



RESEARCH ARTICLE

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STRUCTURAL ANALYSIS OF UPPER ARM EXOSKELETON FOR BIOMEDICAL APPLICATIONS

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ABSTRACT

Upper limb rehabilitation exoskeletons worn on the body have many features, such as compatibility with human structure, safety and training, etc. This paper aims to examine the structural strength of the exoskeleton. Using ANSYS Workbench 15, the static analysis was carried out on the human body's upper limb. The study of the various parameters showed that the design of the titanium exoskeleton satisfied the requirements of an exoskeleton for paralytic patients for a load up to 300N; for the stress value and deformation values for various parameters, a safe design of the exoskeleton has been achieved. The comparison of the exoskeleton structure with that of stainless steel, aluminium, and titanium shows that the titanium structure is most suitable for the exoskeleton since it is lightweight and Young's modulus is similar to that of human bone. The aluminium exoskeleton structure will shear when load is applied and the stainless exoskeleton structure is heavier than the human bone. It is concluded from the Finite element analysis carried out on workbench 15 for the three materials, namely, aluminium, titanium and steel. Titanium is suitable for exoskeleton structure construction since it satisfies design criteria as per biomechanical design considerations.



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I. INTRODUCTION

Millions of patients, around 15 million people all over the world, suffer from paralysis stroke. Out of these, 85% of the patients survive, and only 10% recover completely; the rest of the patients lose their motor functions and old age people have a nervous weakness; the exoskeleton can rehabilitate these patients to lead normal lives. In these exoskeleton robots, the human muscle power is combined with exoskeleton structure energy and gives a synergy effect [1]. It combines the fields of biomechanics, sensors, controllers, and software algorithms to ensure the smooth functioning of the exoskeleton device and improve the standard of living of paralytic patients and old-age people. The other applications of exoskeletons are in the military to help soldiers carry heavy loads like arms, ammunition, and personal belongings of the soldiers and in the labour-intensive construction industry. The upper limb exoskeleton patients carry out routine exercises that improve motor functions and help them to lead a normal life. The difficulty with exoskeletons is the interface between the human body and the exoskeleton structure; in this research, the ergonomics aspect of the exoskeleton is considered; the motion of the upper exoskeleton shoulder rotation should coincide with the human shoulder joint rotation for smooth functioning of the exoskeleton robot. The number of degrees of freedom of the exoskeleton is limited to the human arm, which has seven degrees of freedom. The controller of the exoskeleton robot is programmed with artificial intelligence to align the trajectory of the exoskeleton with human arm movements. Intensive physiotherapy is needed to improve the condition of the patients, and the number of physiotherapists is smaller to bridge the gap between the numbers of therapists. Exoskeletons are used to improve the patient's health [2]. Exoskeletons are used in repetitive and precise control of the motion, which are desirable characteristics for rehabilitation purposes.

The exoskeleton technology was originally designed for military applications as a wearable device on the human body, and it was designed to help soldiers carry heavy loads such as ammunition and luggage, and food soldiers it weighed around 150kg, it increased the capacity of soldier to carry more weight at the same time with little muscle power utilisation more loading carrying capacity of the soldier was increased. Firefighters and other people in the manufacturing and rescue operations also used it. Research in this area has been studied since the 1960s onwards [3]. Today medical rehabilitation of the exoskeleton robot is used to assist paralytic patients to undergo physiotherapy, rehabilitation, and also to do daily activities. With the scarcity of trained physiotherapists and the duration of the physiotherapy long and frequent therapy needed for quick recovery of the patient, the exoskeleton has become a cost-effective device for the treatment of paralytic patients, spinal cord injured patients, stroke patients, and rehabilitation of the injured persons [4].

However, exoskeletons are not widely used due to their heavy weight and the limitations they have to the human degrees of movement of the limbs. In this research, three types of materials were analysed, namely aluminium, steel, and stainless steel, and they are compared in terms of the structure of the exoskeleton suit [5]. Research has been carried out on the structural analysis of the exoskeleton; it was found titanium is light in weight, aluminium fails due to fatigue corrosion, and stainless steel is strong, but the weight of the exoskeleton is heavy when worn on the human body. Since the human bone young's modulus is 20GPa and the steel young's modulus is 210GPa [6], the increased weight of the exoskeleton will harm the structural bone of the humans. Less Young's modulus, such as titanium, can be used for the development of wearable exoskeletons for paralytic patients; titanium is also noncorrosive. It is an ideal material for exoskeletons manufactured for patients [7].

Types of Exoskeleton systems are upper limb, lower limb, and full body. Exoskeletons used for patients are classified further as rehabilitation, haptics, assistive devices, teleoperations, and power augmentation, depending on the purpose for which they are used. Further, exoskeletons are classified as active exoskeletons and passive exoskeletons; the design of exoskeletons for patients is active exoskeletons. They have to work on the limbs of the patients for rehabilitation and exercise [8]. The battery gives power to the BLDC motors. Passive exoskeletons are used in the military and construction industry as normal people wear them to increase their load-carrying capacity. The exoskeleton is designed to assist the upper limb; understanding the anatomy of the shoulder complex helps in designing the exoskeleton more efficiently [9].

The current research emphasises the increasing importance of upper limb exoskeletons in rehabilitation; nonetheless, a notable deficiency exists in the structural optimisation of materials for biomechanical compatibility and patient comfort. Many studies emphasise functional performance while neglecting the ergonomic interaction between the human body and exoskeleton design, which is essential for prolonged use. Furthermore, there is scant research that analyses material properties—such as Young's modulus and density—in connection to the qualities of human bone. The incorporation of AI for motion alignment has been investigated; nevertheless, its coordination with material flexibility remains insufficiently addressed. This study examines appropriate materials and ergonomic design criteria to remedy these deficiencies. This work introduces a novel comparative static structural analysis of upper limb exoskeletons utilising Finite Element Analysis (FEA) in ANSYS Workbench 15, with an emphasis on biomedical rehabilitation applications.

