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Finite Element Analysis to Enhance the Design of Patient Lifting Equipment for Clinical Applications: A computational experimental study

Sameen Iftikhar [1], ***Ahmad Zahid Rao*** [2*], ***Syed Faraz Jawed*** [2], ***Tayyaba Tahira*** [3]

[1] Master of Engineering (Biomedical), NED University of Engineering and Technology, Karachi, Pakistan

[2] Assistant Professor, NED University of Engineering and Technology, Karachi, Pakistan

[3] Lecturer, Dow University of Health Sciences, Karachi, Pakistan

ABSTRACT

Background of the study: Patient lifting equipment (PLE) mitigates the musculoskeletal risks while ensuring safe patient handling. Various designs of PLE are proposed that can be comprehensively analyzed with the advanced Finite Element Method simulations.

Methodology: We designed the CAD models of various PLE designs and analyzed them under a load of 5400 N with a factor of safety of 04. Static structural analysis is conducted using ANSYS software. The deformation and stress distribution simulation results are obtained with the structural steel (E = 200 GPa) PLE model analyzed at two different positions.

Results: The end-bended boom design exhibited the minor deformation and stress of 0.0379 m and 4.98×10^8 Pa, respectively. Therefore, it was used in the complete PLE analysis. The complete PLE analysis showed that maximum deformation for both truss and beam elements is 0.12456 m at the highest position, and 0.11768 m at the lowest position. Stress distribution varied from -2.729e7 Pa to 1.771e7 Pa at the highest and -2.737e7 Pa to 1.941e7 Pa at the lowest position with either element type.

Conclusion: This study offers insights into optimizing the PLE design based on simulation results. It guides the local industry's development of PLE, which lowers the risk of damage for caregivers and patients.

Keywords: *Aged, caregivers, computer-aided design, finite element analysis, healthcare, musculoskeletal diseases, patient transfer*

INTRODUCTION

In order to facilitate the safe and effective transfer of people with mobility challenges [1], such as elderly patients or those suffering from stroke-related symptoms, such as cases of hemiplegia or paraplegia, PLE is an essential tool in healthcare settings [2]. These tools, also called patient lifters, are used in various healthcare settings, including hospitals, assisted living facilities, and private homes. They play a crucial role in transferring patients from one place to another [3], for example, from a bed to a bath or from a chair to a stretcher. Patient lifters have advantages when appropriately used, including a lower chance of harm for both patients and caregivers [4].A PLE has four principal components: spreader bar, shaft, base and boom.

***Corresponding Author:** Ahmad Zahid Rao
Email: ahmadrao@neduet.edu.pk

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The base and shaft don't move because they are fixed, while the boom and the spreader bar are adjustable to ensure that lifting and transferring patients becomes more leisurely. The inclusive design captures all patient lifting needs in many medical facilities; hence, it is versatile and practical. The strong foundation formed by the base supports the mast carrying the hoist system. The mast that holds the hoist system is braced by a base serving as its sturdy foundation. Furthermore, a horizontally extending boom is connected to the said mast with attachment points for either a sling or harness used for lifting together with spreader bars. Controls, which are handheld pendants or panels, usually act as interfaces for carers to regulate lifters through hydraulic, manual or electric systems of lift mechanisms. This ensures that during transfers, caregivers can maintain correct support and positioning of patients by firmly securing them into place on the spreader bar using slings or harnesses so that strain injuries can be minimized or prevented altogether. However, these parts also work together during transfer operations, acting as one unit to keep patients safe and comfortable at every movement stage. The necessity for patient lifters arises from the need to facilitate safe, efficient, and successful transfers, ultimately improving outcomes for healthcare staff and patients [5, 6]. Manual lifting of patients poses significant risks of musculoskeletal disorders (MSDs)[7], including pain, sprains, strains, fractures, hernias, and soft-tissue injuries, to caregivers [8, 9]. To mitigate these risks and enhance patient care standards, mechanical lifting aids or equipment [10, 11], such as patient lifters, are employed. Various designs of PLE have been developed and are available on the market. However, despite the widespread utilization of patient lifters, there is a need to comprehensively evaluate the various designs of the PLE to understand their structural dynamics and performance characteristics. This study integrates FEA to assess the structural integrity of PLE, contributing valuable insights to medical engineering for enhanced safety, compliance with standards, and practical healthcare applications [12]. Furthermore, it is crucial to consider elements such as trusses and beams during analysis to enhance the understanding of identifying critical points in equipment design. In our study, we comprehensively analyzed four types of booms commonly used in the PLE design. Then, we analyzed the most suited boom with the complete PLE at two maximum and minimum height positions

