently applied as a rehabilitation tool for individuals with walking limitations. Robotic exoskeletons are safe and efficient based on the design [2]. The limitation is that most of the existing exoskeletons require special measurements to custom fit the users [6]. The synchronization of these devices has improved within the last decade [3]. The exoskeleton is essential for use by the increased number of aging population in the world. Exoskeletons can be applied in the medical sector for stroke patients [4]. The other applications is on persons with long-term disabilities that limit joint movements [1]. The vast number of exoskeletons are mainly for lower limb and hand functions as well as for Performance augmentation [5].

3.1.2 Student 2 (Mohammed Janshah)

Gorgey, Ashraf S. "Robotic exoskeletons: The current pros and cons." World journal of orthopedics 9.9 (2018): 112.

- The article highlights the disadvantages and advantages of robotic exoskeletons [9].
- The author indicates that robotic exoskeletons are currently applied as a rehabilitation tool for individuals with walking limitations [9].
- Robotic exoskeletons are safe and efficient based on the design [9].
- The limitation is that most of the existing exoskeletons require special measurements to custom fit the users [9].
- The synchronization of these devices has improved within the last decade[9].

3.2: Benchmarking

3.2.1: System Level Benchmarking

There are different designs of hip exoskeleton that have been developed over the years to ensure mobility and effectiveness among individuals with hip and lower body disabilities. The team examined the existing designs and analyzed them into details. The analysis allowed the team to come up with issues relating to the existing designs. The proposed ideas will improve on the issues that are being faced by the current designs. The team examined different sources of information such as books, articles and engineering and medical websites to acquire additional information relating to the design.

3.2.1.1: Existing Design #1: ATOUN Model Y

This design was developed by Panasonic Company and is shaped like an upside-down Y, and it is worn like a backpack that's strapped to both the chest and thighs. It utilizes two independently-controlled motors. The device provides 22Ib-force of support to the waist of the user. The device operates in three modes, which it switches between automatically. The first mode is the assist mode, which helps the user's body to pull up from bending. The brake mode supports the waist when the user is leaning forward. The walk mode facilitates user movement.

Figure 3: ATOUN Model Y

3.2.1.2: Existing Design #2: Hyundai Hip Modular Exoskeleton

The system applies the concept of physical interfacing between the human body and a robot. The system comprises of a mechanical, electrical and electronic subsystems. These subsystems function together to support the user and also facilitate movement.

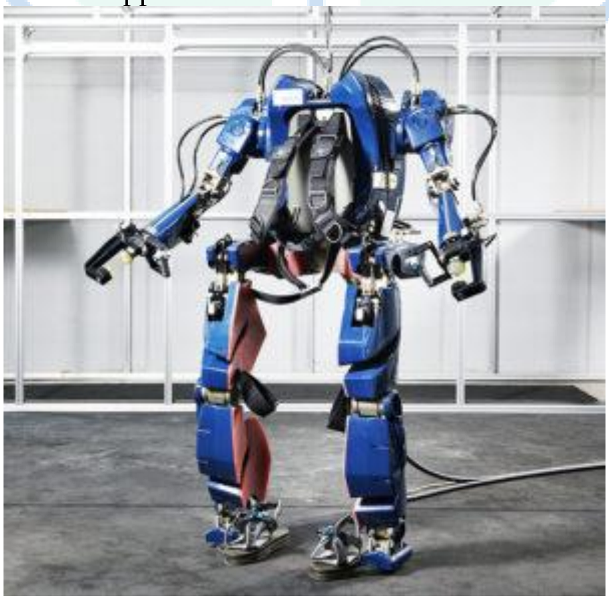


Figure 4: Hyundai Hip Modular Exoskeleton

3.2.1.3: Existing Design #3: ReWalk Exoskeleton

It is a robotic exoskeleton that provides powered hip and knee motion to enable individuals with spinal cord injury (SCI) to stand upright, walk, turn, and climb and descend stairs

Figure 5: ReWalk Exoskeleton

3.2.2: Subsystem Level Benchmarking

3.2.2.1: Subsystem #1: Hip Joint Actuator

3.2.2.1.1: Existing Design #1: Maxon Joint Actuator

It is an actuation unit consisting of a pancake brushless DC motor (EC90 flat) with inertia optimized rotor. The actuator has an internal high resolution 4096 MILE Encoder, planetary gearhead with absolute encoder and EPOS4 position controller with CAN and RS232 interface.