An essential novelty is the thorough assessment of three often utilised materials—aluminium, stainless steel, and titanium—under realistic stress circumstances that replicate human arm motions, especially for those with paralysis. The work distinctly highlights biomechanical compatibility by contrasting material characteristics, including Young's modulus, with those of human bone, a frequently neglected requirement in exoskeleton design. This study incorporates both mechanical strength and physiological compatibility into the material selection process, contrasting with previous studies that primarily focused on load-bearing capability. The designation of titanium as the optimal material, owing to its superior strength-to-weight ratio and bone-like flexibility, enhances the value of future exoskeleton design. This comprehensive material-performance relationship offers a novel viewpoint in assistive biomechanics and exoskeletal device engineering.

II. METHODOLOGY

II.1 SHOULDER COMPLEX ANATOMY

The upper limb exoskeleton includes the hand, shoulder area, elbow, forearm, and wrist. The way exoskeleton moves depends on coordinated action of 3 bones on 4 joints [10]. The shoulder joint also known as glenohumeral joint. The sternoclavicular joint connects the shoulder region to the main part of the body. The acromioclavicular joint is formed at the point where the end of the clavicle connects with the acromion, which is a part of the shoulder blade. The sternoclavicular joint is a complex joint that involves parts of the clavicle, sternum, and cartilage from the first rib [11]. Because of this, the shoulder has a total of five degrees of freedom. Pneumatic powered Exoskeleton arm is designed and used for weight lifting of 20kgs. Basic hand biomechanics through pneumatic actuator is used to work with load [12].

If the exoskeleton structure limits the translational motion, then the range of motion of the shoulder joint is limited, so in this paper ergonomical design of the exoskeleton is considered during the construction of the robot upper arm shoulder system to avoid pain in the joint [13]. In this robotic arm total nine degrees of freedom. The glenohumeral joint, which is part of the shoulder complex, is a ball-and-socket joint that allows the humerus to rotate around the glenohumeral head in three different directions [14]. The sternoclavicular joint has two degrees of freedom, often referred to as shoulder elevation and depression, or retraction and protraction. These movements cause the glenohumeral joint to move in a straight line. So, altogether, the shoulder has five degrees of freedom [15]. The elbow complex can move in two directions, and the wrist joint also has 2 DOF. The axes around which the wrist moves pass through the capitate carpal bone [16].

When raising the arm above the shoulder, the motion of the shoulder girdle is involved, which includes the clavicle and scapula, plays a more important role than the movement of the arm below the shoulder. The shifting of the glenohumeral joint is crucial for lifting the arm high [17], [18]. If this shifting motion is restricted by outside forces, it can limit the range of motion of the shoulder joint and lead to discomfort or pain in the joint [19]. Because there are differences between individuals, the table below shows the usual

range of motion for the shoulder, elbow, and wrist joints [20], [21]. Human shoulder joint anatomy is shown in Figure 1. Table 1 depicts the human normal range of motion for the upper limb.

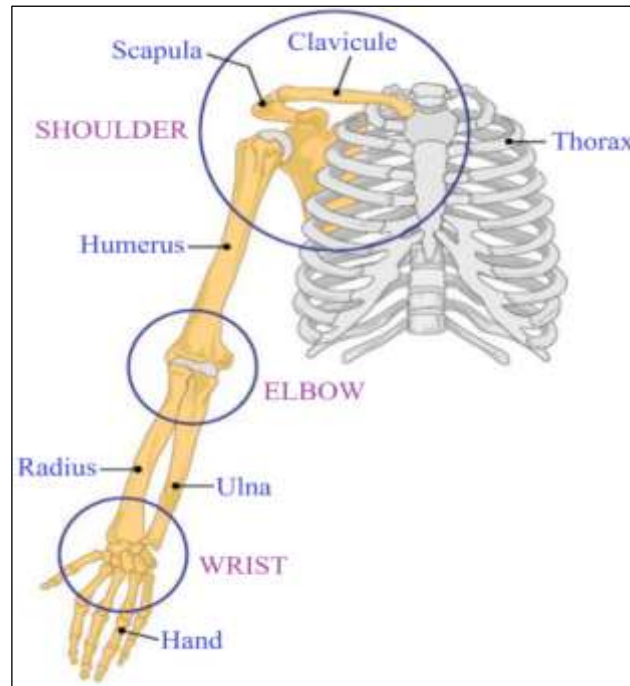


Figure 1: Shoulder joint anatomy.
Source: Authors, (2025).

Table 1: Normal range of motion for the shoulder, elbow, and wrist joints in degrees.

Upper arm description	Position	Angle
Shoulder abduction	From horizontal position	0-90
Shoulder adduction		0-90
Shoulder flexion	From vertical position	0-180
Shoulder extension	-	0-50
Internal rotation (medial)	With the arm at your side	0-90
External rotation (lateral)	-	0-90
Elbow flexion	With upper arm horizontal	0-160
Elbow extension	Until the arm is vertical at your side	145-0
Elbow pronation	-	0-90
Elbow supination	-	0-90
Wrist flexion	-	0-90
Wrist extension	-	0-70
Wrist radial deviation	-	0-25
Wrist ulnar deviation	-	0-65

Source: [22].

II.2 EXOSKELETON DESIGN

The exoskeleton mechanical design for 5 DOF was considered for the shoulder complex. The major difficulty with the exoskeleton is it has to coincide with the movement of the human joints for rehabilitation and exercise for paralytic patients [23]. The exoskeleton was designed for active joints to enhance the patient's muscle power [24]. Table 2 shows the range of motion for the exoskeleton (UMI) compared to humans. The 4 DOFs for the humans.

