Three-Dimensional Finite Element Analysis of Stress Distribution and Displacement to Design of Patient Lifting Equipment

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Abstract

The patients with stroke, especially hemiplegia and paraplegia cases, need to be transferred whether from bed to wheelchair or wheelchair to bed and be transferred whether from wheelchair or bed to car or car to a wheelchair or bed while the patient is admitted to the hospital or stay at home. The accuracy of movement handling is required to be in accordance with the principles of physiology in order to increase the safety of patient moving. The utilization of patient lifting equipment will improve patient handling more efficiently for both patients and staff during health care. Patient-lifting equipment is absolutely helpful in lifting patient movement. The study on the analysis of stress distribution as well as the displacement of the device in the analysis of strength in the structure design is rarely found because of computer program limitations. For appropriate usage in each situation, it is important to apply a comprehensive understanding of principles of strength analysis to design patient-lifting equipment. The objective of the proposed research is to design a spreader bar of the patient lift equipment to support use for transferring from a wheelchair or bed to car or car to a wheelchair or bed. The details regarding concept design and analysing the strength of the structure is solved by finite element method (FEM) with a three-dimensional model. The simulated results obtained from the computational solution are investigated and validated against those obtained from the analytical solution. The study focuses attention on the effects of different angles of the spreader bar on the stress distribution and displacement at various points. It is found that the change in the angle adjustment of the spreader bar directly affects the change in the stress distribution, as well as displacement. The maximum stress distribution, as well as maximum displacement, are reduced when the degree increases. The obtained results can be a helpful information to use as the guideline to design a spreader bar of the patient-lifting equipment to transfer patients suitably under each situation.

Keywords: Finite element method (FEM), Patient lifting equipment, Stress distribution, Displacement
1. Introduction

Transferring patients who move themselves with difficulty including those with paralysis, whether lifting, carrying, supporting or repositioning them will affect the relatives, especially, the hospital’s health service staff who will have the opportunity to recognize injuries such as musculoskeletal injuries, back pain and joint disease [1]. Work-related Musculoskeletal Disorder (WRMD) is a collective and descriptive term for symptoms, i.e. injuries of muscle, tendon or nerves, resulted or aggravated by work and characterized by discomfort impairment, disability or persistent pain in joints which of these problems are common among all healthcare workers [2]. According to the study [3], it has been found that the use of lifting equipment to move including the proper lifting can help prevent injuries to the musculoskeletal disorder and can reduce unexpected accidents while transferring the patients. Besides, it has been found in many studies that when the mechanical patient lifting equipment is used, the risk of musculoskeletal injury caused by moving and handling patients is reduced. Some research shows that the implementation of mechanical patient lift equipment helps to significantly reduce the psychophysical stress, injury rate, discomfort and workers compensation costs in healthcare workers [4,5].

The mechanical transfer lift equipment can be divided into three major categories, according to researches studied on type of mechanical transfer lift equipment, namely, the standing hoist, the mobile hoist, and the gantry/ceiling hoist [6]. There are many types of hoisting devices in the world market which differ in the function of use, types of spreader bar attached to the slings, height, length and number of suspension points, those are two-, four-, six-, and eight-point spreader bars [7], and varying degrees of spreader bars. The above device is suitable for transferring patients from wheelchair to bed or from bed to wheelchair, however, it is not suitable for transferring patients from inside the car to wheelchair or bed or transfer back from wheelchair or bed to the car. Therefore, the design of a new patient lifting equipment that can help reduce these limitations will help to develop health services efficiently and completely.

