

Design and Analysis of a Lower Limb Exo-Skeleton Suit for Post Stroke Patient: Static and Ergonomic Analyses

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ABSTRACT – This paper presents a study on the development of a lower limb exoskeleton suit (exo-suit) for post-stroke patients. The exo-suit is designed and developed for restoration of post-stroke patients' gait motion (ability to use their lower limb joints) and analysis on ergonomics and statics are also considered. The mechanical structure of the exo-suit is proposed according to the anatomy of Asian people with an average mass of eighty kilograms in order that it is fitted perfectly. The conceptual design is established and selected by a dedicated design matrix and compared using the matrix evaluation process, and then Computer-Aided Design (CAD) software CATIA is used to create the 3D model. The design has undergone an evaluation of static structural and ergonomic analysis via CATIA and ANSYS Finite Element Analysis (FEA) software. Two materials are used in the static structural analysis, one is aluminium alloy, the other is steel material. The result of equivalent stress for both materials is within the allowable range of 29.511MPa to 1168.4 MPa. For RULA (Rapid Upper Limb Assessment) Analysis, the results showed that all three postures (static, intermittent, and repeated) yield acceptable final score which is 1 for intermittent and 2 for static and repeated postures.

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INTRODUCTION

In orthopedics, the number of people paralyzed by stroke, spinal cord injury (SCI), post-polio, or other illnesses is on the rise [1]. Secondary problems, such as osteoporosis, muscular atrophy, diabetes, insulin resistance, and pressure ulcers, are becoming more common as a result of the induced paralysis. SCI sufferers, in particular, are primarily young adults who still require employment to support their daily lives [2]. The brain damage causes by post-stroke is an emotional disturbance and make personality change due to physical effects. Furthermore, the patient might find it difficult to move because of paralysis of one part of the body due to stroke. The second commonest cause of death and the third most common cause of disability was a stroke which known as undeniable global health problem (DALYs) [3]. The emotional disorder can affect most stroke survivors, especially their self-confidence. Stroke patients are the norm with mixed feelings of fear, apprehension, and uncertainty. Main problems of post-stroke survivors that they are trying to be independent and feel like a burden to those around them and become depressed. Post-stroke patients mostly having limited movement issues such as stand up and walk. These feelings may lead more difficulty for the recovery process.

The development of lower extremity exoskeletons has advanced dramatically during the last decade (LEEs) [4]. LEEs have been used in gait rehabilitation and motion aid as the number of persons with limited mobility has grown. The intelligence, wearability, and portability of LEEs for motion support have all improved significantly in recent years, and numerous LEEs have been created to aid persons with limited mobility, including ReWalk [5], HAL [6], and Vanderbilt Exoskeleton [7]. Many difficult challenges, such as control, actuators, and humane machine interfaces, remain in the development and use of LEEs (HMI).

Exoskeleton suit is a wearable device that consists of electric motors, levers, pneumatics to assist limb movements especially lower limbs with higher endurance and strength [8]. The purpose of the suit to provide back support, send command signals to motors which manage the gears and sense user's motion. Recently, they are plenty of exo-suits produced to assist stroke patients, such as; Hybrid Assistive Limb (HAL) by Japan's Tsukuba University, The Robotic Orthosis Lokomat developed by Hocoma (Zurich, Switzerland), and Active Leg Exoskeleton (ALEX) from University of Delaware (Newark, DE, USA) [2], [9], [10].

To generalize the concept ideas in designing exo-suit, the proper position of the strapping and actuator need to parallel due to joint of hip, knee and ankle. The location of power management and control systems also need to be considered, properly designed, and analyzed such that a reasonable robustness and comfortness is achieved. To this end, the design process considers the basis of human anatomy of Asian people with an average mass of 80kg. In addition, dedicated software packages (CATIA and ANSYS) are used for evaluating static structural and ergonomic analysis for effective design of exo-suit model.

The remaining parts of the paper are organized as follow. Section 2 describes the concept of wearable exoskeleton suits and common analysis used to evaluate the conceptual design in terms of statics and ergonomics. Then, Section 3

discusses the design methodology. Next, Section 4 provides and discusses the simulation results and finally, Section 5 concludes the paper.

PRELIMINARY

This part provides a brief overview of the concept of wearable exoskeleton suits and common analysis used to evaluate the conceptual design in terms of statics and ergonomics.

A. A WEARABLE EXOSKELETON SUIT

There is an increase in the number of people paralysed due to stroke, spinal cord injuries, or other associated illnesses. Robotic systems that will allow them to recover the mobility to stand and walk are particularly beneficial in order to improve the physical and mental health of these people. The aim of this research is to build a functional exoskeleton suit to help injured patients recover the ability to walk and stand up/sit down (STS) [11].

With the rise of the elderly, stroke, often leading to muscle dysfunction and sometimes lifelong paralysis, has become a widespread disorder. Exoskeleton robots may be classified into treadmill-based and leg orthoses according to their recovery concepts, whereas the end effector robots have footplate-based and platform-based forms [12]. Exoskeleton Robots Treadmill-Based. The standard treadmill-based exoskeleton robots include the Lokomat, LokoHelp, Lopes, and Active Leg Exoskeleton (ALEX) [13]. Treadmill-based exoskeleton robotics usually consist of a weight support mechanism that runs through the lower-limb exoskeleton frame on a treadmill. There are many benefits of the lower-limb rehabilitation robot, and it has demonstrated promising clinical effects and reliability in rehabilitation. While systematic and long-term care can be given by most lower-limb rehabilitation robots, there are still some drawbacks and deficiencies

Based on other research, rehabilitation also can be learned by algorithm prediction. It manufactures an under-actuated horizontal robot with three-link rotation (3R) [14]. The robot is made up of a base, three connections, two actuated joints, one passive joint and three optical rotary encoders. The robot arm holds the foundation. The robot arm had a square beam segment made of aluminium. Three ties and an under-actuated robot are part of the entire framework for this experiment. Joint 1 and Joint 2 are active and Joint 3 is an actuator-free passive joint.

B. STATIC STRUCTURAL ANALYSIS

In simple terms, static structural analysis is a concept developed by the Finite Element Theory (FEM), which was established in connection with the publishing of a series of research papers from the 1940s. Amalgamated as a computational method of solving partial differential equations for approximate solutions to boundary value problems, FEM is based on the partition of a problem domain into simpler sections called finite elements, and on the estimation of variational methods to minimize the function of a related error.

The foundation of the numerical approach is that it is one of the methods that can solve partial differential equations (PDE) and partition one large body into many smaller bodies with each smaller body with unique boundaries [17]. PDEs are then added to each body of the mesh and are solved for each smaller body. It is then completely combined to form a complete solution extracted from several PDEs in the smaller body after receiving the solution for all the smaller body. In Finite Element Analysis, meshing is an important feature since it requires a large body to be separated into smaller, easier-to-solve bodies until the solution of all smaller bodies is sum up.