Table 2: Exoskeleton range of angular movement of arm

DOF - 4	Human	Caden	Exos	MGA	UMI
Ext/Flx	235	180	134	211	224
Abd/Add	172.5	181	141	137	141
Int/Extr	160	161	134	130	161
Elv/Dep	14	-	-	-	11

Source: Authors, (2025).

II.3 EXOSKELETON ROBOT

Modelling a Robotic exoskeleton is completely different from human anatomy; the interaction of the exoskeleton, which is motorised, and the human joints work on the muscle power, is more complex than the robotic joints [25]. In this research, the joints have been designed to work in tandem with the human joints without harming the muscles and range of motion of the human arm [26]. A comprehensive musculoskeletal model was studied analytically by the author an optimal design was suggested for the exoskeleton model. The figure shows the multibody model of the hand; it has two links and a joint at the centre, at the top, that is near the shoulder joint [27]. It is shown as a rigid support; the gravitational forces act at the centre of gravity of each link, and the angle made by each link is also shown in the model in Figure 2. Thus, the muscle activity of the exoskeleton is calculated, along with that of the exoskeleton robot. The exoskeleton biomechanical model was carried out in this research to arrive at the design, and it was modelled and analysed [28].

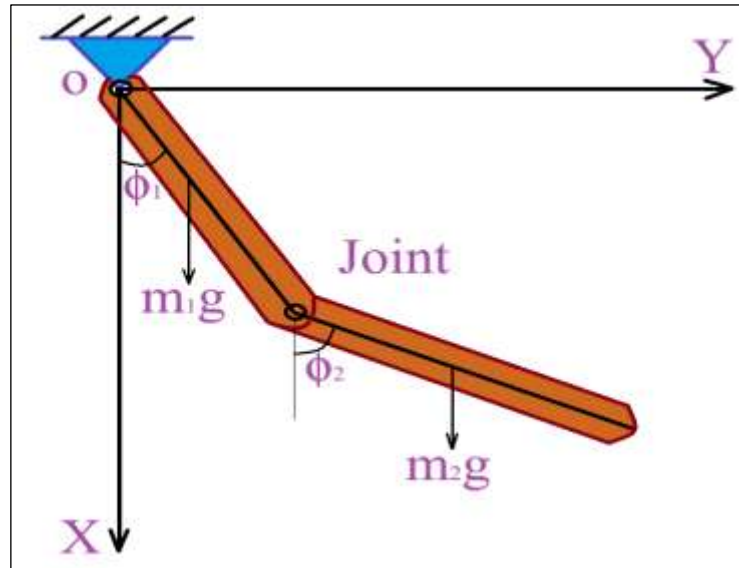


Figure 2: Biomechanical model human hand,
Source: Authors, (2025).

II.4 UPPER-LIMB EXOSKELETON DESIGN CHALLENGES

Exoskeleton design should be kinematically compatible with the patient's motion [29]. In this research, the design of the exoskeleton is such that the four muscles of the shoulder are not constrained. The exoskeleton's range of motion is different from the range of motion of the human anatomy. To achieve this human anatomy, more complex structures are needed; when the structure becomes complex, it becomes heavier, which will be difficult for paralytic patients [30]. In this research new design with lightweight material for the structure was developed in this research to improve the COR of the upper exoskeleton shoulder joint. The discomfort of wearing an exoskeleton suit for paralytic patients is taken care of in the design of the special belt arrangement. Care is taken in the design to align the physiological joints to align with the exoskeleton.

Since the exoskeleton is aligned with the shoulder and wrist, the physiological joints are unique due to the muscle arrangement on the bone and due to the contraction abduction of the muscles, which helps in the movement of the bones due to its complex constructions. As an outcome, the rotational joint axes tend to change their place amid movement [31]. Connections of exoskeletons on human limbs are not the author designs inflexible, special grips to avoid slippage. Thus, lightweight titanium metal is used for the construction of the exoskeletons. The glenohumeral joint is often called a ball-and-socket joint, created where the head of the humerus meets the glenoid cavity. Many studies have mainly focused on the glenohumeral joint when designing a three degrees of freedom (DOF) shoulder model.

II.5 DESIGN CRITERIA FOR EXOSKELETON

The exoskeleton robot should move the upper limb in a way that feels natural, like how a human body would move. At the same time, it should not be heavy, and the wearer should feel ergonomically comfortable.

II.5.1 Increasing loads and discomfort

Increasing load and discomfort on the exoskeleton will affect the human body; the exoskeleton reduces the load on the human, but prolonged use of the exoskeleton will increase the back pain of the wearer. In this research, an active exoskeleton is used to give more power to the paralytic patient and to reduce the workload on the muscles.

II.5.2 Centre of rotation of the shoulder complex

Centre of rotation for the shoulder complex (CR) changes with the motion of the arm motions. So, the exoskeleton is designed by taking into consideration the four muscle forces in the human shoulder joint and the position difference between them.

II.5.3 Wearability

The structures of the exoskeletons are designed similarly to the anatomy of humans, with flexibility, lightweight, and high strength. Those systems have been manufactured with less-weight materials such as titanium to reduce discomfort or fatigue. The materials used in the exoskeleton structure are aluminium, titanium, and stainless steel, which are compatible with human skin and do not slip.

II.5.4 Stress analysis

A stress analysis was conducted to select the material for the exoskeleton structure. After analysing the exoskeleton structure, it is concluded that the titanium is better than the other two materials, aluminium and stainless steel. The stress analysis of the exoskeleton structure of the shoulder flexed 90° and internally rotated 90°.

III. RESULTS AND DISCUSSION

III.1 ANALYSIS OF UPPER ARM EXOSKELETON MODEL

The upper arm exoskeleton model was designed in CATIA modelling software, and then it was imported to Ansys workbench for analysis using different materials with different loading conditions. Figure 3 shows the CATIA exoskeleton model and Ansys meshed structure.