The main components of mechanical transfer lift equipment can be divided into 4 parts which are spreader bar, lift arm, mast and base. Many previous studies on the design of transfer lift equipment components such as Hakamiun et al. [8] designed a patient lift equipment for transporting a person. The equipment consists of a base, a frame, a lifting arm, an actuator as well as an attachment bar. From the base, the frame is extended upwardly and the lifting arm is coupled with an upper end of the frame. To move and lift the arm between the lower and raised position, the actuator is then paired with the lifting arm, which is connected to the attachment bar as well. In addition, a scale, used for weighing a person being lifted, is included in the apparatus. A portable patient transfer, in which a small wheelbase is included, is improved by Brandorff and Campbell [9]. From the wheelbase, a vertically disposed telescoping lifting column extending upwardly. For convenient transfer with a patient, the lift can be closed and temporarily attached to a wheelchair. Huang [10] designed a transfer apparatus for a patient using an electrical system with a linear actuator for moving the lifting arm between the lowered position and a raised position. The difference in the designed equipment was base of equipment has short plates in front and rear, and L invert shape long plate in left and right, which each invert L shape has a guiding slot for bolt for folding the device and length of the apparatus can be folded down. Lear [11] designed a patient lifting apparatus that includes a front and rear independently controlled cable lowering which a patient sitting in a sling suspended from the cables can be assisted out of the sling. It was found that the new design equipment was easy to use. The lifting patient device using the control panel having a micro-controller for remotely controlling the patient lift was presented by Tu [12]. The masts of the device can adjust the lifting angle, a pair of extendable legs extended or folded from the frontal side of the base used to maintain the balance of the device. Wang [13] designed a device for turning over and transferring the patient. A spreader bar of the device can be a turn driving device to control rotation and can be control rotation of the cantilever. A portable assistive lift was designed by Fakhrizadeh [14], the device comprised a vertical member comprising a handlebar and a central wheel controlled by the handlebar disposed at the top and bottom extremities. The highlight of this device was all parts can be disassembled. Runnels [15] presented an apparatus, systems, and methods for providing a mobility device lifting and positioning. A lifting and positioning apparatus included one support structure, a
control unit configured to cause the apparatus to perform operation and lifting mechanism. There is much equipment designed for assisting patient handling, as mentioned earlier; however, the design of the patient lifting is still not comprehensive, especially the equipment for transferring the patient in the limited area such as transfer from wheelchair or bed to inside the car or from car to wheelchair or bed. The main limitation is designing a spreader bar component that is suitable for use in limited sizes. For utilizing patient lifting equipment appropriately, a comprehensive understanding of the influences of key parameters, for example, angle adjustment of spreader bar which affects the strength of the structure, will help the design of patient lifting equipment as a recommendation.

This study focuses on the design of a spreader bar that is the main component of patient lifting equipment. The effects of angle adjustment of the spreader bar on stress distribution and displacement are investigated. The angle adjustment of spreader bar on both sides of 0 degree, 30 degrees, 45 degrees, 60 degrees and 90 degrees are considered. The structural analysis of spreader bar design is carried out computationally by using SolidWorks simulation program. A Three-dimensional model of the spreader bar component of patient lifting equipment is constructed and simulated. In the validation of this simulated model, the accuracy of the proposed computational model is verified by validating the simulated results against the analytical solution, which uses a two-dimensional model for calculating. The simulated results will be used as an information for designing the patient lifting equipment which is used for lifting patients as patient care technologies.

2. Model and Material

The objective of the study is to design the spreader bar components of patient lifting equipment. The structural design and analysis are carried out to study on the stress distribution as well as displacement of spreader bar using Solidworks program. A three-dimensional model of spreader bar component of the patient lifting equipment is designed and constructed, the design corresponds to the sizes of the patient lifting equipment. The overall procedure of the study starts with the literature review. Then, the related data and knowledge on general methods concerning transferring patients are summarized. After that, the conceptual and preliminary designs are conducted, respectively. To study the strength of the structure, the structural analysis is carried out by computer simulation. The computer simulation method is selected in this study due to cost, size factor and convenience. Thereafter, Von-Mises stress distribution from the simulated results is validated against the results from the analytical solution which uses a two-dimensional model with the same configuration to verify the model’s accuracy. The overall flowchart of the research methodology is shown in Figure 1. Figure 2 shows the spreader bar design for analysis of stress distribution and displacement at critical points of 1, 2 and 3, respectively. The angle adjustments of spreader bar on both sides of 0 degrees, 30 degrees, 45 degrees, 60 degrees and 90 degrees on the stress distribution and displacement are studied. The angle adjustments of the spreader bar are indicated in Figure 3. Figures 3(a)-(e) display the angle adjustment of spreader bar on both sides of 0 degrees, 30 degrees, 45 degrees, 60 degrees and 90 degrees, respectively.

For structural strength of the spreader bar, the alloy steel is used as a test material. This material is selected due to its a good combination of all general characteristics of steel strength resulting in high forming ability, high strength and elongation, corrosion resistance and suitable for use on cleanliness and hygiene. The mechanical properties of the material are presented in Table 1.