A static structural analysis analyses the displacements, stresses, strains, and forces in structures or components generated by loads with little inertia and damping. The assumption is that the loading and response conditions will be stable; that is, the loads and the structure's reaction will fluctuate slowly over time. Amongst the software packages that offer and solve for the above-mentioned analysis are ANSYS, SAMCEF, and ABAQUS [18].

C. ERGONOMIC ANALYSIS

Nowadays, ergonomics has a wide range of applications in human civilization. Humans require a more pleasant living environment and a safer working environment. The objective of incorporating ergonomics technology into the design of equipment and systems is to ensure that humans and machines work in full harmony. As a result, engineers are constantly prioritizing ergonomics in their designs. This paper explains the procedure of using the Ergonomic Design and Analysis module in CATIA software, as well as its Human Builder and Human Measurements components, in creating a manikin with varied percentiles while altering joint angles to reflect the postural shift.

The ergonomic analysis is divided into two categories, one is RULA (Rapid Upper Limb Assessment) and Biomechanics Single Action Analysis. The University of Nottingham's Institute for Occupational Ergonomics created the RULA (Rapid Upper Limb Assessment) method. It was created to examine individual worker exposure to hazards associated with work-related upper limb disorders [15]. For Biomechanics Single Action Analysis, this ergonomic tool collects biomechanical data from a worker in a certain position. The Biomechanics Single Action Analysis tool then calculates and output information such as lumbar spinal stresses and forces and moments on manikin joints based on the current manikin position. The model's output is entirely based on research findings and algorithms released by the scientific community [16].

DESIGN METHOD

Figure 1 shows a complete design of exo-suit taken from [14]. It can be seen that only actuator and gear systems are integrated into the structure. In addition, the compartment for the power system is also not considered in this design. Thus, this project embarks on design and integration of compartment for the power system. A dedicated design criteria matrix is used to properly design the compartment and discussed in the following sub-section. Next, design evaluation in terms of statics and ergonomics is formulated and discussed in sub-section statics structure and ergonomics analyses respectively. All the involved processes are illustrated in Figure 2.

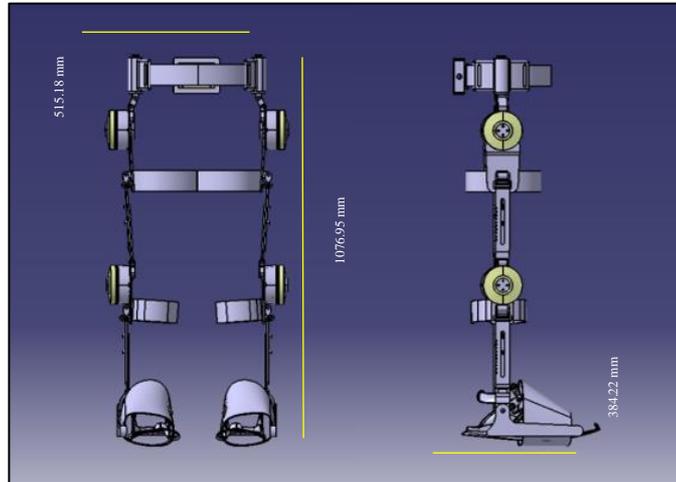


Figure 1. The existing structure design [14]

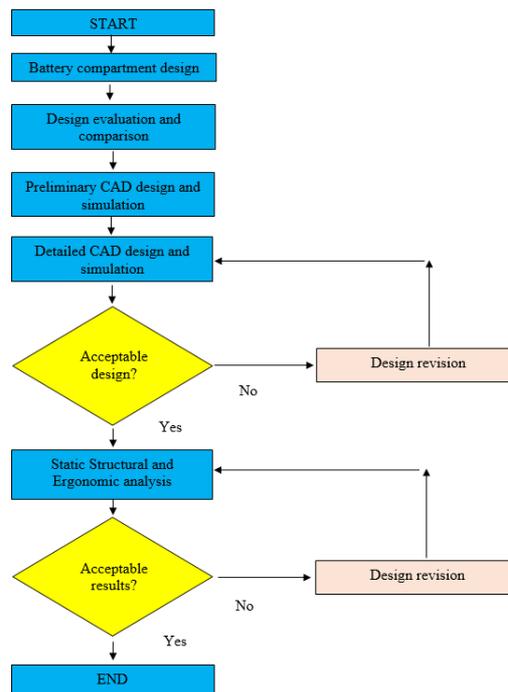


Figure 2. Methodology flowchart

A. POWER SYSTEM COMPARTMENT DESIGN

Battery selection

The exoskeleton mostly divided into two categories which are portable and non-portable. Generally, the power source for portable exoskeleton is from a rechargeable battery such as Lithium-Ion, Nickel Metal Hydride (Ni-MH), and Nickel-Zinc (Ni-Zn) [19]. Many non-portable exoskeletons are either directly connected to an electric source through cables or are powered by huge batteries. This restricts their movement in confined spaces. A similar pattern may be seen in certain portable exoskeletons that require a significant amount of electricity to charge their batteries. For this exo-suit, a 10Ah

Lithium Iron Phosphate (LiFePO₄) Lithium-Ion battery is chosen to power four motors GBM110-150T with 96V, nominal current of 0.3168A and a maximum current of 13A. The mass of each battery cell is about 1.10kg. Each cell can provide 12V voltage with maximum current of 10A. A total eight cells are used to power all four motors. LiFePO₄ Cells is selected for this design compared to others because of several factors, including higher life cycles which up to 80% capacity for 3000 cycles in recommended conditions. The typical sealed lead–acid (SLA) has 300-400 cycles. The weight of 12V 10Ah (1.10kg) lithium battery is only 1/3 of the weight of a lead-acid battery, easy to move and install. And finally high rated capacity as it provides up to 95% of their rated capacity while a lead-acid battery is usually limited to 50%.

Design Selection method

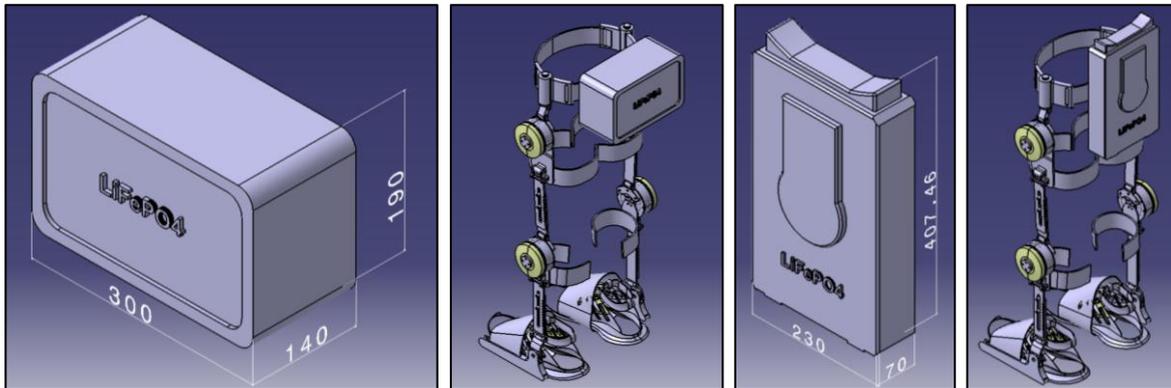


Figure 3. 3D model of (Left) Battery compartment 1, (Right) Battery compartment 2 (dimensions is in mm).