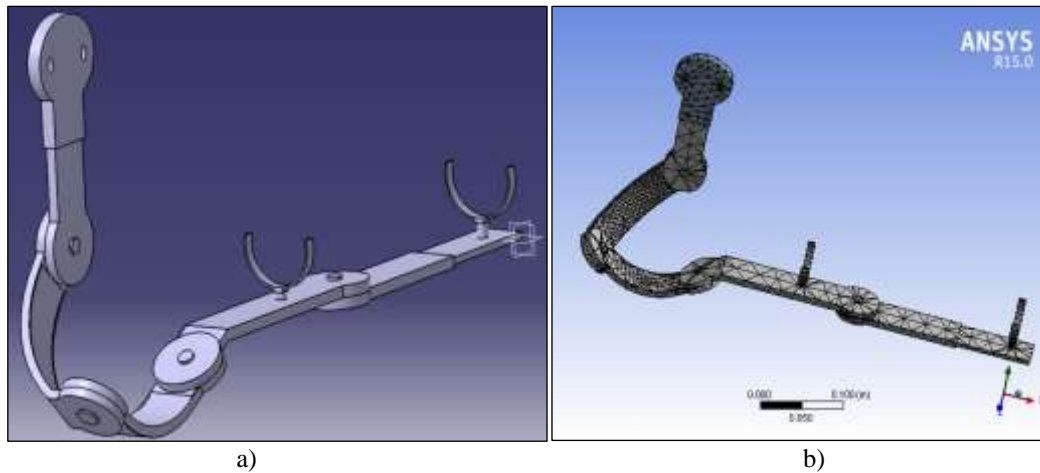
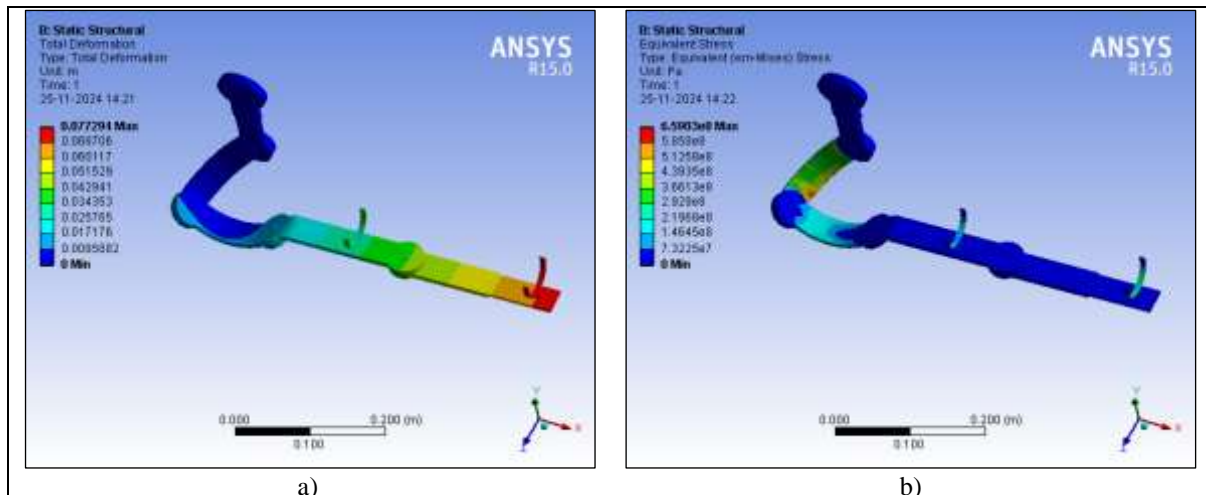


Figure 3: a) CATIA model b) Meshed structure in Ansys.
Source: Authors, (2025).

III.2 FINITE ELEMENT ANALYSIS OF EXOSKELETON TITANIUM STRUCTURE

From the analysis, we found that the total deformation is high near the wrist of the exoskeleton, Equivalent von Mises stress is high near the shoulder joint, Maximum Principal Stress uniform deformation is found on the exoskeleton structure, Minimum principal stress deformation is high on the lower side of the shoulder joint, Equivalent elastic strain the deformation is more near the shoulder joint and safety factor is less in the upper part of the shoulder and deformation is found in the lower part of the shoulder. Normal stress deformation is moderate on the whole exoskeleton structure; directional deformation on the X axis is high in the edges, directional deformation on the Y axis is high on the shoulder joint, and Z directional deformation is high from the shoulder joint to the shoulder attachment. Figure 4 represents a different analysis of the exoskeleton arm structure using titanium material.