In the numerical analysis, the finite element method (FEM) is utilized/employed for solving the mathematical models in order to demonstrate the stress distribution and displacement. Triangular elements are used to discrete the three-dimensional model of the spreader bar and approximately calculate the stress distribution and displacement variations across each element. Appropriate required number of elements is identified by performing the grid independence test. Furthermore, a fine mesh is defined in the sensitive area for good calculation.
Figure 1. The flowchart methodology of this research

Figure 2. A Three-dimensional model of spreader bar designed by SolidWorks software

Table 1. The mechanical properties of material applied in the model

| Property                | Value  | Unit |
|-------------------------|--------|------|
| Modulus of Elasticity   | 210,000| MPa  |
| Shear Modulus           | 78.990 | MPa  |
| Poisson Ratio           | 0.28   | -    |
| Yield Strength          | 620.42 | MPa  |
| Tensile Strength        | 723.83 | MPa  |
3. Methodology

Structural strength analysis using FEM is an effective and popular method. SolidWorks simulation software is applied to analyze the strength of the spreader bar to determine the appropriate stress and displacement for the safety of users. There is a total of 5 cases in which the data are collected. Von-Mises stress distribution and displacement at critical points of 1, 2 and 3 include the maximum stress and maximum displacement on the spreader bar in each case is considered.

3.1 Governing Equation

The basic strength equations to calculate the balance of a flexible solid in three-dimensional can be written in the form of partial differential equations as follows [16]:

\[
\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + F_x = 0 \\
\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + F_y = 0 \\
\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_z}{\partial z} + F_z = 0
\]

(1)

Where \( \sigma_x, \sigma_y, \sigma_z \) are normal stress components in x, y, z direction (MPa), respectively

\( \tau_{xy}, \tau_{yz}, \tau_{xz} \) are shearing stress components (MPa)

\( F_x, F_y, F_z \) are body force in x, y, z direction (N), respectively

3.2 Boundary Conditions

The characteristics of the spreader bar will be attached to the lifting arm of the patient lift equipment as shown in Figure 4. This study assumes that the weight in each point on spreader bar is constant and the same at the connection point. Based on general requirements for basic security and important competencies from Ministry of industry, casting materials are not damaged due to wear when stretching less-than 5%. In addition, the structural strength analysis will specify the tensile factor of safety equal to 4. The patient lifting device is assumed that can lift the patient with the maximum weight equal to
135 kg, therefore the load used in the analysis is equal to 540 kg. The load is distributed evenly at the 4 ends of the spreader bar with equal to 135 N is assumed. Figure 4(a) shows the characteristics of the spreader bar will be attached to the lifting arm of the patient lift equipment and Figure 4(b) displays the mesh independence test. In stress distribution as well as displacement analysis, the boundary condition assigned at various points are illustrated in Figure 5. For evaluating a suitable number of elements which leads to the accuracy of the numerical results, the mesh independent solution is carried out. It is found that the number of elements in case the angle of 0 degrees approximately 625,014 elements, in case the angle of 30 degrees approximately 583,000 elements, in case the angle of 45 degrees approximately 573,023 elements, in case the angle of 60 degrees approximately 581,589 elements, and in case the angle of 90 degrees approximately 575,401 elements, as shown in Figure 5(a)-(e), respectively.

![Figure 4](image_url)

**Figure 4.** The characteristics of the spreader bar in the calculation (a) The characteristics of the spreader bar will be attached to the lifting arm of the patient lift equipment and (b) Relationship between the total element and maximum Von-Mises stress
Figure 5. Mesh element analysis and boundary conditions of the angle adjustment of spreader bar on both sides of (a) 0 degrees, (b) 30 degrees, (c) 45 degrees, (d) 60 degrees and (e) 90 degrees.