Figure 3 shows two 3D models of compartment for power system designed based on dimensions of LiFePO₄ battery cells. Design 1 is a typical design, while design 2 is narrower (thinner). The design criteria are tabulated in Table 1. Next, the drawings (models) are analysed using the parameters alluded in each design description (Table 1). As the model of choice, design 1 is chosen by the selection matrix shown in Table 2.

Table 1. Design criteria of model 1 and 2

Criteria	Design 1	Design 2
Fabrication difficulty	Less complexity during fabrication process	More complexity during fabrication process
Design difficulty	Simple cuboid design	Complex design with several edges fillet and chamfer
Aesthetic value	Acceptable to the eye	Pleasing to the eye
Surface finish	Smooth with minimal defects	Smooth with minimal defects
Assembly level	Does not need complicated assembly techniques	Need complicated assembly techniques
Production cost	Production cost was manageable	Production cost was manageable

Table 2. Selection criteria for choosing best design

Criteria	Weightage	Design 1		Design 2	
		Score	Weighted Score	Score	Weighted Score
Fabrication Level	0.25	5	1.5	6	1.25
Design Difficulty	0.25	4	1.5	6	1
Aesthetic Value	0.2	5	1.4	7	1
Surface Finish	0.17	5	1.02	6	0.85
Assembly Level	0.08	6	0.48	6	0.48
Cost	0.05	5	0.25	5	0.25
Weighted Total	1		6.15		4.83

B. STATICS STRUCTURAL ANALYSIS

The statics structural analysis employs a computational approach based on stress and strain to determine how load affects the proposed design. It is normally used to facilitate product analysis via a simulation environment and thus alleviate the need for unnecessary prototyping processes. ANSYS is one of the comprehensive Finite Element Analysis (FEA) software packages that provide such a complete simulation feature. The typical procedure of managing statics structural analysis in ANSYS software is illustrated in Figure 4.

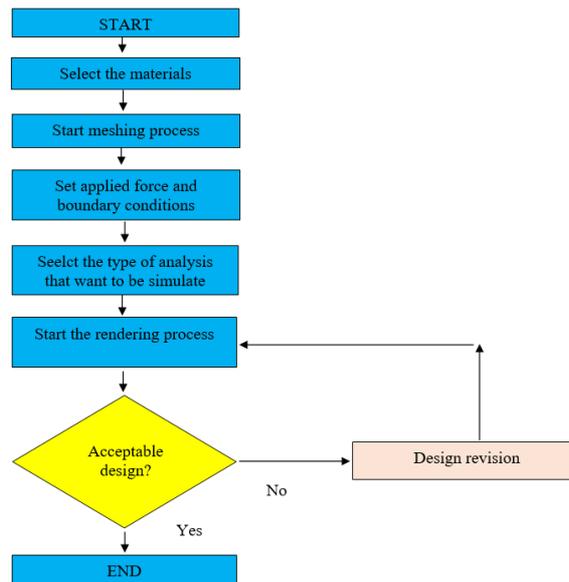


Figure 4. Typical procedure of conducting FEA analysis in ANSYS

Firstly, the material is selected. In this regard, two materials are used, one is aluminium alloy while the other is structural steel. Next is the meshing process. Then, the boundary conditions and forces are applied onto the structure as depicted in Figure 5 to Figure 7. In this case, 40 kg of load is applied on both legs in vertical axis based on average mass of Asian people of 80 kg. On the waist part, the mass of the battery compartment is 9 kg, but considering the mass of electronic parts to manage the power and control the four motors is another 1 kg. Thus, 5 kg of horizontal force is applied on each side of the waist. Meanwhile, boundary condition is set to simulate force application and to determine the stress and strain on the assembly. Figure 7 shows the boundary conditions for static configuration with respect to the actual force applied on each configuration to simulate stress and strain of it. Finally, the type of stress and strain to be simulated and analysed are set. This simulation experiment focuses on analysis of equivalent elastic strain, equivalent stress, total deformation, and safety factor.

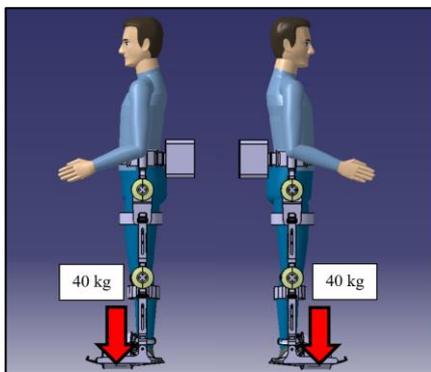


Figure 5. Forces applied on both legs.

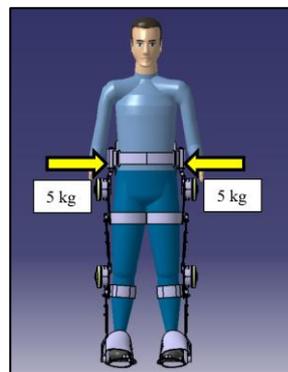


Figure 6. Forces applied on waist.

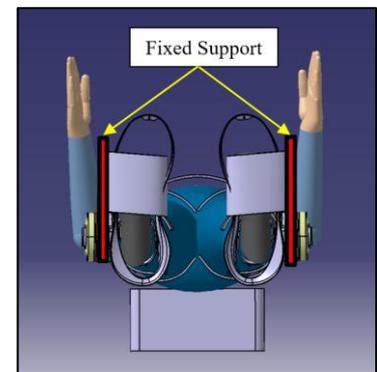


Figure 7. Fixed support boundary conditions.

C. ERGONOMIC ANALYSIS

This subsection provides the typical procure of establishing ergonomic analysis. A dedicated CAD i.e., CATIA V5R21 software package is used as the analysis tool.

Creating Mannequin

Figure 8 depicts the steps of creating a manikin for ergonomics analysis. In the Human Builder work bench, select insert manikin icon located on top of the Human Builder Sub Toolbar. The Manikin Dialog Box appears which consists of two tabs: Manikin and Optional. In Manikin tab Select Father product and write the name of manikin (2). From the 'Optional' tab, select Japanese as population and "Whole Body" Model with 'H-Point' Referential. Indeed, there are many options available to configure including eye point, right foot, H-Point (default), Left foot, lowest foot, and Crotch parameter but whole body is selected because this project goal is to analyze the whole body when wearing the proposed exo-suit (3).

