Structural analysis of three-dimensional finite element model to design multifunction wheelchair for patients

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Abstract
The disabled and patients, especially hemiplegia and paraplegia cases and elder need to use a wheelchair for movement and admitted to the hospital or stay at home. The problem of using wheelchairs for patients and the elder is due to their different shapes. There is only a standard type of wheelchair in a hospital, therefore could not respond to differences in shape and usability. The ability of a wheelchair that does not provide enough facilities will result in the service as being ineffective in achieving and will make patients feel uncomfortable. The basis of the strength analysis, as well as stress distribution of the device structure design, is still minimal due to computer program limitations. A comprehensive understanding of the fundamentals of strength analysis will support the recommendation to design of wheelchair to handle patient for appropriate use in each situation. This research aim provides strength analysis to design the multifunction wheelchair. The multifunction wheelchair is designed to be turned into a bed, height-adjustable to use in a situation where a standard wheelchair could not be achieved due to the height is not enough and arm rest’s width adjustable for the convenience of patients with different body shapes. The detail regarding concept design and strength analysis of main components are solved by the finite element method (FEM) with a three-dimensional model. The results obtained from the simulation solution are examined and compared with the analytical solution. It is found that the highest maximum stress value does not exceed the yield strength of the material. The obtained results can be helpful in determining the basis for the guideline of wheelchair design and develop medical instruments situation by using principles of engineering.

Keywords: Finite element method, Multifunction wheelchair, Stress distribution

1. Introduction
Nowadays, society becomes an aging society which means the amount of elder in the country may increase compared to other ages [1]. Since the population average age is higher than before and there are some problems from the economy effect that most people do not expect to have more heirs to reduce their expenses. Therefore, the number of patients in hospitals is higher and part of them are elder patients. Some patients need to use a wheelchair because of their health problems. However, the wheelchairs are manufactured in one standard size and therefore cannot respond to the different shapes of patients and usability. The main problem of the limitation of standard size wheelchairs can be as
follows. First, the different shapes of the patient do not fit in the wheelchair, resulting in the patient feeling that the wheelchair is inconvenient to use and may cause other health problems such as aches. Second, the patients who sit in a wheelchair for a long time to wait for medical service may develop several diseases. In which case the staffs need to transfer the patient to a bed. In addition, if there is any incorrect physiological movement, it will affect the health of the patient and the staff [2]. The staffs and caregivers who have to help and support patients need to learn how to use any equipment. They need to know the technique to handle and move patients safely using medical equipment [3]. There are instructions for using any patient handling tasks associated to reduce injuries. These tasks are including wheelchair and patient lifting equipment. The staffs and caregivers must know practicing for safe patients’ movement [4]. Reductions of injuries associated with patient handling were studied by Wardell H. [5]. It was observed that in the 3 months following the implementation of the program, the hospital experienced only 9 reported strain and sprain injuries associated with patient handling, a 61% reduction in the reported injury rate. Lastly, it takes a long time to transfer patients, especially those who are unable to help themselves, which may affect the time they provide medical services. The design of the multifunction wheelchair will improve patient handling patients more efficiently in health care for both patients and staffs.

There are many kinds of wheelchairs produced and available to be using nowadays. These productions were designed and developed to respond to the patient’s need. The recline and tilt function were found by using a mechanic and electrical control system of the wheelchair. Some research to study the function of wheelchair by using MATLAB and to calculate the patient’s average wheelchair usage time. It is found that most patients use their wheelchair 9-15 hours per day and the longest single continuous is 14.2 hours per day. The recline and tilt feature also be used together for about 5 hours per day [6]. Moreover, wheelchair also has been developed a new seat-adjustable power wheelchair to prevent pressure ulcers from long periods of sitting [7]. The lower rear portion of the power wheelchair was movable along a ball screw to change the tilting angle of the seat of the wheelchair resulted in the patient to be able to change the high-pressure area of the bottom. The mechanism can also be employed to convert the center of gravity of the wheelchair to increase the stability while the wheelchair was moving. The standard size of the wheelchair in the hospital cannot be adjusted the height of the seat but this feature is important as well. Some research described a biomechanical assessment of electric lifting chair with hip-up function. Experimental measurements of three-dimensional (3D) motion data and electromyogram (EMG) on the femoral muscle when the subject performs the standing motion on the predetermined seat height. The results showed that 15 degrees of the hip-up angle were suitable for the hip-up function and that the higher seat position was more effective to assist for standing up motion [8]. In the same year, the contour detection and localization of intelligent wheelchair for parking into and docking with U-shape bed was proposed [9]. Lines contained in the back-view image of the wheelchair were projected into the bed's superface plane and separated into several groups based on conditions of parallelism and perpendicularity.