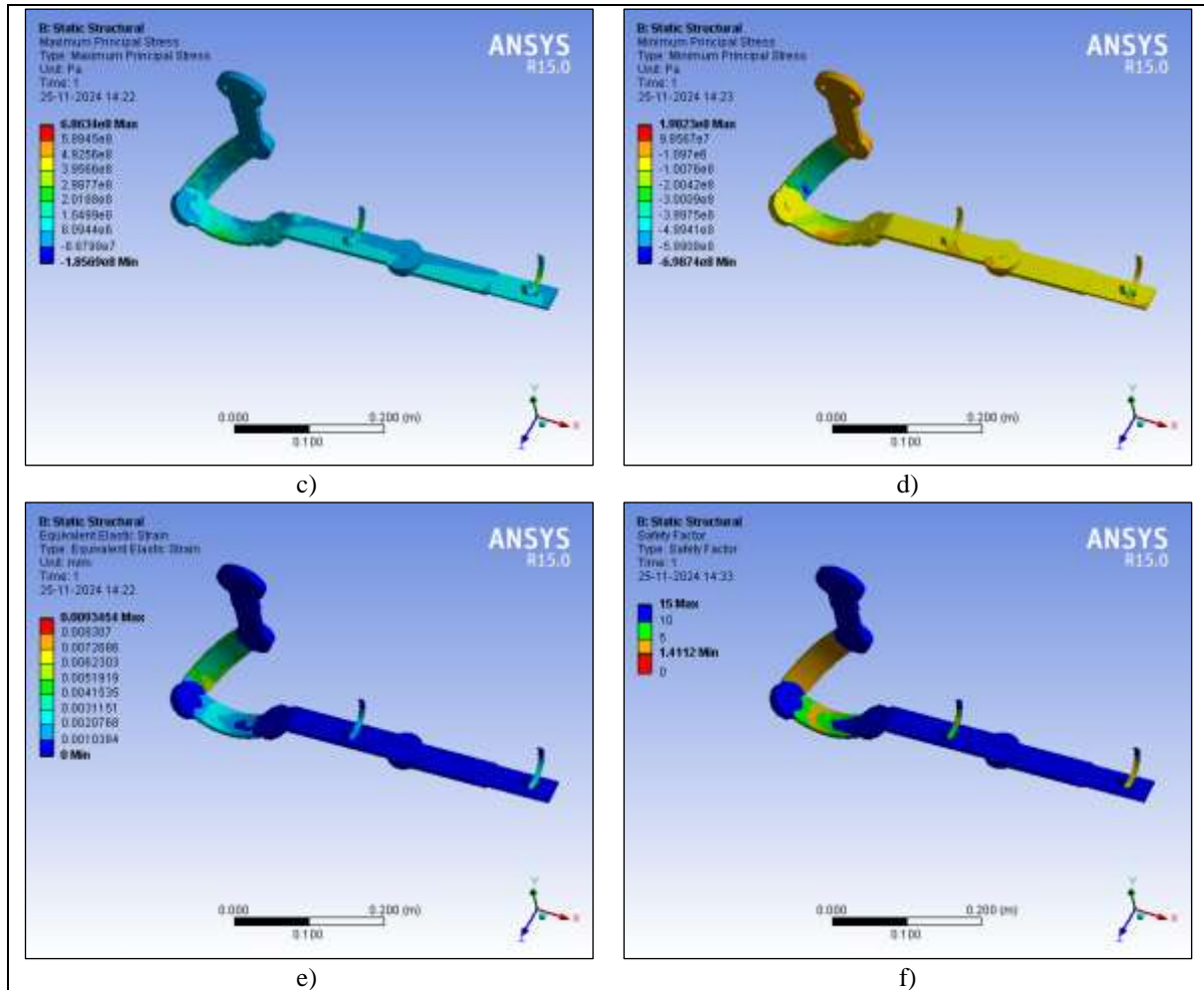
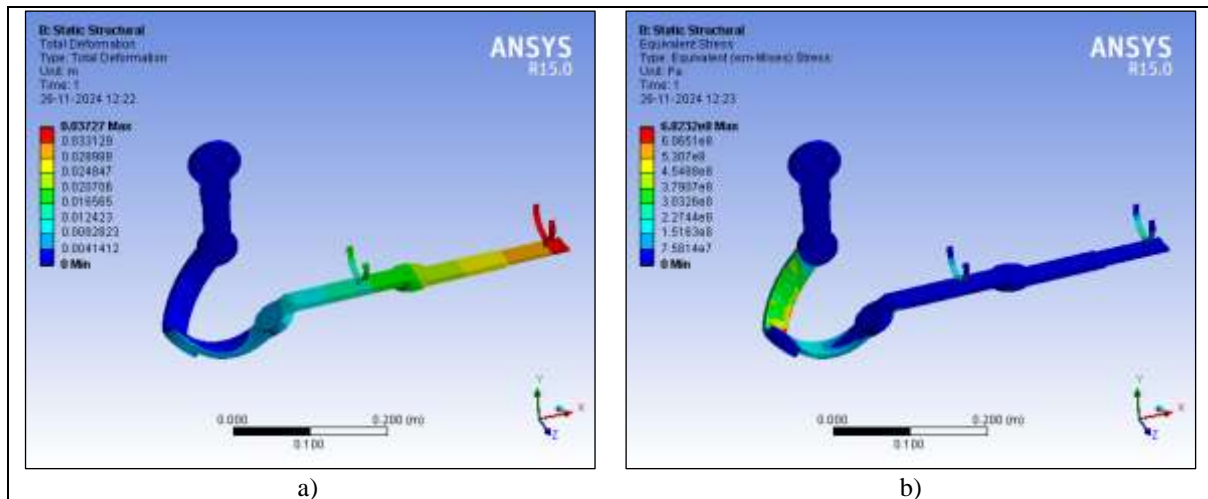


Figure 4: Titanium material structure analysis of 300N load applied a) Total deformation b)Equivalent Stress c) Maximum Principal Stress d) Minimum Principal Stress e)Equivalent Elastic Strain f) Safety factor.
 Source: Authors, (2025).

III.3 FINITE ELEMENT ANALYSIS OF EXOSKELETON STEEL STRUCTURE

Figure 5. Shows different analyses of exoskeleton arm structure using steel material. For the steel structure, we found the total deformation is high near the wrist, Equivalent stress is high near the upper shoulder joint, Maximum Principal Stress uniform deformation is found on the exoskeleton structure, Minimum principal stress is high in whole of the structure except the upper shoulder joint, Equivalent elastic strain is high near the shoulder joint, and the safety factor is high near the upper shoulder joint. Normal stress is high in the exoskeleton edge near the shoulder joint, directional deformation about the x-axis is high from the shoulder to the shoulder joint, y-axis deformation about is high in the area surrounding the shoulder joint, and directional deformation about the z-axis deformation is high near the shoulder joint and the exoskeleton attachment near the human spinal cord.