Figure 6: Maxon Joint Actuator

3.2.2.1.2: Existing Design #2: Dynamixel MX-64T Robot Actuator

The MX-64T Dynamixel Robot Servo Actuator is one of the latest generation of Robotis Dynamixel actuator. It comprises of an onboard 32bit 72mhz Cortex M3, a contactless magnetic encoder with 4x the resolution over the AX/RX series, and 3mpbs using the new TTL 2.0 bus.

Figure 7: Dynamixel MX-64T Robot Actuator

3.2.2.1.3: Existing Design #3: Maxon EC flat motors

The brushless motors are designed as internal and external rotors and can reach speeds of up to 20,000 rpm. These motors can also be combined with gearheads and encoders. The features of these actuators include external, multipole rotor for high torques.

Figure 8: Maxon EC flat motors

3.3: Functional Decomposition

The purpose of this project is to design and implement a Hip exoskeleton. The design was motivated by the need to develop affordable and non-invasive device. The hip joints will be actuated by DC motors. Carbon fibre frames are used for the pelvic and thigh support. The sensors are located on the hip and knee joints to acquire data from the human input.

3.3.1 Black Box Model

All body movement signals are generated by the brain. The input is the brain activity that initiates the pelvic movement which transfers the signals to the sensors in the hip area. The brain perceives the movement of the pelvic and the control signal from the brain reaches the hip muscles. The hip muscles is another input that requires energy to increase the strength. The electrical energy is the energy input and the outputs are the hip movement and the brain signal.

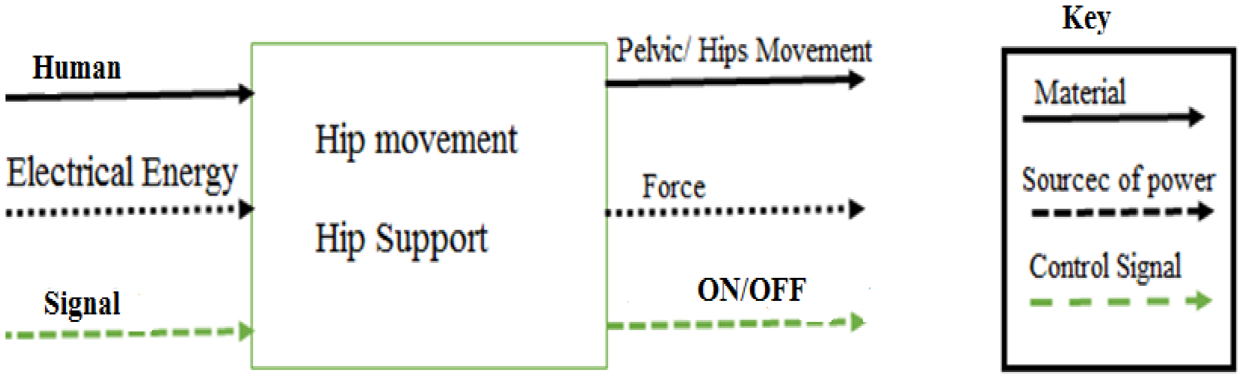


Figure 9: Black Box Model

3.3.2: Functional Model/Work-Process Diagram/Hierarchical Task Analysis

Hip Movement is initiated by the control signal from the brain. Sensors establishes the hip movement and the processing of the sensor output and control signal. Generation of the exoskeleton actuation. The electric power is controlled based on the present movement of the exoskeleton and the required strength. The feedback method for power control and the exoskeleton movement with the required force.