4. Results and Discussion

4.1 Verifications of the model

To evaluate the accuracy of the present numerical models, Von-Mises stress distribution of the simulated result is validated against the analytical result in the same condition. Due to the spreader bar model studied is complex geometry, it is difficult to calculate by an analytical solution. Therefore, a simple spreader bar model of 0 degree is used for verifications of the model. The computational domain for validation in case the angle of 0 degree is shown in Figure 6. The two-dimensional strength equations for calculating the analytical solution is described by the following equation:

\[
\begin{align*}
\sigma_1, \sigma_2 &= \frac{\sigma_x - \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2} \\
\sigma_y &= \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2}
\end{align*}
\]

Where \( \sigma_1, \sigma_2 \) are principal stresses (MPa)
\( \sigma_x, \sigma_y \) are normal stress components in x and y direction (MPa)
\( \tau_{xy} \) is shearing stress component (MPa)
\( \sigma_y \) is Von-Mises stress (MPa)

For verifications of the model, the two-dimensional model is assigned with triangular elements. The number of mesh element which is selected to use in verifications of the model is 625,014 elements. The Von-Mises stress distribution result from the numerical solution of the present study is indicated in Figure 7. The comparison of the Von-Mises stress distribution of a spreader bar between the numerical solution and analytical solution is illustrated in Table 2. The results
show that the maximum value of Von-Mises stress from numerical solution and one from the analytical solution are 287.7 MPa and 278.2 MPa, respectively. The error between the two solutions is equal to 3.415 %. This favorable comparison presents the accuracy of the numerical model confidently. However, some errors may occur in simulations by the numerical scheme.

**Figure 6.** The computational domain for validation in case the angle of 0 degree

**Table 2.** Comparing solution methods between the analytical solution and numerical solution

|                      | Analytical Solution | Numerical Solution | Error  |
|----------------------|---------------------|--------------------|--------|
| Von-Mises stress     | 278.2 MPa           | 287.7 MPa          | 3.415 %|

**Figure 7.** Von-Mises stress distribution result from the numerical solution of the present study
4.2 Effects of angle adjustment on the Von-Mises stress distribution

The Von-Mises stress distribution of spreader bar influenced by various angle adjustments is exhibited in Figure 8. Figure 8(a)-(e) shows the Von-Mises stress distribution in the case of the angle of 0 degree, 30 degrees, 45 degrees, 60 degrees and 90 degrees, respectively. The results showed the corresponding results in all cases, where the maximum Von-Mises stress distribution of them take place at the connection point. The comparison of the Von-Mises stress value by varying the angle adjustment of the spreader bar is presented in Figure 9. Figure 9(a) displays the maximum Von-Mises stress distribution influenced by various angle adjustments of spreader bar. The results show that in the case of 0 degree, the highest maximum Von-Mises stress distribution occurs and is followed by the case of 30 degrees, 45 degrees, 60 degrees and 90 degrees, respectively. Figure 9(b) displays the Von-Mises stress distribution at the critical points influenced by various angle adjustments. The three critical points of 1, 2 and 3 are exhibited in Figure 2. The results show that at the critical point 1, in the case of 0 degree causes the highest Von-Mises stress value that equal to 46.21 MPa while in the case of 90 degrees causes the lowest Von-Mises stress value that equal to 7.49 MPa. At the critical point 2, in case of 0 degrees causes the highest Von-Mises stress value that equal to 1,379 MPa while in the case of 90 degrees causes the lowest Von-Mises stress value that equal to 23.73 MPa. At the critical point 3, in the case of 0 degree causes the highest Von-Mises stress value that equal to 379.8 MPa while in case of 90 degrees causes the lowest Von-Mises stress value that equal to 269.7 MPa. Considering the Von-Mises stress value, it is seen that in the case of 90 degrees is most suitable for design specification because it has the lowest Von-Mises stress value. Furthermore, considering the maximum Von-Mises stress value, it is found that in the case of 60 degrees and in case of 90 degrees not exceed the yield strength of the material at 620.42 MPa, referred to the Table 1.

![Figure 8](image_url)  
**Figure 8.** The effects of angle adjustment on the Von-Mises stress distribution of spreader bar in case the angle of (a) 0 degree, (b) 30 degrees, (c) 45 degrees, (d) 60 degrees and (e) 90 degrees
Figure 9. Comparison of Von-Mises stress distribution by varying the angle adjustment of spreader bar: (a) maximum Von-Mises stress distribution and (b) Von-Mises stress distribution at critical points 1, 2 and 3.