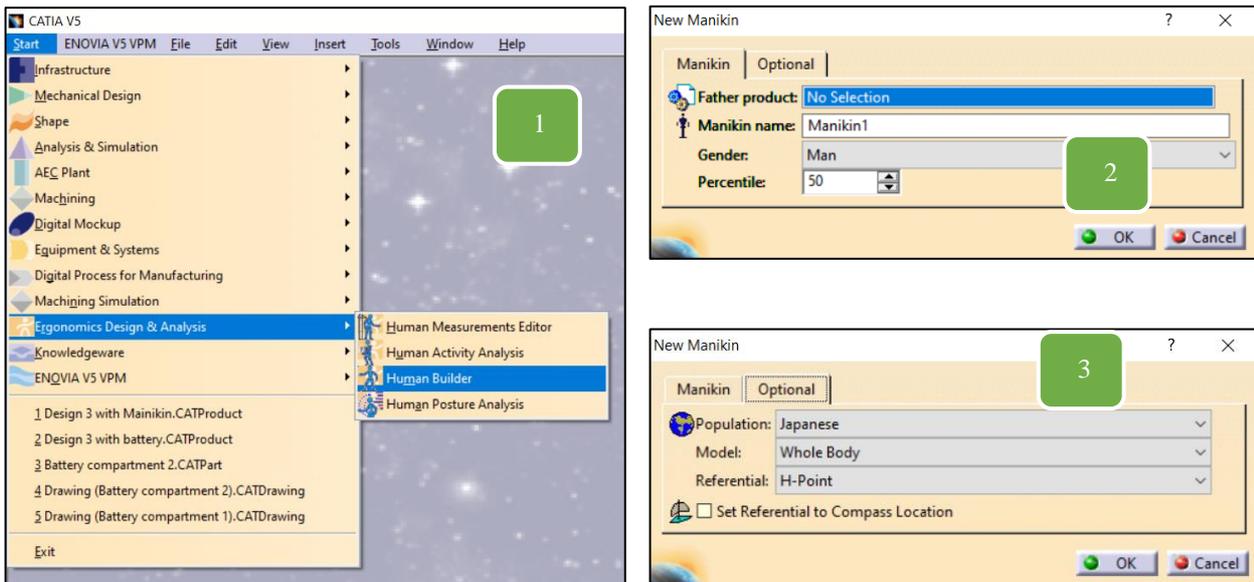


Figure 8. Illustration of creating a manikin in CATIA software environment.

Mannequin Modelling

Figure 9 (Left) illustrates a mannequin reference used to determine the exo-suit's geometrical design. The whole length from hip to ground is 1000 mm, while the width is 320 mm. The average body mass is set to 80kg, and the body weight acting on the exo-suit is about 784.8N due to gravitational acceleration [20]. Figure 9 (Right) illustrates the mannequin wearing the proposed exo-suit. The goal of structural design is to guarantee that the load of the patient's body weight is completely sustained without the structure failing.



Figure 9. (Left) Reference Manikin Body Dimension in mm, (Right) Manikin wearing the proposed exo-suit.

RULA Analysis

RULA is an essential survey instrument designed to investigate workplace ergonomics where work-related upper limb problems are documented. This instrument does not require any extra equipment to assess the postures of the neck, trunk, and upper limbs, as well as muscle function and the external stresses that the body is subjected to. This RULA is established to examine individual worker exposure to risk variables linked to work-related upper limb diseases, and it is simple to apply because it is an embedded analysis tool within the CATIA software as depicted in Figure 10. RULA study in this paper looks at the following risk factors:

- a) Number of movements,
- b) Static muscle work,
- c) Force,
- d) Working posture, and
- e) Time worked without a break.

All these variables add up to produce a final score ranging from 1 to 7 as tabulated in Table 3.

Table 3. RULA Analysis Score

Score	Details
1 and 2 (Green)	If the pose is not sustained or replicated for long periods of time, it is acceptable.
3 and 4 (Yellow)	Indicates that further research is necessary and that changes may be required.
5 and 6 (Orange)	This indicates that further investigation and improvements are needed soon.
7 (Red)	Indicates that immediate investigation and changes are needed.

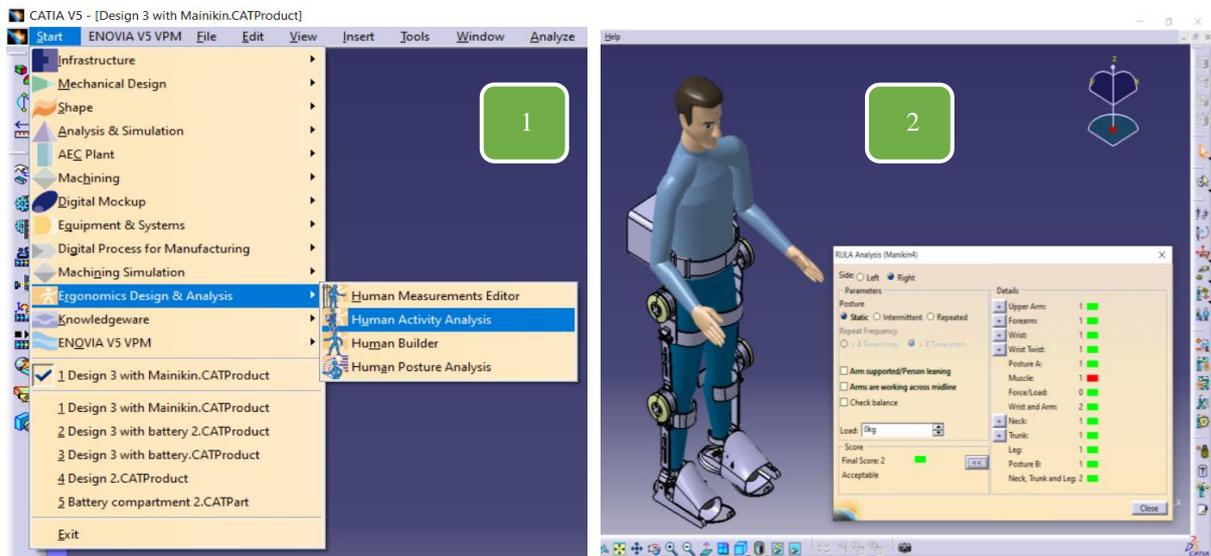


Figure 10. Conducting RULA study in CATIA software.

Biomechanics Single Action Analysis

To evaluate the proposed design, a Biomechanics Single Action Analysis is utilized to measure biomechanical data on a worker for three different postures namely static, intermittent, and repeated postures. The single-action analysis function calculates lumbar spinal loads (abdominal pressure, abdominal force, and body movements) and forces and moments on different body segment joints which are responsible for different injuries of humans. The Biomechanics Single Action Analysis dialog box depicted in Figure 11 shows each tab with detailed analysis results.