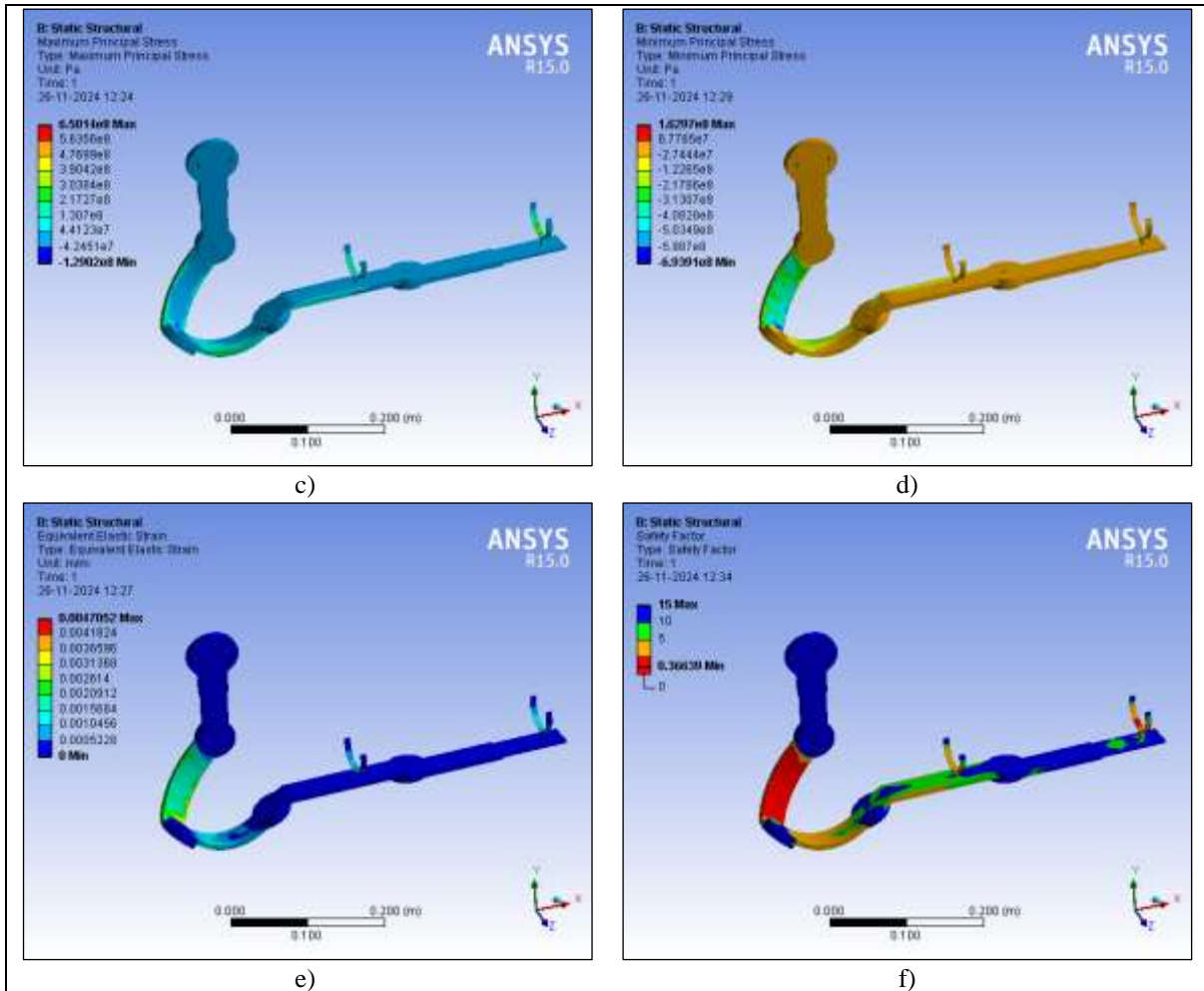
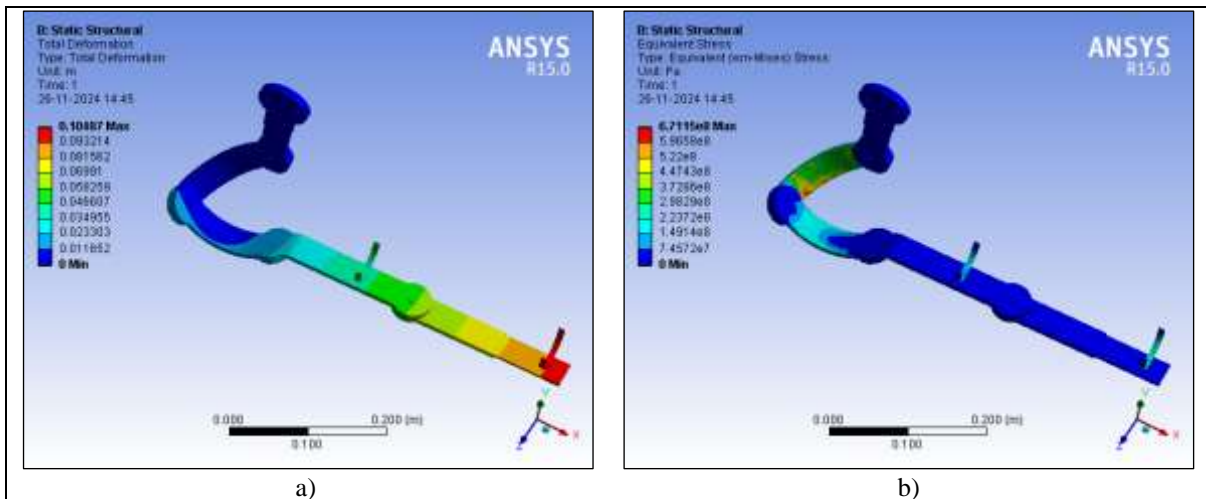


Figure 5: Steel material structure analysis of 300N load applied a) Total deformation b)Equivalent Stress c) Maximum Principal Stress d) Minimum Principal Stress e)Equivalent Elastic Strain f) Safety factor
 Source: Authors, (2025).

