# Investigation into the suitability of AA 6061 and Ti6Al4V as substitutes for SS 316L Use in the paraplegic swivel mechanism.

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# Investigation into the Suitability of AA 6061 and Ti6Al4V as Substitutes for SS 316L Use in the Paraplegic Swivel Mechanism

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**Abstract:** SS 316L, a low-carbon 316 Stainless Steel, has been used to manufacture swivel mechanisms for paraplegic patients, but its weight is relatively high compared to a few materials in its range of properties. Aluminum alloy 6061 and Titanium alloy (Ti6Al4V) offer lightweight and incredible strength-to-weight ratio, hence their use for medical, aerospace, and automotive applications. This study, therefore, seeks a replacement for SS 316L. A 3D model of a swivel mechanism was developed to compare the performance of the swivel mechanism made with SS 316L, AA 6061, and Ti6Al4V. The kinematic analysis of the mechanism based on a range of weights: 1kN, 1.1 kN, 1.2 kN, 1.3 kN, 1.4 kN, and 1.5 kN was carried out to generate the inputs for the simulation. The 3D model was made with SolidWorks, and the results of the kinematic analysis were used to define the simulation parameters for the mechanism. Two scenarios generated depicted the full collapse of the mechanism and the full extension. The results showed that AA 6061 and Ti6Al4V outperformed SS 316L with higher yield strength and factor of safety. Therefore, swivel plates made with AA 6061 and Ti6Al4V have higher yield strength than those made with SS 316L, adding to the advantage that they have a higher strength-to-weight ratio. From this analysis and known knowledge of the cost of these materials, the optimal replacement considering cost with yield strength is AA 6061. However, Ti6Al4V is a better alternative for the strength-to-weight ratio for SS 316L.

**Keywords:** SS 316L; AA 6061; Ti6Al4V; swivel mechanism; mechanical properties



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## 1. Introduction

People who are paraplegics are those whose lower bodies have been paralyzed, usually because of a spinal cord injury. With minimal or no mobility and sensation below the site of damage, paraplegia is a form of paralysis that often affects the legs and, occasionally, the lower part of the trunk [1,2]. Many factors, including traumatic injuries from fall accidents or illnesses that harm the spinal cord, might contribute to this disorder [3,4].

The use of a swivel mechanism for paraplegic patients is about a century old. Various models and test trials have been evaluated to investigate the suitability, comfortability, and use of this assistive method [5,6]. This mechanism is suitable for all age groups [7,8] with an emphasis on engineering design, maneuverability, flexibility, impact, and durability [9–11].

Swivel mechanisms are used for assistive medical purposes to help prevent further deformity while ensuring stability, good body posture, and improved physiological intervention [12]. The swivel design has the advantage of ease of maneuvering, especially for manual assistive mechanisms. It reduces the efforts needed to transfer patients between platforms while allowing patient flexibility during examination [13]. Safety concerns are vital considerations when considering patient transportation. Though some vehicles have integrated disabled persons' safety measures, the impact during emergency braking and seat belt tension have been studied [14].

Low-carbon stainless steel SS 316L has been found to be useful for medical applications due to its mechanical properties and ease of manufacturability. The physio-assisted mechanisms usually have complex shapes and multiple components; hence, the manufacturing can be complicated. The SS 316L and Titanium alloy Ti6Al4V have desirable properties and are suitable for medical devices used externally [15,16]. Further treatment of these alloys has been shown to enhance the mechanical properties of SS 316L and Ti6Al4V for medical interventions [17,18]. Use cases of these materials that focus on improvements in their lifespan and corrosion prevention have been reported for orthopedic implants [19,20]. AA 6061 has a good strength-to-weight ratio and has been used in the transportation industry, like SS 316L and Ti6Al4V. A detailed analysis performed of the manufacturing process, application, and mechanical properties is vital [20–22]. AA 6061 and Ti6Al4V are either used independently or as reinforcement in their variants to enhance aesthetics, surface finish corrosion resistance, and heat treatments [19,21,23–25].