The mechanical design that suitable for functionality and safety for a wheelchair or medical device is essential. Preliminary design of a mechanical transfer lift for the disabled patient in a Malaysian hospital was presented by Jusoh M.A. et al. [10]. It was found that the safety factor of 1.04 during static loading analysis using mild steel as the base was achieved. Mahmoud Z. et al. [11] determined the importance weights for engineering characteristics of wheelchair design by integrating a Quality Function Deployment (QFD) framework with a Fuzzy Analytic Network Process (FANP).

Although there have been studies and designed wheelchair, the wheelchairs which are available to purchasing have only one special feature for one product such as recline wheelchair will have only recline feature and height-adjustable wheelchair will have only height adjustable feature. The wheelchair features are reclined and tilt adjustable and height seat adjustable are necessary. Furthermore, comprehensive knowledge of the fundamentals of strength analysis will support the approval to design and create of the wheelchair to handle patient for appropriate use in each situation. The model of multifunction wheelchair and strength analysis is representative the basis of the model that will be used in the construction of the wheelchair.
2. Design and Simulation
This research focuses on the strength and ability to work in 3 features including recline and tilt adjustable, height-adjustable and armrest width’s adjustable. The multifunction wheelchair is designed by using SolidWorks software and simulation models to analyze the strength of the main components. The size of human used in calculating is the average standard size.

2.1 Wheelchair design
The wheelchair is assembled by various parts, which are base of the wheelchair, wheel, leg rest and footrest, X-lifter, seat, armrest and backrest. Thus, the design is separated into a part and assembly to become a complete multifunction wheelchair as shown in Figures 1 and 2.

![Figure 1. Side view of a multifunction wheelchair design](image1)

![Figure 2. 3D structure of a multifunction wheelchair design](image2)

2.2 Equilibrium of wheelchair design
The conditions of design defined is user has maximum weight of 120 kg and maximum height 165 cm. Furthermore, the research of the distribution of weight on each man’s proportions from human body dynamics showed that the weight distributed to each part on the wheelchair as shown in Figure 3 [12].

Consider at point A, the reaction force \( F_A \) is calculated using Equation (1) and found that the value can be calculated equal to 255.50 N, which the wheelchair is in balance.

\[
\sum_{A} M_A = 0 \quad (1)
\]

The X-lifter is used for adjusting the height of the wheelchair. The calculation for maximum load act to X-lifter uses Equations (2) and (3) with definite equal to 1200 N acts on the centroid of X-lifter as shown in Figure 4. Therefore, \( F_{r1} \) and \( F_{r2} \) are equal and can be calculated equal to 1475 N.
\[ \sum F_x = 0 \quad (2) \]
\[ \sum F_y = 0 \quad (3) \]

\[ F_1 = 146.40 \text{ N} \quad F_x = 296.88 \text{ N} \quad F_z = 756.72 \text{ N} \]

**Figure 3.** People's weight distribution on the wheelchair when the human weight is 120 kg and 165 cm in height

As can be seen in Figure 5, the rear of the backrest is used for recline and tilt features. Linear actuator at the rear of backrest gets a reaction force \( (F_r) \). Calculating for the value of reaction force \( (F_r) \) by Equation (1) The calculation result will be able to calculate the reaction force \( (F_r) \) is equal to 1991 N.