METHODOLOGY

The methodology employed in this research encompasses a systematic approach, beginning with the meticulous design of simplified CAD models using ANSYS software (ANSYS, Inc., Canonsburg, Pennsylvania, United States) for integral components of PLE. Through FEM analysis [(13)], the study aims to comprehensively evaluate stress distribution and deformation patterns within the PLE framework under patient load conditions. ANSYS software is crucial in simulating how designs will perform in real-world conditions, helping engineers optimize performance and reduce the need for physical prototypes.

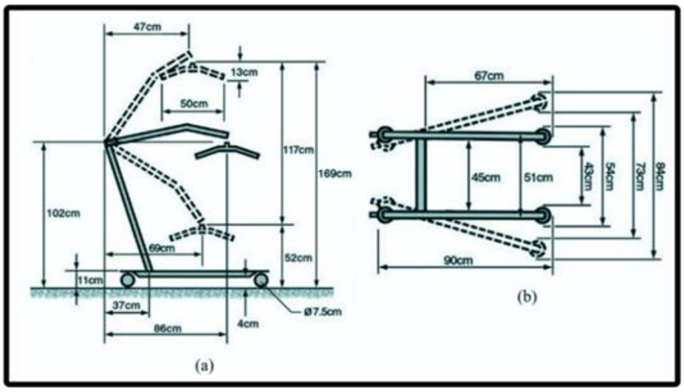

Figure 1. The dimensions of the (a) entire PLE (b) base of the PLE

CAD Model Design

The research began with the meticulous design of simplified CAD models using Ansys Software [14] for the integral components of PLE, including boom and the complete PLE framework. These CAD models meticulously perfected each component's intricate detail and operation. This fact is particularly significant since the performance indicators within PLE are actual equipment dimensions, as presented in Figure 1, which contributes to a more realistic study with more remarkable similarities with actual field conditions. The study tried to enhance its overall value by using actual data matching the practical scenarios. In addition, these CAD models showed the PLE at both maximum and minimum achievable positions overload conditions for getting an appropriate structural performance study of equipment.