Manufacturing of low-cost assistive devices has been advised since only about 10% of people with disabilities can afford one [26]. However, AA 6061 and Ti6Al4V are lightweight materials, but only AA alloys are relatively cheaper than SS 316L [27]. This underscores the need to investigate and compare the mechanical properties of the suggested alternatives to the known SS 316L. Another consideration for SS 316L replacement is its low yield strength, which is an austenitic alloy. In some applications, the yield strength was improved by reinforcing with other materials, which changed the weight and chemical properties [28]. When most paraplegic patients are assisted, their weights also contribute to the load to be overcome. A lighter material will reduce the drudgery in helping the patients in moving from one position to another. There is no literature directly linking material use for paraplegic mechanisms and their interactions with users or the negative health effect of the swivel mechanism on patients. Since the mechanism does not interact with the body or is absorbed into the bloodstream, the only possible complaint may be in the design. Hard surfaces cause discomfort and can result in extreme skin reactions when contact extends for a prolonged period. The suggested alternatives have a high strength-to-weight ratio; hence, it can be easier for the patients and those assisting them to maneuver.

This study presents an analytical investigation of the comparison of the performance of a swivel mechanism made with SS 316L, AA 6061, and Ti6Al4V for paraplegic patients. AA 6061 and Ti6Al4V have less weight than the SS 316L. Hence, the investigation presents the condition at the collapsed and fully extended stages for each material to determine if AA 6061 or Ti6Al4V can be used as replacements for the SS 316L.

## 2. Materials and Methods

In the design of the swivel plate mechanism for paraplegic car seats, several factors were considered, as it is imperative to understand the multifaceted nature of the failure. Aside from being functional, the mechanism must be secure, convenient to use, durable, and compatible with the broader vehicular ecosystem.

### *2.1. Materials Properties and Selection*

In selecting materials for this mechanism, various factors were considered, such as weight, yield strength, yielding of the material, stress concentration, and factor of safety. Three materials, SS 316L with a density of 8 g/cm$^3$, AA 6061 with a density of 2.7 g/cm$^3$, and Ti6Al4V with a density of 4.43 g/cm$^3$, were selected. The mechanical properties of the three materials are presented in Table 1. The aim was to reduce the weight of the swivel plate mechanism at an affordable price, as this mechanism was originally designed with SS 316L with a density of 8 g/cm$^3$. The range of values for the young modulus of SS 316L is 199 GPa and 211 GPa.

**Table 1.** Mechanical and failure properties of SS 316L, AA 6061, and Ti6Al4V.

| Materials Properties | Density ($g/cm^3$) | Young's Modulus (GPa) | Ultimate Tensile Strength (MPa) | Elongation at Break (%) | Poisson Ratio | Tensile Yield Strength (MPa) | Fatigue Strength (MPa) | Shear Modulus (GPa) |
|---|---|---|---|---|---|---|---|---|
| SS 316L | 8.0 | 193 | 515 | 60 | 0.3 | 205 | 146.45 | 193 |
| Al6061 | 2.7 | 68.9 | 310 | 13 | 0.33 | 276 | 96.5 | 26 |
| Ti6Al4V | 4.43 | 114 | 951 | 14 | 0.342 | 882 | 510 | 44 |

#### 2.1.1. AA 6061 Alloy

AA 6061, as a general-purpose alloy, exhibits good weldability and is usually manufactured by extrusion. It has found acceptance in the automotive, aeronautic, and food industries to produce aircraft wings and fuselages, automotive flashlights, canned foods, and beverages.

#### 2.1.2. SS 316L

SAE 316L grade stainless steel (SS 316L) is the second most common austenitic stainless steel after 304/A2 stainless steel. Its primary alloying constituents, after iron, are chromium (between 16–18%), nickel (10–12%), and molybdenum (2–3%), with small (<1%) quantities of carbon, silicon, phosphorus, and sulfur also present. Molybdenum adds corrosion resistance to the alloy, and the cold-worked Mb exhibits a high yield and tensile strength.