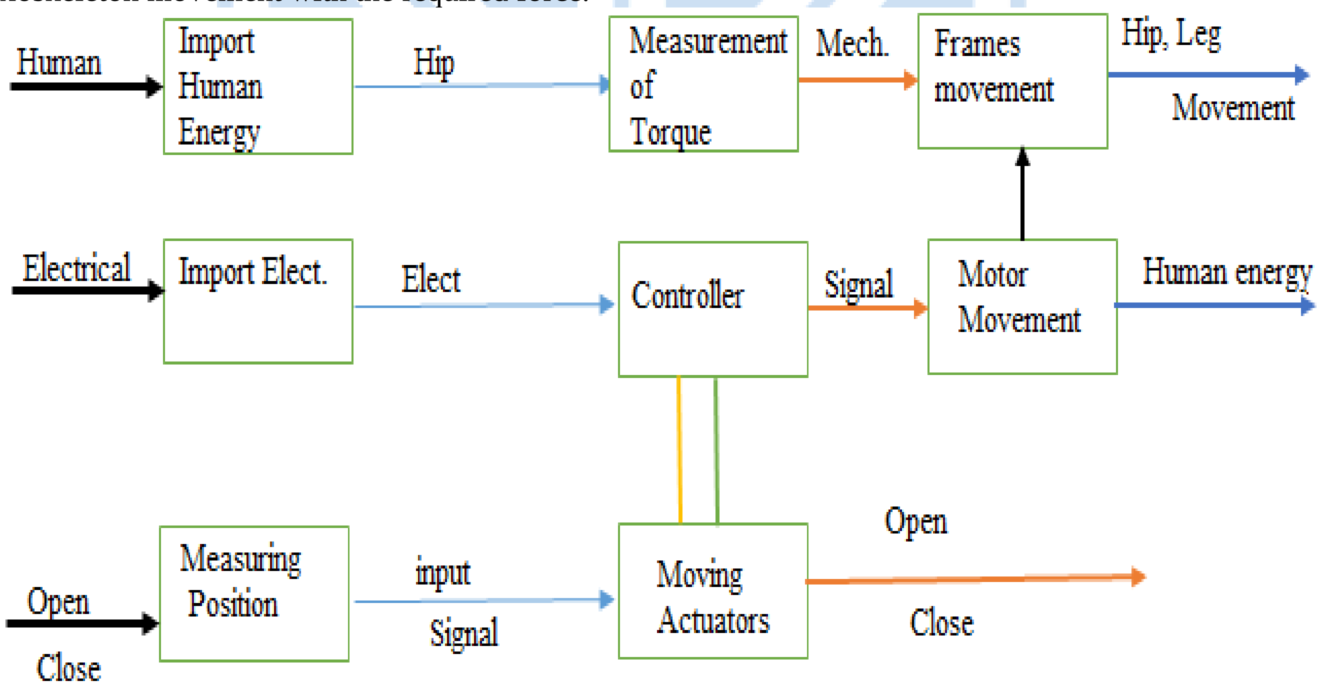


Figure 10: Functional Model

4.0: CONCEPT GENERATION

4.1: Full System Concepts

4.1.1 Full System Design #1: Pelvic Support and Leg Support

The design has three subsystems

a. The pelvic subsystem design
b. The thigh sub-system design
c. Leg support subsystem

The other parts of the system include hip actuator, knee actuators, pelvic support, thigh support frame, legs frame straps,the thigh frame straps, the leg frame and the foot.

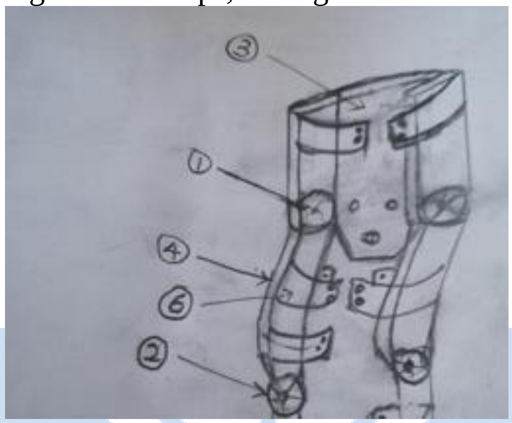


Figure 1: Design #1

4.1.2 Full System Design #2: Lower body Support Suit

This system design comprises of the full suit for lower body and it uses small motors for actuation. The design also has inbuilt sensors that acquire information regarding the required hip joint movement in order to transmit the electric signals to the actuators. The other parts of the system include hip actuators, thigh frame suit, hip frame suit, foot, leg frame suit and the inbuilt movement controls.