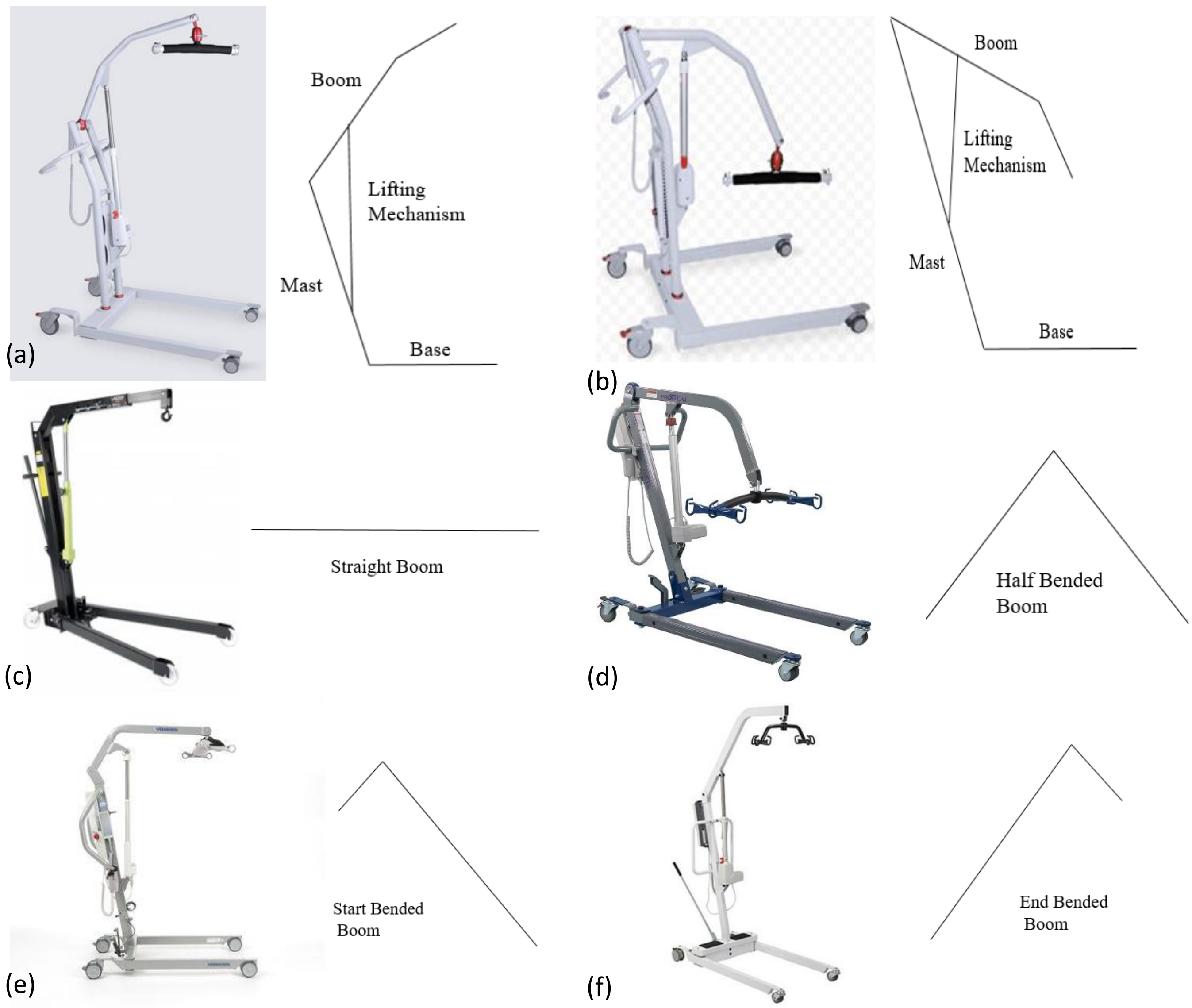

Figure 2. Actual and Simplified geometry of (a) PLE at its maximum position (b) PLE at its minimum position (c) Straight boom (d) Half Bended Boom (e) Start Bended Boom (f) End Bended Boom

As illustrated in Figure 2, simulations were run on four distinct boom types to fully comprehend the PLE's behaviour. A straight boom was used in the first scenario, and a half-bended boom with a bend in the middle was used in the second. Furthermore, a start-bended boom was simulated in the third situation, where the bend was at 25% of the boom's length, while an end-bended boom was examined in the fourth scenario, where the bend was at 75% of the boom's length. Because of the wide variety of boom configurations available, it was possible to thoroughly examine the strengths and structural responses of different boom designs, yielding insightful information for maximizing PLE performance and safety.

Load Calculation for FEM Analysis

FEM simulations were performed on the boom's CAD models as well as the entire PLE architecture. The truss and beam elements were thoroughly incorporated into these simulations to study the structural behaviour of the overall PLE system[15]. Equation 1 and the results of a prior investigation [(6)] were used to compute the load for analysis.

$$F=ma \qquad \text{(Equation 1)}$$

Where, F=Force, m=Mass, a=Acceleration

In order to faithfully simulate real-world conditions, a safety factor of 4 was given to the patient load, which was determined to be 5400N. The study sought to obtain essential insights into stress distribution and deformation patterns inside the PLE framework by putting the CAD models through FEM simulations [(16)].