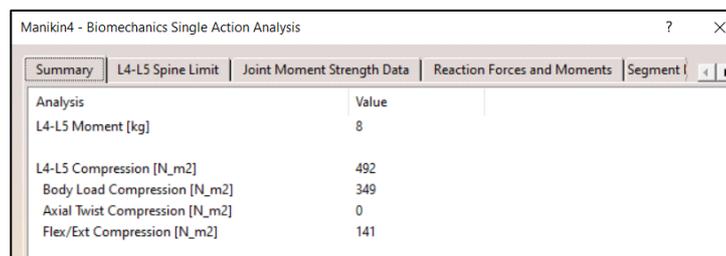


Figure 11. Multiple tabs of analysis results.

RESULTS AND DISCUSSIONS

A. STATIC STRUCTURAL ANALYSIS

Equivalent Elastic Strain

Evaluating on strain analysis also generates strain contour profiles, with strain indicating the elongation of the component in mm/mm. The contour profiles are shown in Figure 12 while the maximum and minimum strain of each material is listed in Table 4. Based on the tabulated results, it can be induced that that aluminium alloy has higher equivalent elastic strain value compared to structural steel.

Table 4. Equivalent elastic strain values of Aluminium Alloy and Structural Steel materials

Material	Max Strain (mm/mm)	Min Strain (mm/mm)	Avg. Strain(mm/mm)
Aluminium Alloy	0.00044537	4.0732x 10 ⁻⁷	2.2269 x 10 ⁻⁴
Structural Steel	0.0061669	1.741 x 10 ⁻⁸	2.8931 x 10 ⁻³

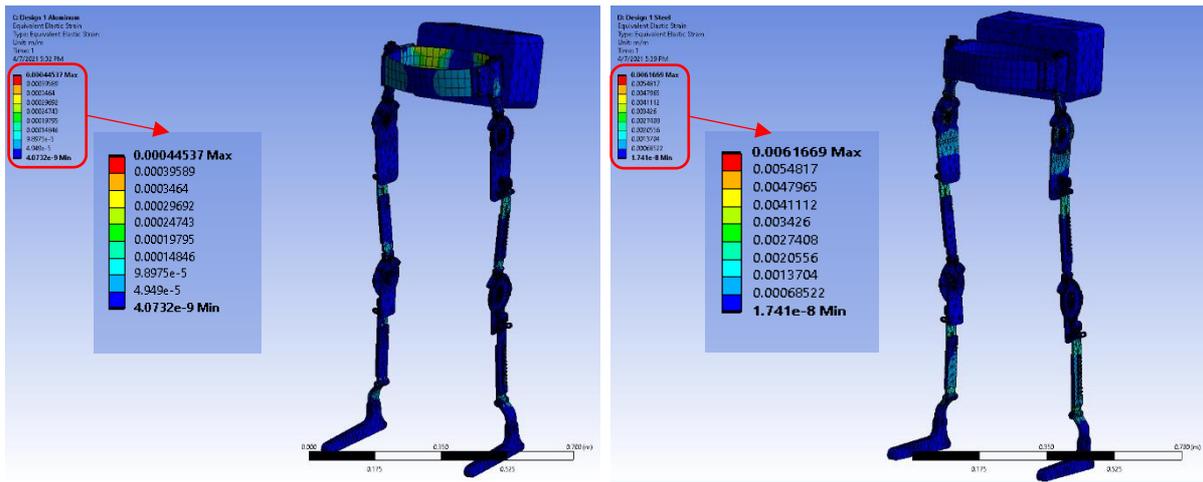


Figure 12. Equivalent Elastic Strain for (Left) Aluminium Alloy, (Right) Structural Steel.

Equivalent Stress

Figure 13 illustrates the equivalent stress contour for both aluminium alloy and structural steel materials. Even though aluminium alloy can withstand higher stress than structure steel but, on both materials, the stress is not significant and stress experienced by both materials are at a minimum. It can be concluded that all design parts meet the strength requirements and none of them exceed average stress as tabulated in Table 5.

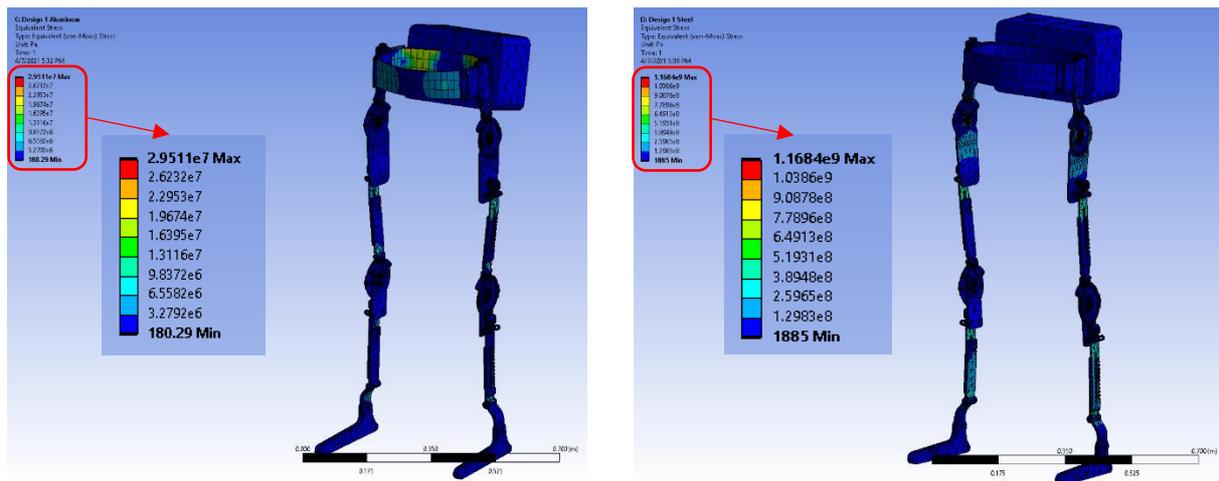


Figure 13. (Left) Equivalent Stress for Aluminium Alloy, (Right) Equivalent Stress for Structural Steel

Table 5. Equivalent stress values of of Aluminium Alloy and Structural Steel materials

Material	Max Stress (Pa)	Min Stress (Pa)	Avg. Stress(Pa)
Aluminium Alloy	29.511 x 10 ⁶	180.29	14.7556 x 10 ⁶
Structural Steel	1168.4 x 10 ⁶	1885	583.3402 x 10 ⁶

Total Deformation

The structure design is also undergone deformation analysis to determine the amount of deformation that may occur when the structure is loaded. Figure 14 shows the distribution of deformation that occurs when the structure is loaded. Table 6 shows the maximum, average, and minimum deformation on both sides of the structure. Indeed, steel offers better rigidity but its mass is higher than aluminium resulted in greater total deformation.