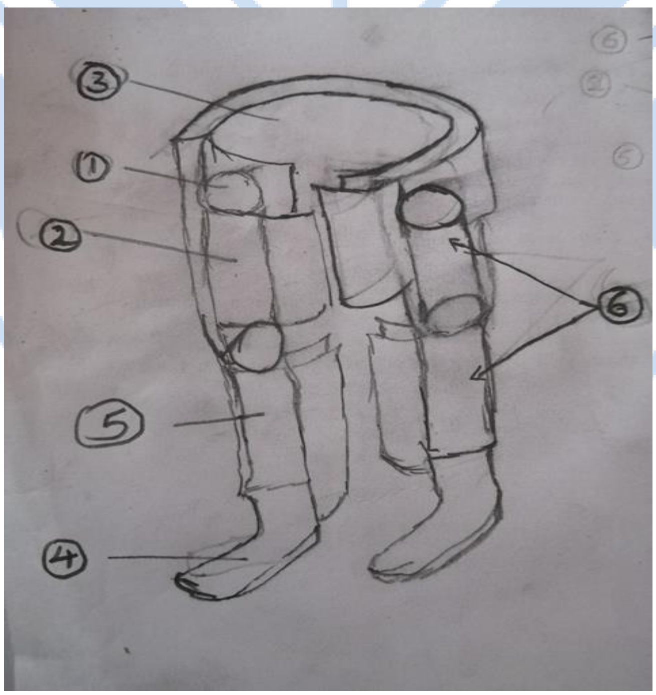


Figure 11: System design #2

4.1.3 Full System Design #3: Robotic Exoskeleton

The design for this system was adopted from the existing Rewalk robotic exoskeleton. Modifications on the existing design are done in the context of reduced weight, improved size flexibility. The system aims at minimizing the pressure on the hips, transfering the human weight to the ground. It is also fully automated and uses sensors to detect and control movement of the hips and thighs.

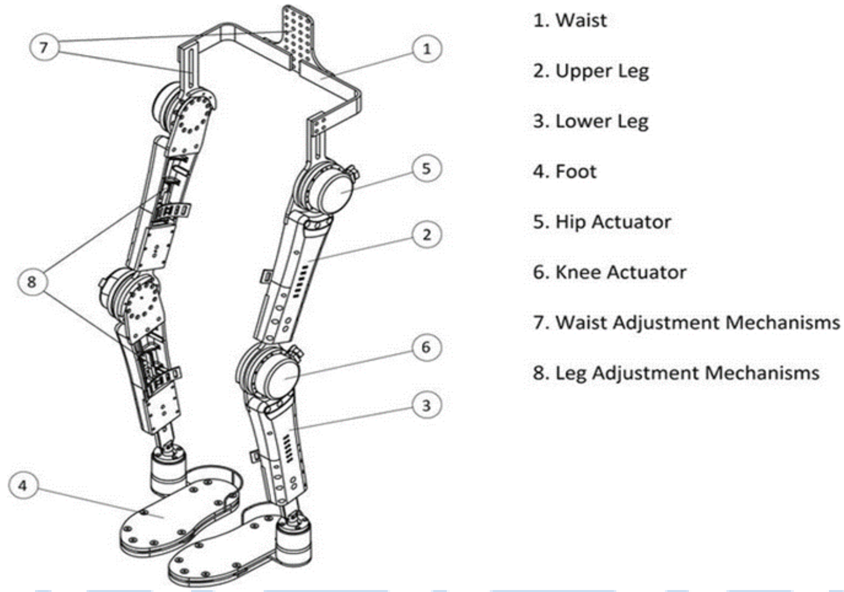


Figure 12: System design #3

4.2: Subsystem Concepts

4.2.1: Subsystem #1: The Pelvic subsystem

4.2.1.1: Design #1: Support belt with motors

This design of the pelvic area comprises of two actuators on either side of the hip and a wearable fabric belt for supporting the system.