**Figure 5.** Forces act on the rear of the backrest

The leg rest will use a linear actuator for adjusting similar to the backrest. It can be calculated by the equation of equilibrium force and rotation as set out in Equation (1). Thus, the value of reaction force \( (F_r) \) that acts is equal to 840 N. The force distribution is given in Figure 6.

**Figure 6.** Forces act on the rear of leg rest

The above calculations are used to select the linear actuators for each part of the wheelchair design.
2.3 Governing equation
The equations below are calculated the solution of differential equations for the balance of solids with the flexibility in 3D [13]:

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + F_x = 0$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + F_y = 0$$

$$\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_z}{\partial z} + F_z = 0$$

(4)

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

2.4 Properties of material
The carbon steel SS400 is used as a material for the structural strength of wheelchair in this research as shown in Table 1. Table 1 presents the mechanical properties of the carbon steel SS400.

The mathematical models are solved by using FEM to establish the stress distribution of 4 main components of wheelchair design. The 3D model is discretized using triangular elements to approximate the stress distribution variations through each element. A grid independence test is carried out to identify the appropriate number of elements required. To obtain a good calculation, a fine mesh is specified in the sensitive areas.

Table 1. The properties of carbon steel SS400 used in the calculation procedure [14]

| Property             | Value   | Unit    |
|----------------------|---------|---------|
| Elastic Modulus      | 2.1 x 10^{11} | N/m²    |
| Poisson’s Ratio      | 0.26    | -       |
| Mass Density         | 7860    | kg/m³   |
| Tensile Strength     | 3.0 x 10^{8} | N/m²   |
| Yield Strength       | 2.45 x 10^{8} | N/m²   |

This study has discussed the design of wheelchair, the stress distributions of 4 main components namely the lower base of the wheelchair, X-lifter, the linear actuator holder at the front of the seat and the linear actuator holder at the rear of the backrest. The mathematical model, boundary condition and the number of the mesh of each component are also provided in the Results and Discussion sections.

3. Results and Discussion

3.1 Verifications of the model
To evaluate the accuracy of the present numerical solution, the reaction force \( F_r \) of the simulated result is validated against the analytical result in the same condition. The X-lifter is used in the validation test case. It can be seen from the data in Figure 4 that the X-lifter model and free body diagram used to compare the accuracy of the results by using a computer program. The reaction force acting along the x-axis and y-axis is calculated as provided in Equations (2) and (3). The results of the reaction force acting along x-axis and y-axis from the analytical solution are as follows:
Considering x-axis:
\[ \sum F_x = 0 \quad (5) \]
\[ F_{r1} \cos(24^\circ) + F_{r2} \cos(24^\circ) = 0 \quad (6) \]

Considering y-axis:
\[ \sum F_y = 0 \quad (7) \]
\[ F_{r1} \sin(24^\circ) + F_{r2} \sin(24^\circ) = 1200 \quad (8) \]
\[ F_{r1} = F_{r2} = 1475 \text{ N} \quad (9) \]
\[ \therefore F_{r1} \cos(24^\circ) = F_x = 1347 \text{ N} \quad (10) \]
\[ \therefore F_{r1} \sin(24^\circ) = F_y = 600 \text{ N} \quad (11) \]

The reaction force acting along with the x-axis and y-axis results from the numerical solution of the current study is given in Figure 7 and Figure 8, respectively. The comparison of the reaction force acting along the x-axis and y-axis of the X-lifter between the numerical solution and analytical solution is explained in Table 2.

![Figure 7](image)

**Figure 7.** The reaction force acting along the x-axis from numerical solution

![Figure 8](image)

**Figure 8.** The reaction force acting along the y-axis from numerical solution

The error between the 2 solutions is equal to 6.24 % and 0% along the x-axis and y-axis, respectively. This favorable comparison lends confidence to the accuracy of the present numerical model.
Table 2. Comparing solution methods between the analytical solution and numerical solution

|                                      | Analytical Solution | Numerical Solution | Error  |
|--------------------------------------|---------------------|--------------------|--------|
| The reaction force acting along x-axis | 1347 N              | 1263 N             | 6.24 % |
| The reaction force acting along y-axis | 600 N               | 600 N              | 0 %    |