Table 6. Total deformation values of of Aluminium Alloy and Structural Steel materials

Material	Max Deformation (m)	Min Deformation (m)	Avg. Deformation (m)
Aluminium Alloy	0.0020465	0	1.0232 x 10 ⁻³
Structural Steel	0.049012	0	24.5 x 10 ⁻³

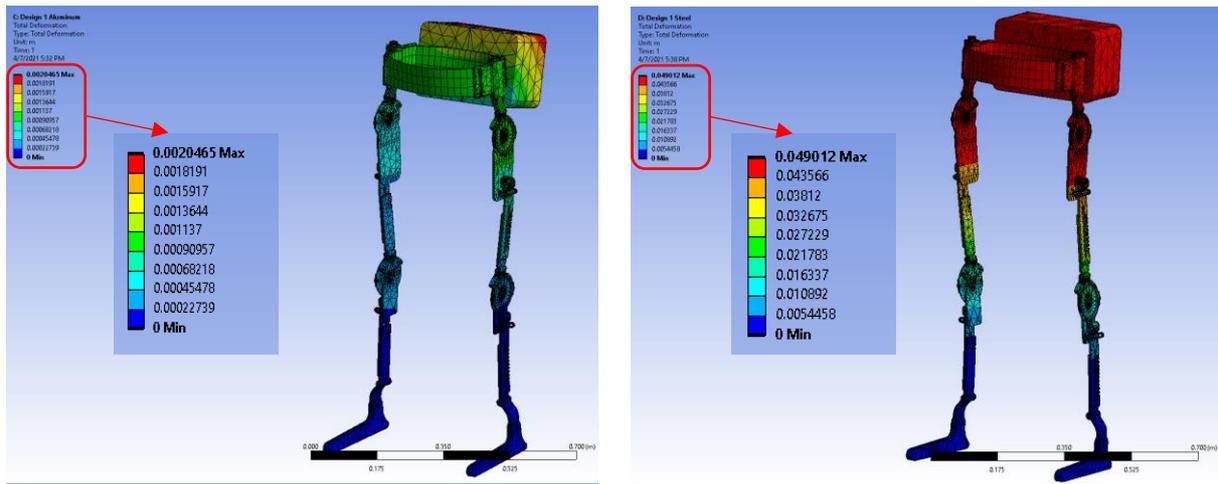


Figure 14. Total Deformation of (Left) Aluminium Alloy, (Right) Structural Steel.

Safety Factor

In general, the Safety Factor is a value that is used to indicate how safe a certain structure is. In this section, each section is analyzed, and the mapping distribution of the Safety Factor is depicted in Figure 15. Meanwhile Table 7 shows the maximum, average, and minimum of the Safety Factor values. Essentially, the maximum value of the Safety Factor is the same for both materials. However, it can be seen that aluminium alloy is better in terms of the Safety Factor's average value.

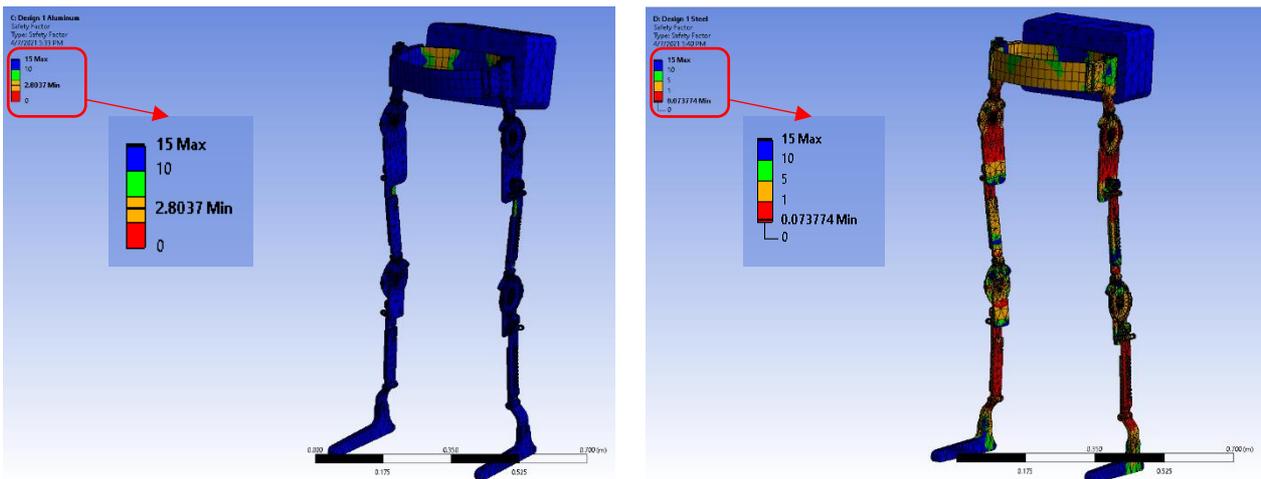


Figure 15. (Left) Safety Factor for Aluminium Alloy, (Right) Safety Factor for Structural Steel

Table 7. Safety Factor values of of Aluminium Alloy and Structural Steel materials

Material	Max Safety Factor	Min Safety Factor	Avg. Safety Factor
Aluminium Alloy	15	2.8037	9.2679
Structure Steel	15	0.073774	6.2148

B. ERGONOMIC ANALYSIS

RULA Analysis

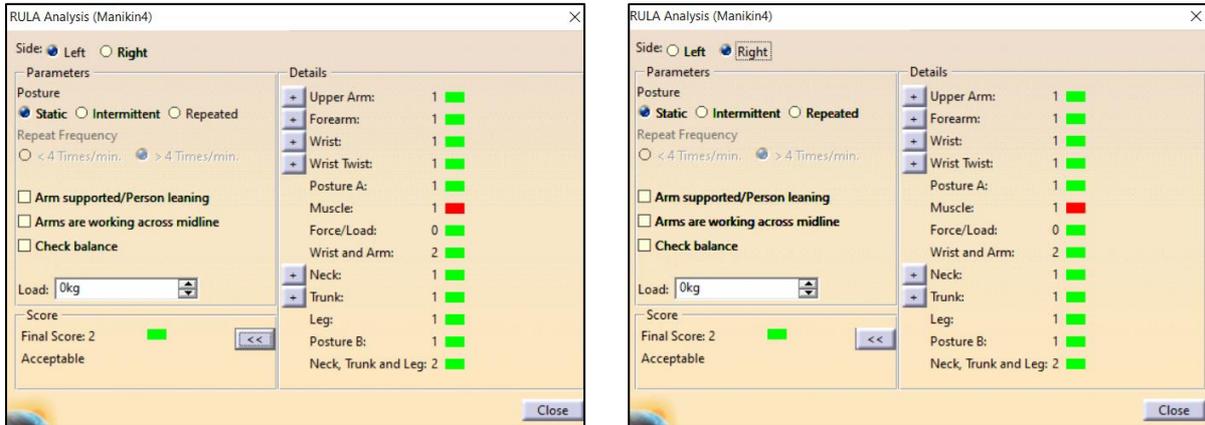


Figure 16. RULA result for the static posture of the left and right sides of the mannequin.