4.2.1.2: Design #2: Motors and pelvic frame

This design comprises of a carbon fibre frame that extends to the back. The frame comprises of a fabric lining and straps. Also, the motors are located on both sides of the pelvic for movement actuation.

4.2.1.3: Design #3: Motors, Sensors and electronic frame

The sensors are located on the electronic frame that covers the back region of the pelvic. The sensor receives and transmits signals from the hip joints to the electronic board. The signal is then transferred to the actuators to activate the approproprate movement and support.

4.2.2: Subsystem #2: The Thigh support System

4.2.2.1 Design #1: Carbon fibre frame with fabric inner lining

This system comprises of a complete frame that covers the entire thigh area. It has a fabric lining inside to ensure comfort. The frame is linked to the hip and knee joints using a spring system.

4.2.2.2 Design #2: Carbon fibre frame with straps

This system comprises of a complete frame that covers the entire thigh area. It has two straps on each thigh to support the frame. The frame and the inbuilt wiring system links the frame to the actuators on the knee and the hip joints.

4.2.2.3 Design #3: Spring system enclosed in a fabric with straps

The spring system is located between the knee joint and the hip joint actuators. The systems helps the movement of the thighs in response to the actions of the knee and hip actuators. The straps ensure safety and stability of the system when the user is walking.

5.0: DESIGNS SELECTED

5.1: Technical Selection Criteria: Decision Matrix

All design process involves identification of possible alternatives and selecting the best among them. Each of the alternatives is thoroughly analyzed and its suitability for the given requirements is considered. Customer and the engineering requirements were used to develop the Pugh Chart and the decision matrix to select the most suitable design among the three best designs. The technical factors considered include cost, weight, implementation time, flexibility, strength, reliability, comfortability and durability.

5.2: Rationale for Design Selection

All the proposed 3 designs were thoroughly analyzed and the design criteria were considered to converge at the top three. The best of the three designs were considered for the design. The final selected design was design #1 (figure 9), which comprises of two systems; Pelvic Support and Leg Support.

The Pugh Chart in table 3 shows that Designs #6, #8 and #10 based on the design criteria. These three designs are more suitable in the context of meeting the engineering and customer requirements in the selection criteria. Design #8 is adjustable and lightweight and stable. It meets most of the required design criteria to significantly compared to the other proposed designs.

Table 3: The Pugh Chart

Pugh Concept Selection Process Summary Chart											
PROJECT	DESIGN OF AN HIP EXOSKELETON										
	DATUM	Thigh Design	Pelvic Design	Hip Suite design	Hydraulic Hip exoskeleton design	Electrical Powered Design	Robotic Exoskeleton	Assist mode Design	Pelvic and leg support	Pelvic, Thigh and Arms support Design	Lower body Support Suit
Cost	0	-1	0	-1	0	1	-1	-1	1	-1	1
Durability	0	0	-1	0	1	0	-1	1	1	1	0
Comfortability	0	1	1	1	1	1	1	1	0	1	0
Weight	0	1	-1	0	0	1	-1	0	1	-1	1
Flexibility	0	-1	1	1	0	-1	1	1	0	-1	0
Ease of design implementation	0	1	1	-1	-1	-1	0	-1	-1	0	0
Designs meet customer requirements	0	0	0	1	1	0	1	0	1	1	1
Number better: S+	+0	+3	+3	+3	+3	+3	+3	+3	+4	+3	+3
Number worse: S-	0	-2	-2	-2	-1	-2	-3	-2	-1	-3	0
Number same: S0	7	2	2	2	3	2	1	2	2	1	4

The three designs were further examined using a decision matric in order to select the most appropriate design. The decision matrix is shown in Table 4. Based on the outcome of the decision matrix, design #1 among the three designs meets the requirements in the selection criteria greatly compared to design #2 and #3.