3.2 *The lower base of the wheelchair*

As can be seen from Figure 9, the lower base of the wheelchair model is considered as carbon steel SS400. The number of mesh which is suitable for analysis is about 62,000 elements. Figure 10 shows the boundary condition for analysis and Von-Mises stress distribution of the lower base of the wheelchair. It is found that the maximum Von-Mises stress value of simulation results that is equal to 117.6 MPa at the position for wearing the wheel. Likewise, considering the maximum Von-Mises stress value, the outcomes also show that in case of the lower base of the wheelchair does not exceed the yield strength of the material at 245 MPa (see also Table 1).

![Figure 9. The lower base of the wheelchair](image9)

![Figure 10. Results from the simulation of the lower base of the wheelchair](image10)
3.3 The X-lifter

Corresponds to the above part, the X-lifter model is considered as carbon steel SS400 as illustrated in Figure 11. The number of mesh which is suitable for analysis is about 23,350 elements. Figure 12 gives the boundary condition for analysis and Von-Mises stress distribution of the X-lifter. It revealed that the maximum Von-Mises stress value of simulation results is equal to 111.3 MPa. Besides, considering the maximum Von-Mises stress value, the outcomes also indicate that in the case of the X-lifter does not exceed the yield strength of the material at 245 MPa (refer to Table 1).

![Figure 11. The X-lifter](image)

![Figure 12. Results from simulation of the lower base of the X-lifter](image)

3.4 The linear actuator holder at the front of seat

Figure 13 presents the linear actuator holder at the front of the seat model and is considered as carbon steel SS400. The number of mesh is suitable for analysis and is about 42,000 elements. Figure 14 shows the boundary condition for analysis and Von-Mises stress distribution of the linear actuator holder at the front of the seat. It is found that the maximum Von-Mises stress value of simulation results is equal to 34.82 MPa. In the same vein, considering the maximum Von-Mises stress value, it is able to explain that in the case of linear actuator holder at the front of seat does not exceed the yield strength of the material at 245 MPa (see also Table 1).
3.5 The linear actuator holder at the rear of backrest

The last part of the analysis regards the actuator holder at the rear of the backrest. The actuator holder at the rear of the backrest model is considered as carbon steel SS400 in relation to the linear actuator holder at the front of the seat part (see Figure 15 below). The number of mesh which is suitable for analysis is about 31,000 elements. Figure 16 illustrates the boundary condition for analysis and Von-Mises stress distribution of the actuator holder at the rear of the backrest. It is observed that the maximum Von-Mises stress value of simulation results is equal to 121 MPa. In addition, considering the maximum Von-Mises stress value, it also shows that in the case of the actuator holder at the rear of backrest does not exceed the yield strength of the material at 245 MPa (refer to Table 1).

Figure 13. The linear actuator holder at the front of the seat

Figure 14. Results from simulation of the linear actuator holder at the front of the seat

Figure 15. The actuator holder at the rear of the backrest
After simulating in each part using the methods and equation above. It has found that the values which are suitable to create a wheelchair. The findings of this study suggest that the next step is to create a wheelchair according to the design.

4. Conclusion
The aim of the present research was to examine computer simulation of stress distribution to prepare the preliminary design of multifunction wheelchair. The most obvious finding to emerge from this study is that the multifunction wheelchair design has features as recline and tilt adjustable, height-adjustable and armrest width adjustable with the maximum weight equal to 120 kg. SolidWorks software is used in the design including analysis of the strength of 4 main components i.e., the lower base of the wheelchair, X-lifter, the linear actuator holder at the front of the seat and the linear actuator holder at the rear of the backrest by FEM via 3D model. The simulation results with computer programs are validated with analytical results. The results show a good agreement between the analytical results and present simulated stress distributions. It can be seen that the maximum Von-Mises stress value in all components does not exceed the yield strength of the material. The results of this research support the idea that the multifunction wheelchair will not be damaged when used. The findings reported here shed new light on the basic knowledge obtained from computer analysis can be used to improve the structure and build a prototype of the multifunction wheelchair.

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