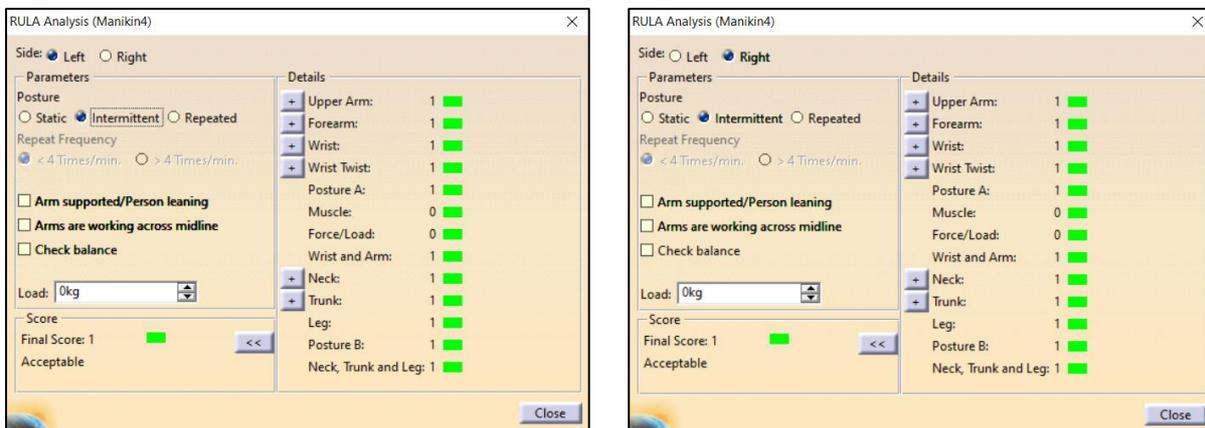


Figure 17. RULA result for the intermittent posture of the left and right sides of the mannequin.

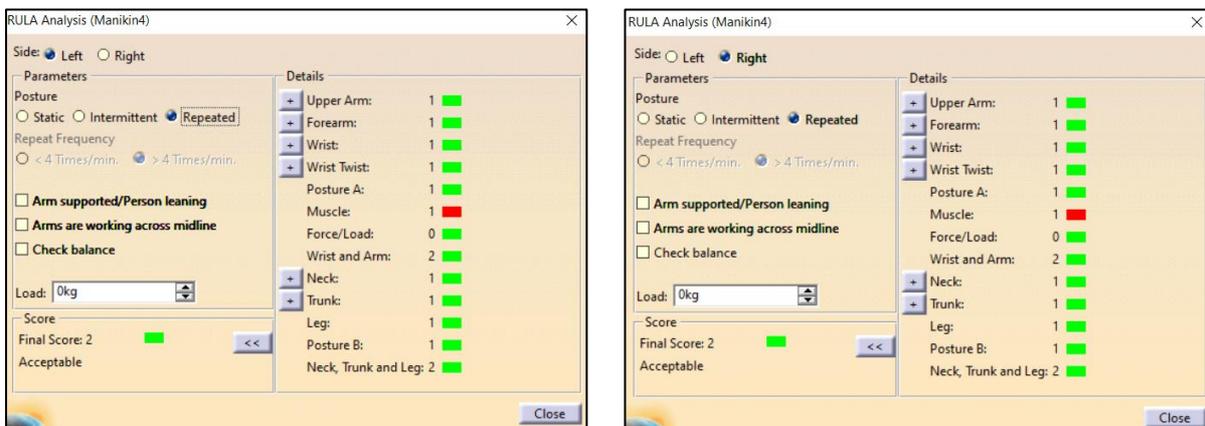


Figure 18. RULA result for the repeated posture of the left and right sides of the mannequin.

The RULA analysis for all three postures yields a final score of 1 for intermittent and 2 for both static and repeated postures as illustrated in Figure 16 to Figure 18. The obtained scores are all acceptable if the pose is not sustained or replicated for long periods of time. But at muscle aspect for the static and repeated postures which highlighted in red colour is indicating that immediate investigation such as redesign is needed.

Biomechanics Single Action Analysis

Biomechanics Single Action Analysis is also an ergonomic tool that is available in CATIA software. It is used to analyze a worker's biomechanical data in a specific posture. This tool computes data such as lumbar spinal stresses as well as forces and moments on the mannequin joints. Figure 19 shows the considered posture of the mannequin during wearing the proposed exo-suit for the purpose of Biomechanics Single Action Analysis.

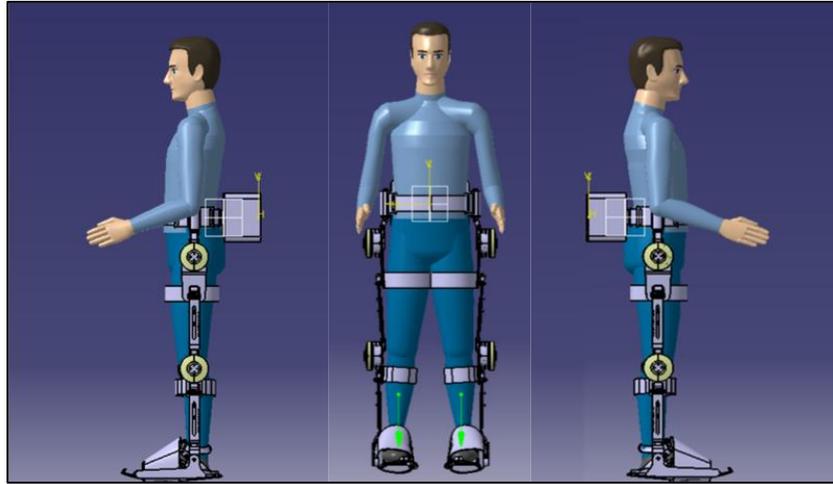


Figure 19. The posture of the mannequin during wearing the proposed exo-suit.

Load Definition

Essentially, the main improvement of the current design is the inclusion of the battery compartment to the exo-suit. For the load definition, the original mass of exo-suit is set at 10kg while the mass of battery compartment is about 9kg, so the total mass is 19kg. Figure 20 shows all the configured parameters for the Biomechanics Single Action Analysis.