Table 4: Decision Matrix

		Pelvic and Leg Spport		Lower Body Support Suit		Robotic Exoskeleton	
Criteria	Weighting	**Rating**	**Total**	**Rating**	**Total**	**Rating**	**Total**
Cost of Materials	0.11	100	11	85	9.35	0	0
Implementation time	0.07	95	6.65	90	6.3	70	4.9
Reliabilty	0.12	100	12	60	7.2	95	11.4
Necessary Modifications	0.03	100	3	100	3	0	0
Flexibilty	0.15	90	13.5	75	11.25	100	15
Weight	0.14	100	14	80	11.2	65	9.1
Durabilty	0.12	100	12	100	12	80	9.6
Comfortability	0.14	100	14	70	9.8	100	14
Assembly	0.12	80	9.6	90	10.8	50	6
Totals	**1**		**95.75**		**80.90**		**70.00**
Relative Rank							
			1		**2**		**3**

6.0: REFERENCES

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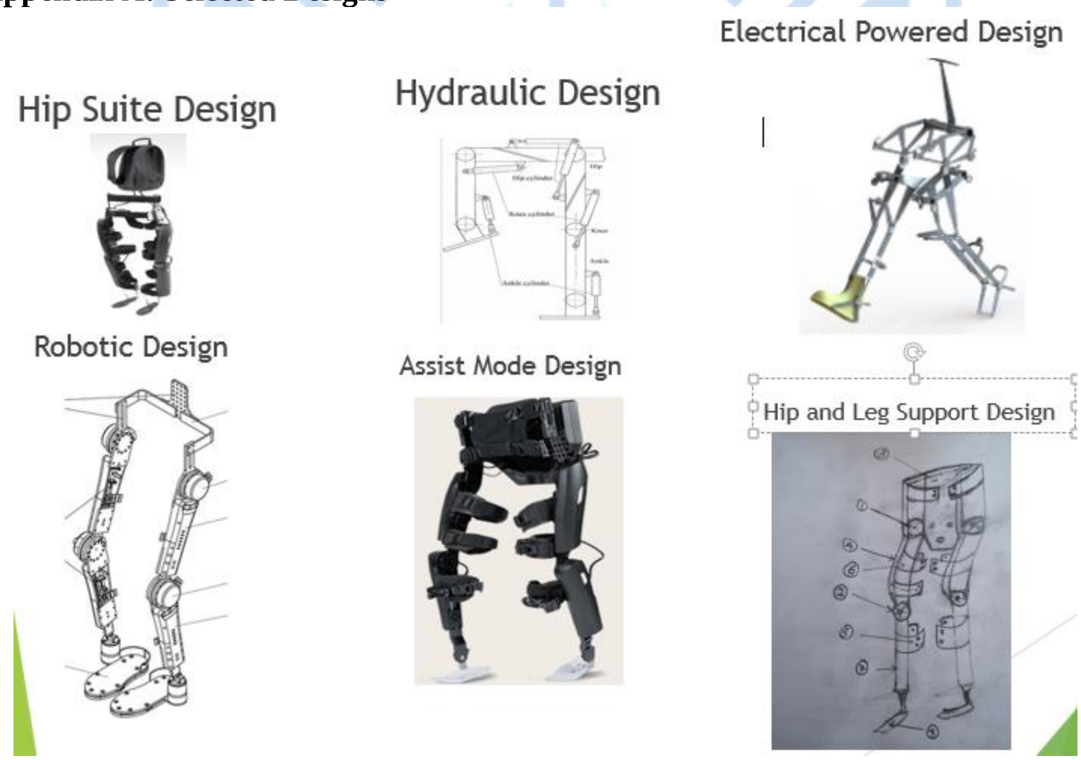
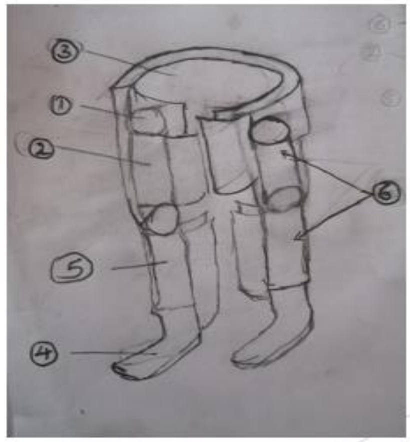
7.0: APPENDICES