Elements and Solution of FEM Analysis

The solution of FEM analysis comprised finding the deformation and stress produced in the PLE as a result of the applied load. Based on equation 2 of Hooke's law, the deformation is found where the object is modelled as a spring element.

$$F=kd \qquad \text{(Equation 2)}$$

Where, F=Force, K=Spring stiffness, d=Displacement

The meshing produced around 5000 elements for each analysis. To solve for so many elements, equation 2 is modified as equation 3, where each vector contains values for all elements.

$$[K]\{U\}=\{F\} \qquad \text{(Equation 3)}$$

[K]=Stiffness matrix, {U}=Displacement vector, {F}=Force vector

The stiffness matrix (K) is based on the element's material property. In our analysis, we considered structural steel to have a Modulus of Elasticity (E) of 200 GPa. The formula to find the stiffness matrix is given in Equation 4.

$$K=\frac{AE}{L} \qquad \text{(Equation 4)}$$

Where, K=Spring stiffness, A=Cross-sectional area, E= Modulus of Elasticity, L=Length

The other important parameter analyzed in this study is the stress. Stress is found using the equation 5.

$$\sigma=\frac{F}{A} \qquad \text{(Equation 5)}$$

Where, σ=Stress, F=Force, A=Cross-sectional area

However, von Mises stress is a way to combine multiple stress components into a single equivalent stress value to assess yielding criteria. In simple terms, stress tells you how much force is applied to a material, while von Mises stress accounts for both the magnitude and orientation of the stress components to predict material failure. Since our analysis is in two dimensions, the von Mises stress formula uses two principal stresses, as shown in equation 6.

$$\sigma_v=\sqrt{\sigma_1^2-\sigma_1\sigma_2+\sigma_2^2} \qquad \text{(Equation 6)}$$

Where σ_v=Von Mises stress, σ_1^2, σ_2^2=Principal stresses whose formula are given by equation 7.

$$\sigma_1,\sigma_2=\frac{\sigma_x-\sigma_y}{2}\pm\sqrt{\left(\frac{\sigma_x-\sigma_y}{2}\right)^2+T_{xy}^2} \qquad \text{(Equation 7)}$$

Where σ_1,σ_2= Principal stresses, σ_x,σ_y=Normal stresses in x and y directions, T_{xy}= Shear stress in xy plane.

In this study, we used two types of elements, namely Truss and Beam elements. Truss elements, designed to endure axial forces and deformation along their axial direction, play a vital role in skeletal truss structural systems [17, 18, 19]. On the other hand, Beam elements resist transverse loading through bending action, generating internal bending moments [16]. Understanding the behavior of these elements within patient lifters is crucial for optimizing their design and ensuring their safe and efficient operation in healthcare environments.

RESULTS

Analysis of Booms

Figure 3 shows the displacement and stress analysis of the four different designs of the boom. The analysis revealed that the end-bended boom exhibited the most minor deformation of 0.037m and the lowest stress of 4.98×10^8 Pa. In comparison, the straight boom showed the highest stress levels, 7.083×10^{8} Pa. Across all designs, the maximum deformation was localized at the boom's end, where the patient load was applied. The joint between the boom and shaft emerged as a high-stress zone, particularly in the straight and half-bended configurations.