III.4 FINITE ELEMENT ANALYSIS OF EXOSKELETON ALUMINIUM STRUCTURE

For the aluminium material, we found the total deformation is high near the wrist. Equivalent stress is high above the shoulder joint, Maximum Principal Stress the deformation is uniform on the exoskeleton structure, Minimum principal stress is high in the shoulder and elbow joint, and Equivalent elastic strain deformation is higher in the joint above and below. The Safety factor is high above the shoulder joint. Normal stress is minimal in the whole of the exoskeleton structure, directional deformation about the x-axis is high on the edge of the exoskeleton, Directional deformation about the y-axis is high in the shoulder and directional deformation z-axis is high near the shoulder joint and the exoskeleton joint at the centre. Figure 6. Shows a different analysis of the exoskeleton arm structure using aluminium material.



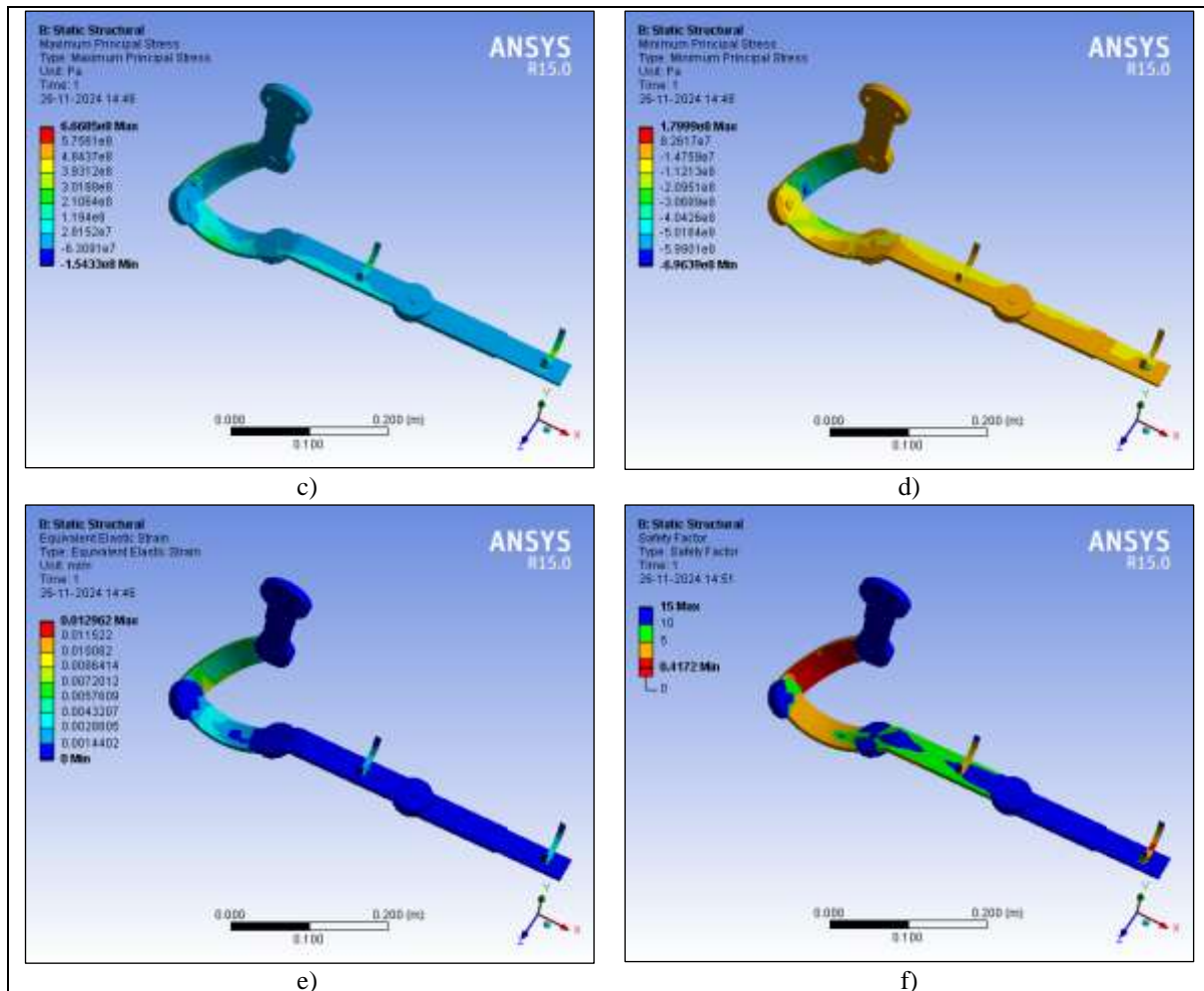


Figure 6. Aluminium material structure analysis of 300N load applied a) Total deformation b)Equivalent Stress c) Maximum Principal Stress d) Minimum Principal Stress e)Equivalent Elastic Strain f) Safety factor
Source: Authors, (2025).