7.1: Appendix A: Selected Designs



Pelvic, Thigh and Arms support Design

Lower Body Support Suit

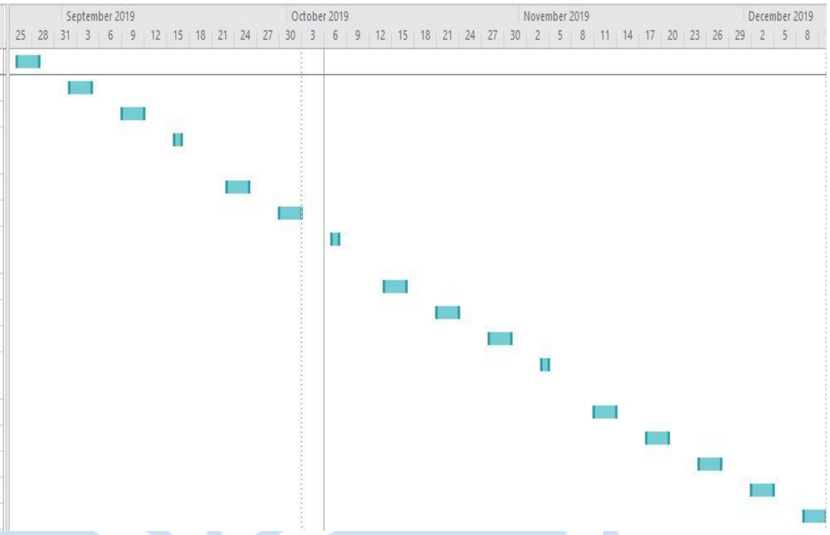


7.2 Appendix B: Bill of Materials, gantt chart, house of quality, pugh chart and decision matrix.

Bill of Materials

Part #	Part Name	Qty	Description	Functions	Material	Dimensions	Cost	Link to Cost estimate
1	Frame	2	Contains holes at different parts for holding other parts	support the upper body and the legs	Carbon Fibre	4 ft (each)	$150	https://www.compositesworld.com/blog/post/composites-in-exoskeletons
2	Arrestors	3	2-for the thighs 1-Pelvic area support	Supporting the thights and hips during movement	PVC	2 ft	$10	https://www.made-in-china.com/cs/hot-china-products/Pvc_Sheet.html?gclid=Cj0KCQjwoebsBRCHARIsAC3JP0KUNNkYmUqF1O70eydGnnHo6DAad--qTy7EUK72KDkQPQGk5bv9atsaApaWEALw_wcB
3	Small Motors	4	For hip and knee joints	Joint actuation	Carbon	19mm	$180	https://www.maxongroup.com/maxon/view/category/sensor?etcc_cu=onsite&etcc_med_onsite=Product&etcc_cmp_onsite=Encoders&etcc_plc=Overview-Page-Sensors&etcc_var=%5bcom%5d%23en%23_d_&target=filter&filterCategory=encoder
4	Sensors	2	Placed on the hip	Detecting the movement signal		5mm	$10	https://www.maxongroup.com/maxon/view/category/sensor?etcc_cu=onsite&etcc_med_onsite=Product&etcc_cmp_onsite=Encoders&etcc_plc=Overview-Page-Sensors&etcc_var=%5bcom%5d%23en%23_d_&target=filter&filterCategory=encoder