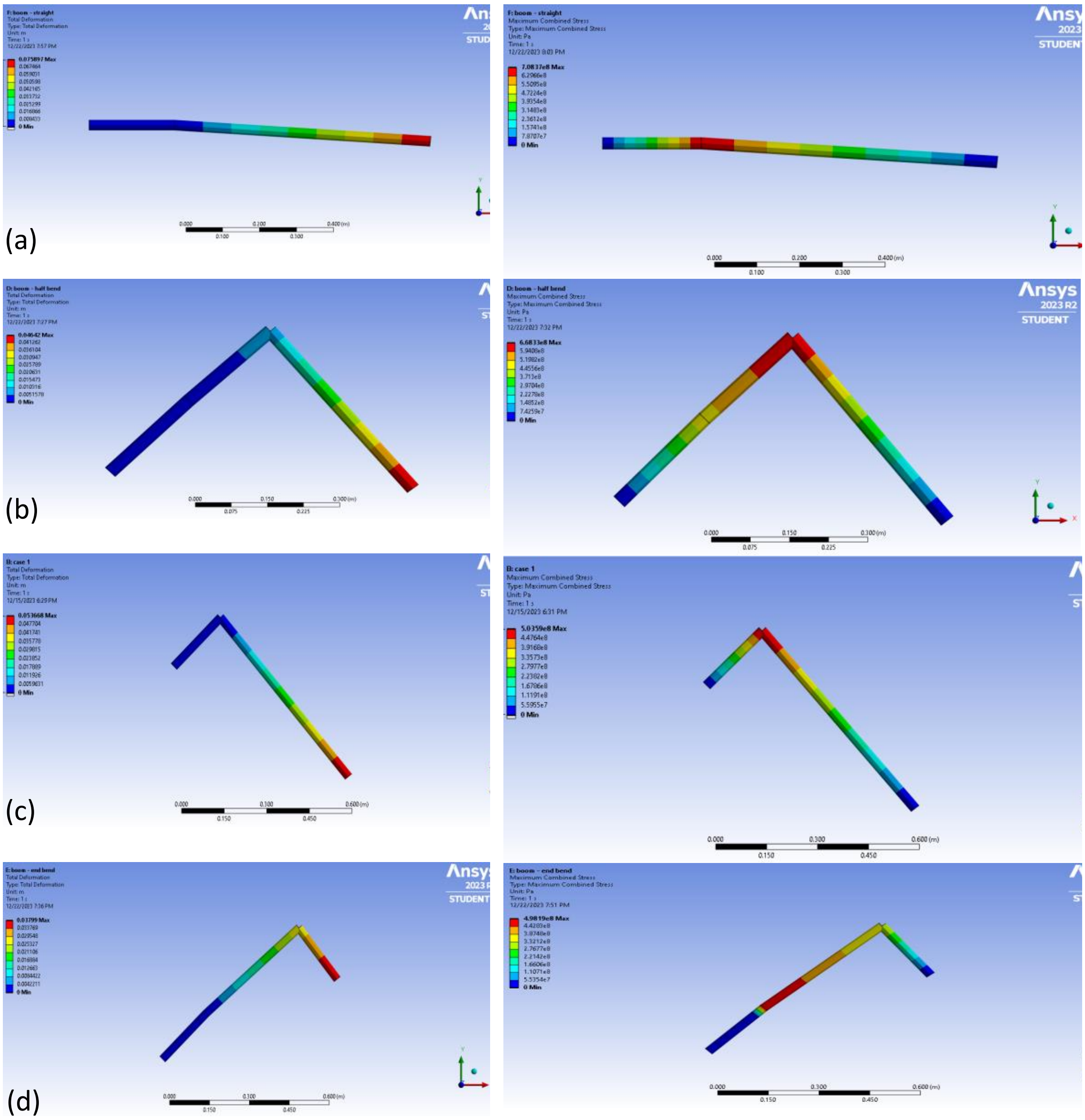

Figure 3. Displacement and stress analysis of boom (a) straight (b) half bent (c) start bent (d) end bent.

Analysis of Patient Lifting Equipment with Truss Elements

Figure 4(a) illustrates the total deformation of the PLE at the maximum position under a patient load of 5400 N, ranging from 0 to 0.1246 m. The stress analysis indicates that direct stress values vary between -2.729 $\times 10^7$Pa to 1.771 $\times 10^7$ Pa, identifying potential areas of structural weakness. These findings emphasize the need for careful material selection and structural design to ensure safety and reliability.