#### 2.1.3. Ti6Al4V

Ti6Al4V is a versatile titanium alloy used extensively for medical, aerospace, and automotive applications. Its desirability is in its lightweight combination with high-yield strength, which is usually not so for other metals. However, this property is improved through the addition of other materials, which adds to its hardness, hence the consideration of the alloy with Aluminum and Vanadium to form Ti6Al4V.

### *2.2. Swivel Mechanism Design*

To determine the relative motions associated with the swivel mechanism, the analysis of the linear motion was determined with mathematical expressions presented in Table 2. The design was to accommodate a human weight of 120 kg, which would allow for an extensive range of patient weights. As the mechanism demonstrates, this weight acts vertically like a vertical load. There are two swivel plates in the mechanism: the upper one, where the patient sits, and the lower plate, which is the base. The upper plate slides and rotates over the lower plate to transfer the patient between platforms. This shows that the mechanism is to be analyzed dynamically, considering the parameters involved in its movement.

**Table 2.** Table of the basic equations of motion used for motion analysis.

| Parameters | Expression | |
|---|---|---|
| Linear Displacement (S) | $S = ut + (½)at^2$ | $a = 0.0116\ ms^{-1}$ |
| Linear velocity (v) | $v = u + at$<br>$v^2 = u^2 + 2as$ | $v = 0.058\ ms^{-1}$ |
| Angular Displacement (θ) | $\theta = \theta_0 + \omega_0 t + (1/2)\alpha t^2$ | |
| Angular Velocity (ω) | $\omega = \omega_0 + \alpha t$ | $\omega_0 = 1.028\ rads^{-1}$ |
| Angular Acceleration (α) | $\alpha = (\omega - \omega_0)/t$ | $\alpha = 0.0596\ rads^{-2}$ |
| Linear Displacement (d) at a certain radius (r) | $d = r\theta$ | |

The centrifugal force, $F_c$, is the force that appears to act on an object moving in a circular path. It is directed away from the center around which the object is moving. This force plays a significant role in determining the experience of passengers in a vehicle, especially those seated on mechanisms such as the swivel car seat when the vehicle turns. When a car takes a curve, passengers inside feel a force pushing them toward the outer side of the turn. This force is particularly noteworthy for swivel car seat users, as they need to counteract this force to stay in position. The visual representation of this force is the arrows for force direction on the swivel seat, especially during left and right curves, as shown in Figure 1. The forces that are exerted on the seat are the force of gravity, normal force, frictional force, shear forces, and torsional forces.

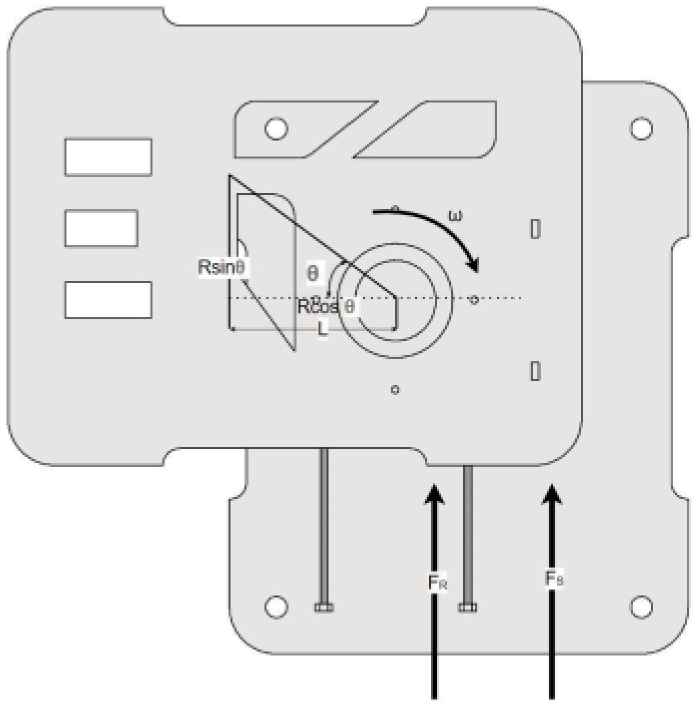



**Figure 1.** 2D Detailed illustration of the swivel seat and acting forces.

Centrifugal force is expressed as follows:

$$F = \frac{mv^2}{r} \quad (1)$$

The torque acting with force F about radius r from the origin of the reference frame is given as follows:

$$F_c(r\sin\theta) = m^2r^2\sin\theta \quad (2)$$

For forces acting backward on the seat and rail as follows:

$$\sum F_y = 0; \quad (3)$$

$$-W + N + F_r + F_s = 0 \quad (4)$$

Taking moment about point O as follows:

$$-Wl + Nl - m^2r^2\sin\theta = 0; \quad (5)$$

$$l(N - W) = m^2r^2\sin\theta \quad (6)$$

Substituting for W in (ii) as follows:

$$F_r + F_s = m^2rl^2\sin\theta; \quad (7)$$

$$F_s = m^2\frac{r^2}{l}\sin\theta - F_r \quad (8)$$

$m_s$ = mass of seat in kg; $m_u$ = mass of user in kg; r = swivel plate readius; N = normal force l = length of swivel plate centre of rotation to the centre of gravity; $F_r$ = frictional force; g = accleration due to gravity; v = linear velocity; θ = angle of inclination; $F_s$ = shear force.

### 2.3. Simulation Parameters

The 3D model of the swivel plate was made using SolidWorks 2023. The parameters considered for the simulation are the headroom of the car, the dimensions of the car seat, the distance between the dashboard and the car seat, and the maximum weight that the car can carry. The physical dimensions of the swivel plate mechanism are presented in Table 3, while Table 4 shows the values of the force and torque derived from the kinematic analysis.

**Table 3.** Physical dimensions of parts of the swivel mechanism.

| Part | Dimension (mm) |
|---|---|
| Guide rail | 350 |
| Base plate | Length: 320; Breadth: 400 |
| Swivel plate | Length: 320; Breadth: 400 |
| Groove Inner Diameter | 112.84 |
| Groove Outer Diameter | 160 |
| Distance traveled by swivel plate | 145 |

**Table 4.** Kinematic analysis values for input into the simulation.

| Parameter | Value |
|---|---|
| Centrifugal force ($F_c$) | 6.9599 N |
| Torque (T) | 0.386 Nm |
| Frictional force ($F_r$) | 412.02 N |
| Shear force $F_s$ | −405.077 N (acts in the opposite direction) |

For the preprocessing, the geometry was defined based on the 3D model and the parameters presented in Table 3. Subsequently, the assembly was carried out, and the desired solutions were selected. The loads were added in the order 1 kN, 1.1 kN, 1.2 kN, 1.3 kN, 1.4 kN, and 1.5 kN, and the von Mises stress, displacement, and factor of safety (FOS) were determined. Two scenarios were performed for each application: when the swivel was completely collapsed and secondly when it was completely extended. This procedure was necessary to capture the extreme positions of the swivel plate. The derived kinematic parameters were inputted to create the motion study, which set the mechanism as a dynamic system. A new simulation study was then created to insert the points of action of the force representing the human weight, the magnitude, and the line of action. The boundary conditions were set, depicting the extent of the rotation of the upper plate and the rigidity of the lower plate. Mesh testing was carried out to select the best mesh parameters. The vertical load was set to a range of 1 kN to 1.5 kN with an interval of 0.1 kN.