	Task Mode	Task Name	Start	Finish
1		Project signup	Mon 8/26/19	Wed 8/28/19
2		Staff/Team meetings	Mon 9/2/19	Wed 9/4/19
3		Staff/Team meetings	Mon 9/9/19	Wed 9/11/19
4		Presentation 1: CNs/Ers and Background	Mon 9/16/19	Mon 9/16/19
5		Staff/Team meetings	Mon 9/23/19	Wed 9/25/19
6		Staff/Team meetings	Mon 9/30/19	Wed 10/2/19
7		Presentation 2: Concept Gen and Eval	Mon 10/7/19	Mon 10/7/19
8		Staff/Team meetings	Mon 10/14/19	Wed 10/16/19
9		Staff/Team meetings	Mon 10/21/19	Wed 10/23/19
10		Staff/Team meetings	Mon 10/28/19	Wed 10/30/19
11		Presentation 3: Final presentation	Mon 11/4/19	Mon 11/4/19
12		Staff/Team meetings	Mon 11/11/19	Wed 11/13/19
13		Staff/Team meetings	Mon 11/18/19	Wed 11/20/19
14		Staff/Team meetings	Mon 11/25/19	Wed 11/27/19
15		Prototype demo	Mon 12/2/19	Wed 12/4/19
16		Finals	Mon 12/9/19	Wed 12/11/19



House of Quality (HoQ)

Customer Requirement	Weight	Engineering Requirement	Weight	Flexibility	Ease of putting ON/OFF	Yield Strength	Cost	Non-invisible	Young Modulus	Torque
Light weight	7		9	5	9	9	5	8	5	9
Low Mobility	3		2	9	3	3	3	9	7	3
Adjustable size	9		5	3	1	3	6	6	1	1
Comfortable	8		7	4	1	7	8	3	5	2
Reliability	9		1	8	2	9	9	2	3	5
Durabiilty	9		3	3	1	1	1	5	9	8
Ease of Wearing	4		7	8	7	1	3	1	2	3
Range of Motions	9		6	9	3	2	1	3	1	1
Absolute Technical Importance (ATI)			**288**	**333**	**171**	**267**	**273**	**255**	**230**	**235**
Relative Technical Importance (RTI)			14%	16%	8%	13%	13%	12%	11%	11%
Target ER values			80N	18in	40 s	210Gpa	$2,500	-	215Gpa	7N.m
Tolerances of Ers			2	5	10	3	500	5	2	2
Testing Procedure (TP#)			6	4	5	3	8	1	2	7

Pugh Concept Selection Process Summary Chart

PROJECT	DESIGN OF AN HIP EXOSKELETON										
	DATUM	Thigh Design	Pelvic Design	Hip Suite design	Hydraulic Hip exoskeleton design	Electrical Powered Design	Robotic Exoskeleton	Assist mode Design	Pelvic and leg support	Pelvic, Thigh and Arms support Design	Lower body Support Suit
Cost	0	-1	0	-1	0	1	-1	-1	1	-1	1
Durability	0	0	-1	0	1	0	-1	1	1	1	0
Comfortability	0	1	1	1	1	1	1	1	0	1	0
Weight	0	1	-1	0	0	1	-1	0	1	-1	1
Flexibility	0	-1	1	1	0	-1	1	1	0	-1	0
Ease of design implementation	0	1	1	-1	-1	-1	0	-1	-1	0	0
Designs meet customer requirements	0	0	0	1	1	0	1	0	1	1	1
Number better: S+	+0	+3	+3	+3	+3	+3	+3	+3	+4	+3	+3
Number worse: S-	0	-2	-2	-2	-1	-2	-3	-2	-1	-3	0
Number same: S0	7	2	2	2	3	2	1	2	2	1	4

		Pelvic and Leg Spport		Lower Body Support Suit		Robotic Exoskeleton	
Criteria	Weighting	**Rating**	**Total**	**Rating**	**Total**	**Rating**	**Total**
Cost of Materials	0.11	100	11	85	9.35	0	0
Implementation time	0.07	95	6.65	90	6.3	70	4.9
Reliabilty	0.12	100	12	60	7.2	95	11.4
Necessary Modifications	0.03	100	3	100	3	0	0
Flexibilty	0.15	90	13.5	75	11.25	100	15
Weight	0.14	100	14	80	11.2	65	9.1
Durabilty	0.12	100	12	100	12	80	9.6
Comfortability	0.14	100	14	70	9.8	100	14
Assembly	0.12	80	9.6	90	10.8	50	6
Totals	**1**		**95.75**		**80.90**		**70.00**
Relative Rank							
			1		**2**		**3**