III.5 COMPARISON SUMMARY:

Titanium Equivalent elastic strain, titanium body exoskeleton deformation is higher near the shoulder joint Aluminium Equivalent elastic strain deformation is higher in the joint above and below the shoulder joint. Steel Equivalent elastic strain is high near the shoulder joint, which results in high deformation near the shoulder joint and the stretching of the muscles near the shoulder joint. Design changes should be made near the shoulder joint to take the load falling on the shoulder. Titanium Equivalent Von-mises stress is high near the shoulder joint. Aluminium Equivalent stress is high above the shoulder joint. Steel Equivalent stress is high near the upper shoulder joint. Von-mises stresses predict when a material will yield when complex loading is applied on the exoskeleton shoulder. Low-yielding material is used in the exoskeleton structure. Titanium Maximum principal elastic strain deformation is high near the connecting plates of the shoulder joint. Steel's Maximum principal elastic strain is high around the shoulder joint, yielding on the exoskeleton structure, so the design is carried out in such a way that the exoskeleton structure does not yield compression and tension.

Titanium Maximum Principal Stress uniform deformation is found on the exoskeleton structure. Aluminium Minimum principal stress is high in the shoulder and elbow joint. Titanium Minimum principal elastic strain deformation is high on the whole exoskeleton structure. Aluminium Minimum principal elastic strain is high above and below the shoulder joint. Steel Minimum principal elastic strain is high on the shoulder joint forearm and near the shoulder attachment. Since strain is high near the shoulders, muscle elongation may occur near the shoulder joint. Titanium Minimum principal stress deformation is more on the lower side of the shoulder joint. Aluminium Minimum principal stress is greater in all the other portions of the exoskeleton than in the upper portion of the shoulder joint. Steel Minimum principal stress is greater in the whole structure than in the upper shoulder joint. Titanium Normal elastic strain deformation is moderate on the whole exoskeleton structure.

Aluminium Normal elastic strain is minimal in the whole of the exoskeleton structure. Steel Normal elastic strain is minimal in the entire exoskeleton. Since the strain is minimal, the normal strain did not have any adverse effect on the exoskeleton structure. Titanium Normal stress deformation is moderate on the whole exoskeleton structure. Aluminium Normal stress is minimal throughout the exoskeleton structure. Steel Normal stress is high in the exoskeleton edge near the shoulder joint. When a force acts perpendicular to the surface of an exoskeleton structure, it exerts normal stress. When a force acts parallel to the surface of an exoskeleton structure, it exerts a shear stress. Aluminium can be used since the normal stress is minimal; in titanium, the normal stress is moderate, and steel deformation occurs at the edges.

Titanium safety factor is lower in the upper part of the shoulder, and deformation is found in the lower part of the shoulder. The Aluminium Safety factor is high above the shoulder joint. The Steel Safety factor is high near the upper shoulder joint. The safety factor should be increased to avoid tearing of the shoulder muscle that can occur at the shoulder joint. Titanium Directional deformation X axis is high in the edges of the exoskeleton structure. Aluminium Directional deformation about the x-axis is high on the edge of the exoskeleton. Steel Directional deformation about the x-axis is high from the shoulder to the shoulder joint; since the directional deformation is safe on the x-axis, the deformation on the edges does not affect the exoskeleton structure. Titanium Total deformation is high near the wrist of the exoskeleton. Aluminium Total deformation is high near the wrist. Steel Total deformation is high near the wrist. The wrist bone is weak, and high deformation should be avoided to eliminate injury to the wrist.

Titanium Directional deformation y-axis deformation is high on the shoulder joint. Aluminium Directional deformation about the -axis is high in the shoulder. Steel Directional deformation about the y-axis is high in the area surrounding the shoulder joint. Since the directional deformation is high in the y-axis. Titanium Directional deformation of the z-axis is high from the shoulder joint to the shoulder attachment. The Aluminium Directional deformation z-axis is high near the shoulder joint and the exoskeleton joint. Steel Directional deformation about the z-axis is high near the shoulder joint and the exoskeleton attachment near the human spinal cord. The attachment near the spinal cord will affect the spinal cord joint, and the exoskeleton should be redesigned to minimise the effect. Aluminium Shear stress is minimal in all the portions of the exoskeleton. Steel Shear stress deformation is moderate on the whole exoskeleton structure. Aluminium fails due to shear; in this analysis, the shear stress is minimal for aluminium, and it can be used.

IV. CONCLUSIONS

Upper-limb exoskeleton systems are used in rehabilitation. In this paper, an extensive analysis of upper-limb exoskeletons was carried out for different design parameters. Moreover, the authors have reviewed exoskeletons to modify their future design for more comfort and rehabilitation purposes. The new design challenges were also identified in the mechanical design of the exoskeleton shoulder joint and the biomechanical design aspects of the exoskeleton for human upper-limb anatomy. In this paper, based on biomechanical design considerations, three types of upper-hand exoskeleton materials were used. The comparison of the parameters was discussed, and it was found that the shoulder joints undergo maximum deformation, hence the muscles adjoining the shoulder joint supraspinatus, infraspinatus, teres minor and subscapularis undergo deformation; if the design has to take care of the deformation to keep the humeral head stable. The spinal cord muscles, rhomboids, and trapezius muscles connecting shoulder blades to the spine also undergo deformation due to the exoskeleton, which may result in pain and discomfort to the patients. It is concluded that with less Young's modulus than steel and more shear strength than aluminium, and it satisfies biomechanical and biocompatibility criteria, it is a better choice for upper-hand exoskeleton construction.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Vijayakumar K, Bubesh Kumar D and Sangeetha Krishnamoorthi.

Methodology: Vijayakumar K, Bubesh Kumar D.

Investigation: Vijayakumar K, Bubesh Kumar D.

Discussion of results: Vijayakumar K, Bubesh Kumar D.

Writing – Original Draft: Vijayakumar K.

Writing – Review and Editing: Vijayakumar K, Bubesh Kumar D and Sangeetha Krishnamoorthi.

Resources: Vijayakumar K.

Supervision: Bubesh Kumar D and Sangeetha Krishnamoorthi.

Approval of the final text: Vijayakumar K, Bubesh Kumar D and Sangeetha Krishnamoorthi.

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