4.3 Effects of angle adjustment on the displacement

Figure 10 shows the displacement of the spreader bar influenced by various angle adjustments. The difference in displacement by varying the angle adjustment of spreader bar in case the angle of 0 degrees, 30 degrees, 45 degrees, 60 degrees and 90 degrees are shown in Figure 10(a)-(e), respectively. The results showed the corresponding results in all cases, where at the position at the ends of the spreader bar, the maximum displacement take place. This is because of the distance between load and fulcrum point that is the point that must support the weight. The comparison of the displacement value by varying the angle adjustment of the spreader bar is displayed in Figure 11. Figure 11(a) demonstrates the effects of angle adjustment of the spreader bar on the maximum displacement in each case. As can be seen, the figure shows that in case of 0 degrees has the highest maximum displacement, followed by the in case of 30 degrees, in case of 45 degrees, in case of 60 degrees and in case of 90 degrees has the lowest value of maximum displacement, respectively. The results have shown that the maximum displacement value in case of 0 degrees is 9.017 mm, in case of 30 degrees is 7.896 mm, in case of 45 degrees is 6.588 mm, in case of 60 degrees is 4.944 mm and in case of 90 degrees is 2.336 mm, respectively. The effects of angle adjustment and position of the spreader bar on the displacement in each point are illustrated in Figure 2. The obtained results displayed that at critical points of 1 has the highest displacement value in case of 0 degrees that equal to 8.851 mm while the lowest displacement value in case of 90 degrees that equal to 2.269 mm, at critical points of 2 has the highest displacement value in case of 45 degrees that equal to 1.404 mm while the lowest displacement value in case of 90 degrees that equal to 1.181 mm and at critical points of 3 has the highest displacement value in case of 90 degrees that equal to 0.019 mm while the lowest displacement value in case of 30 degrees that equal to 0.015 mm. Considering the displacement value, it is found that in the case of 90 degrees is most suitable for design specification because it has the lowest displacement value which of the following corresponds to Von-Mises stress distribution value.
Figure 10. The effects of angle adjustment on the displacement of spreader bar in case the angle of (a) 0 degrees, (b) 30 degrees, (c) 45 degrees, (d) 60 degrees and (e) 90 degrees.

Figure 11. Comparison of displacement by varying the angle adjustment of spreader bar: (a) maximum displacement and (b) displacement at critical points 1, 2 and 3.

5. Conclusion
This study focused on the use of computer modeling and simulation of stress distribution and displacement to prepare the preliminary design of the spreader bar of patient lifting equipment. The patient lifting equipment is assumed that can lift the patient with the maximum weight equal to 135 kg, therefore the maximum weight used in the analysis is equal to 540 kg for considering the tensile factor of safety equal to 4. SolidWorks software is used in the design including analysis of the strength of spreader bar by FEM via three-dimensional model. The various angle adjustment on the stress distribution and displacement by varying the angle adjustment of the spreader bar is investigated. The simulated results obtained by implement of computer programs are validated against the calculated results obtained by analytical solution with the two-dimensional model. The results clearly show a good agreement of the analytical results and present simulated stress distributions. Considering of model-based testing for designing of 5 cases with different angle adjustment namely angle of 0 degree, 30 degrees, 45 degrees, 60 degrees and 90 degrees, it is found that in case of 0 degrees has the highest...
maximum stress distribution, followed by the in case of 30 degrees, in case of 45 degrees, in the case of 60 degrees and in the case of 90 degrees, respectively. The change in the displacement from the angle adjustment change gives the result that corresponds to the change of stress distribution. The simulation results show that in the case of 0 degree has the highest maximum displacement, followed by the in case of 30 degrees, in case of 45 degrees, in case of 60 degrees and in case of 90 degrees, respectively. The change in the displacement from the angle adjustment change gives the result that corresponds to the change of stress distribution. The simulation results show that in the case of 0 degree has the highest maximum displacement, followed by the in case of 30 degrees, in case of 45 degrees, in case of 60 degrees and in case of 90 degrees, respectively. The maximum displacement will be reduced when the degree increases. Considering the Von-Mises stress value and displacement value, it can be seen that in case of 90 degrees is most suitable for design specification because it has the lowest Von-Mises stress value and lowest displacement values. In addition, considering the highest maximum Von-Mises stress value, it is found that in case of 60 degrees and in case of 90 degrees not exceed the yield strength of the material. Consequently, this favourable result lends confidence that the spreader bar will not be damaged when really used. The basic knowledge obtained from computer analysis can be used to improve the structure in order to build a prototype of patient lifting equipment. This research, studied the effects of angle adjustment of spreader bar on stress distribution and displacement to ensure that the spreading bar will not damage when actually used. The obtained results will be compared with the results of actual/real testing in the future.

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