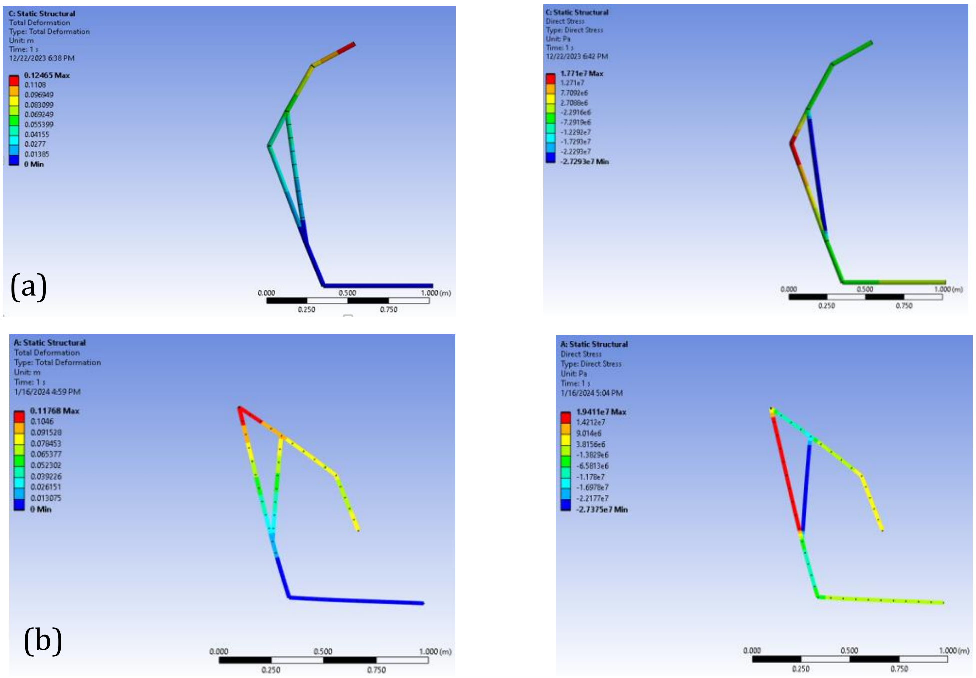

Figure 3. Displacement and stress analysis of PLE with applied load at (a) maximum and (b) minimum position

Figure 4(b) presents the displacement and stress analysis at the PLE's minimum position, showing a maximum deformation between 0 and 0.11768 m. The most significant deformation occurs at the joint between the shaft and boom, indicating it is a critical area for structural integrity. Direct stress values at this position range from -2.737 $\times 10^7$ Pa to 1.941 $\times 10^7$ Pa, with the highest stresses concentrated at the upper part of the shaft. These stress patterns highlight the presence of both compression and tension forces, reinforcing the importance of maintaining structural robustness to ensure reliability.

Figure 5(a) shows the PLE at its maximum position under a patient load of 5400 N, with total deformation ranging from 0 to 0.1246 m. Stress levels fluctuate between -2.729 $\times 10^7$Pa and 1.771 $\times 10^7$ Pa. The maximum deformation occurs at the end of the boom where the load is applied, while the highest direct stress is concentrated at the joint between the shaft and boom. These critical areas are essential for ensuring structural robustness and improving lifter efficiency.