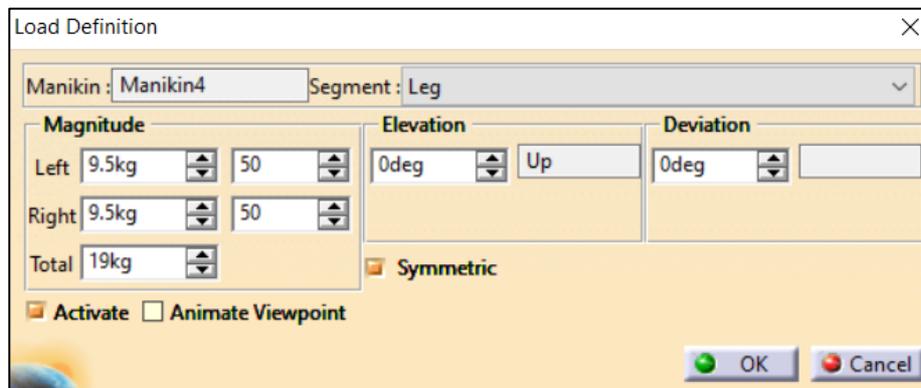


Figure 20. Load configuration on both legs of the mannequin

L4-L5 Spinal Limit motion analysis

Figure 21 displays the posture assessment on the L4-L5 Spinal Limit and whether it reaches the compression and joint shear limits suggested by NIOSH and the University of Waterloo. The analysis result shows that the exo-suit passed the compression limits and joint shear limits because it does not reach the threshold value of 3433 N/m² (NIOSH) and 500 N/m² (University of Waterloo). It can be concluded that the posture condition during standing is not causing negative effects on L4-L5 vertebrae. Meanwhile, Figure 22 shows the exact values for the Compression Limits which are 492 N/m² while 32 N/m² for Joint Shear Limits.

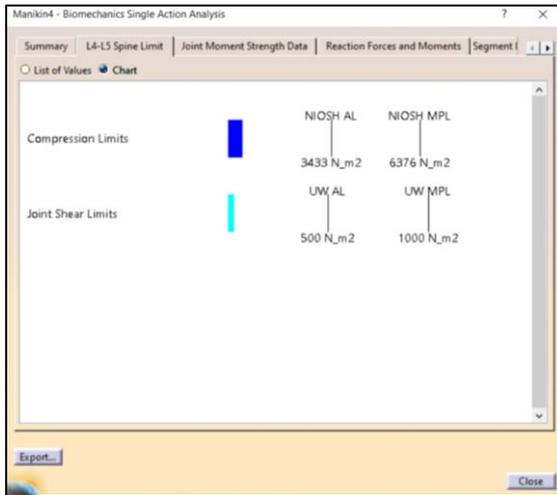


Figure 21. L4-L5 Spine Limit (Chart)

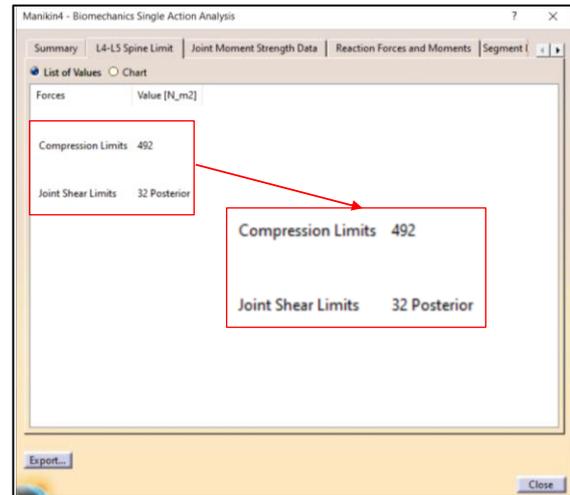


Figure 22. L4-L5 Spine Limit (List of Values)

Biomechanics L4-L5 spinal motion analysis

It can be seen that in Figure 23 that moment value on the L4-L5 spinals is 8kg. The L4-L5 Moment is obtained following the convention of an extensor moment expressed as positive. With respect to the lumbar spine, the L4 and L5 vertebrae are compressed together by the forces due to the mass of the body, the forces acting upon the hands and the trunk muscles/ligaments that are used to generate the support moment. The L4-L5 compression value is 492 N/m². The obtained L4-L5 compression value represents the compressive force acting upon the L4-L5 intervertebral joint.

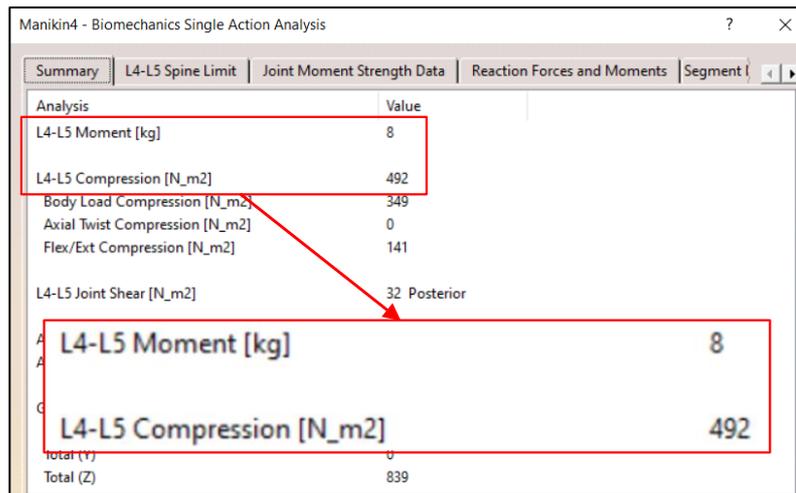


Figure 23. Biomechanics Single Action Analysis L4-L5

To maintain stability, or static equilibrium, the mannequin must actively resist the load moment created by these forces by activating his/her trunk muscles. This resistive moment is referred to as the support moment. To conclude it, the lower value of Moment (kg) and Compression (N/m²) the better the results in terms of stability or static equilibrium.

CONCLUSIONS

The ultimate goal of this project to design an exoskeleton suit that capable of restoring the gait motion (ability to use the lower limb joints) amongst the post-stroke patients. In particular, this project focuses on the design and integrating the battery compartment into the existing exo-suit model and carries out detailed analysis on statics ergonomics aspects. In terms of design, two new models are proposed and evaluated using a dedicated design selection criteria matrix. With the optimal design in hand, the static analysis is carried out to investigate the level of equivalent elastic strain, equivalent stress, total deformation, and safety factor obtained by the proposed exo-suit. Results of the statics analysis proved that aluminium alloy is better than structural steel in all aspects. In ergonomic analysis, two category analysis is carried out. The first one is RULA analysis to investigate workplace ergonomics where work-related upper limb problems are documented. It can assesses the postures of the neck, trunk, and upper limbs, as well as muscle function and the external stresses that the body is subjected to. The second category is devoted into ergonomic analysis on a specific posture using Biomechanics Single Action Analysis. The RULA analysis for all three postures yields a final score of 1 for intermittent and 2 for both static and repeated postures. All the obtained scores are acceptable if the pose is not sustained or replicated

for long periods of time. Finally, the results from Biomechanics Single Action Analysis suggest the proposed exo-suit is safe to be used since the obtained values are 492 N/m² for Compression Limits and 32 N/m² for Joint Shear Limits is lower than the threshold specified by the NIOSH and the University of Waterloo. It can be concluded that the posture condition during standing is not causing negative effects on L4-L5 vertebrae.

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