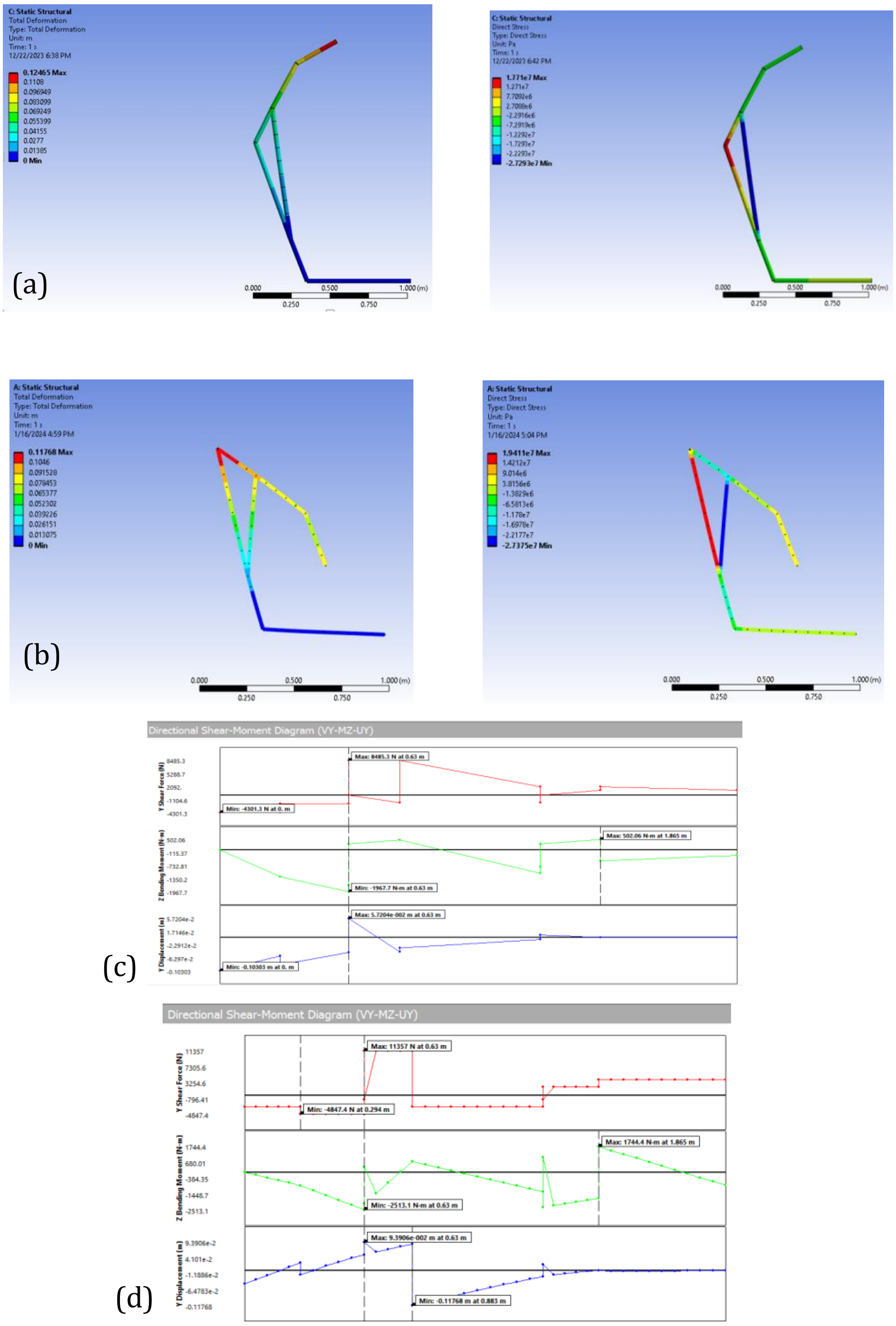

Figure 3. Analysis of PLE displacement and stress at (a) maximum and (b) minimum positions with applied load, along with a shear moment diagram for (c) maximum and (d) minimum positions

Figure 4 (b) illustrates total deformation at the PLE's lowest position, ranging from 0 to 0.11768 m, with stress values between -2.737 $\times 10^7$ Pa and 1.941 $\times 10^7$ Pa. The shaft's upper section experiences the highest stress, while the maximum deformation occurs at the boom-shaft connection. These findings highlight vulnerable zones, guiding strategies to optimize lifter performance and maintain structural integrity under varying loads. Figures (c) and 5(d) present directional shear moment diagrams, illustrating bending moment and shear force variations along the PLE's length at maximum and minimum positions.

Comparison of Results for Truss and Beam Element

The maximum total deformation for two different structural elements, a beam and a truss, at both positions is given in Table 1.

Types of Element	Maximum Total Deformation	
	At maximum position	At minimum position
Truss	0.12456m	0.11768m
Beam	0.12456m	0.11768m

Table 1. Maximum Total Deformation Values for Beam and Truss Elements

Beam and truss elements exhibit uniform deformation characteristics, with maximum deformation reaching 0.12456m at the highest position and 0.11768m at the lowest. This consistency across both components indicates similar behavior under load, ensuring structural reliability. The uniform deformation also confirms that stress is distributed homogeneously, supporting the effectiveness of the PLE design in real-world conditions.

DISCUSSION

The study results have significant implications for enhancing PLE in patient care environments. By additionally considering how PLE behaves in loads [6], manufacturers can use that understanding to enhance patient comfort, ensure safety and optimize efficiency. Therefore, complex finite element analysis is essential to reliably assess intricate structural systems like PLE through all designing and engineering checking decisions [20].Additionally, this can improve current medical engineering projects which adhere to caregiver safety and patient care. These results are promising, and we believe that PLE efficiency can be improved as a potential protective measure to reduce the risk of injuries during lift or transfer tasks in healthcare environments: benefitting both patients and caregivers [2]. Interdisciplinary collaboration between engineering and healthcare disciplines is necessary to foster innovation and streamline the creation of solutions that advance patient care quality and outcomes [21, 22].Furthermore, of all the boom scenarios that have been assessed, the end bend is a good option since it strikes a compromise between deformation rate and manoeuvrability. The end bend has the lowest stress values and deformation rate compared to the straight boom, highlighting its structural integrity[23] and suitability for practical applications. This positive result highlights the end bend as the best option, allowing caregivers to go closer to the floor for patient pickup without sacrificing stability. Its improved agility makes it easier to navigate confined locations precisely, enhancing overall effectiveness and patient care[24]. This research initiative has provided significant information on structural behaviour and PLE design optimization. Because of meticulous CAD modelling, FEA simulations [19], and numerical validations, we comprehensively understand how PLE reacts to various load conditions. Genuine data gathered from accurate equipment dimensions ensured the applicability and reliability of our findings. Furthermore, simulation analyses demonstrate several boom designs' structural advantages, offering valuable guidance for increasing PLE performance and safety requirements [25].While the simulation results are satisfactory, further experimental testing will be necessary to further validate it in a natural environment. Controlled laboratory tests can validate the performance of the end bend configuration in actual loading conditions. Thus, these observed simulation benefits might work in the natural environment. Testing the different materials and structural variations in physical prototypes would also confirm the integrity and long-term reliability of the proposed design enhancements. Such additional experimental verification would provide for a more complete performance evaluation of PLE under operation and facilitate design toward more robust and reliable medical devices. Considering all aspects, this work provides a reasonable basis for future research in PLE design optimization to improve their performances and safety in medical environments.

CONCLUSION

In this study, the structural integrity of a variety of PLE designs had been thoroughly investigated under patient load conditions using FEM models [20]. Our results show that the end-bended boom design has lower stress and deformation magnitudes than other designs, so it is most suitable for PLE applications. The overall results of the PLE show that both beam and truss elements consistently showed maximum deformation values, demonstrating their reliability and stability under realistic conditions. This study provides essential knowledge to advance the risk of injury reduction approach in patient transfer and handling by designing PLE that is safe, comfortable for patients, and effective practice

AUTHORS' CONTRIBUTION:

The following authors have made substantial contributions to the manuscript as under:
Conception or Design: Sameen Iftikhar, Ahmad Zahid Rao, Syed Faraz Jawed, Tayyaba Tahira
Acquisition, Analysis or Interpretation of Data: Sameen Iftikhar, Tayyaba Tahira
Manuscript Writing & Approval: Ahmad Zahid Rao, Syed Faraz Jawed, Tayyaba Tahira
All authors acknowledge their accountability for all facets of the research, ensuring that any concerns regarding the accuracy or integrity of the work are duly investigated and resolved.

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