## 3. Results

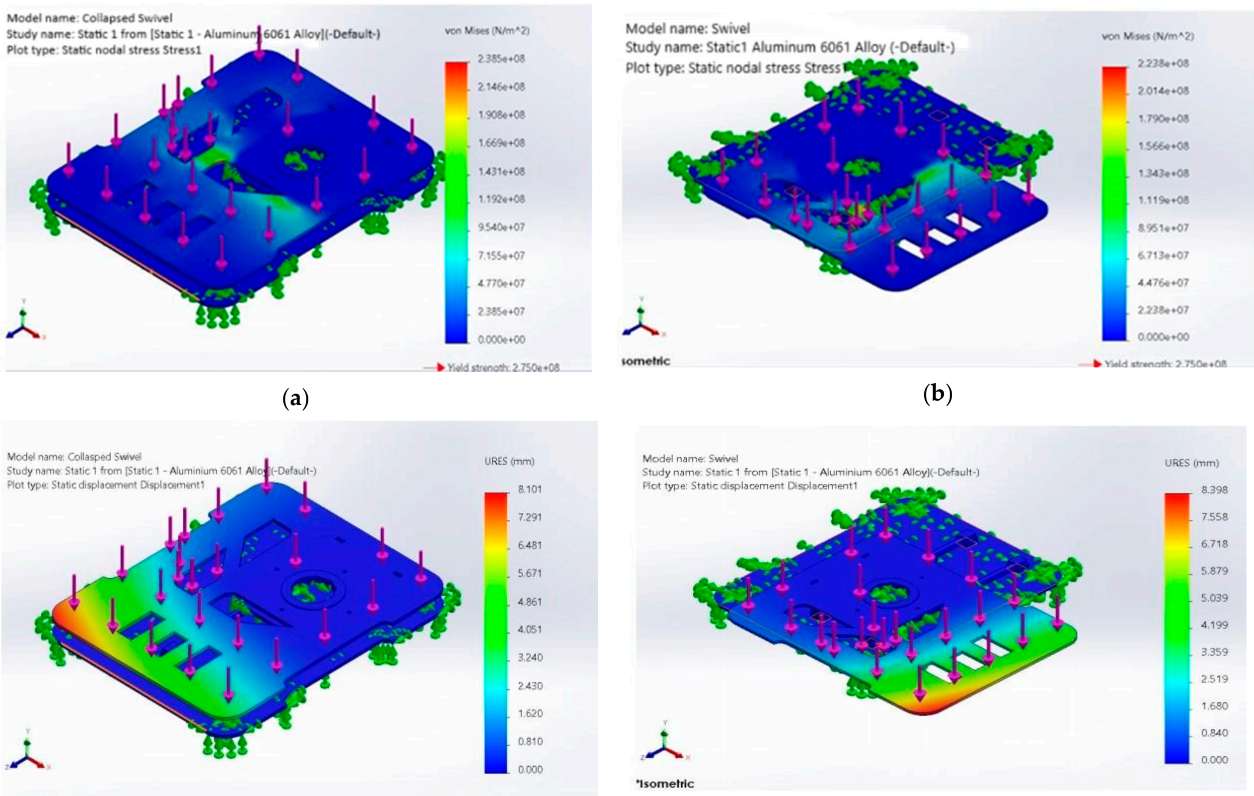
In this section, the output of the simulation of the swivel plate under loading conditions 1 kN, 1.1 kN, 1.2 kN, 1.3 kN, 1.4 kN, and 1.5 kN are presented. The implication of these results was discussed.

### 3.1. Simulation Results for Collapsed and Fully Extended AA 6061, Ti6Al4V, and SS 316L

Simulation results for SS 316L, AA 6061, and Ti6Al4V are presented in Table 5; Figures 2–4 represent the graphical output of the von Mises stress, displacement, and FOS, respectively. Each material was assigned to the 3D models, and the load was applied individually. Static analysis was carried out using the configurations in Tables 3 and 4. The points of load application and reactions on the swivel were the top of the plate and the joint of the swivel, respectively. Table 5 and Figures 2–8 present the solutions when the plates were fully collapsed and extended, respectively.

**Table 5.** Yield strength and Von Mises stress for collapsed and fully extended.

| Forces (kN) | SS 316L | | AA 6061 | | Ti6Al4V | |
|---|---|---|---|---|---|---|
| | Yield Strength ($1.724 \times 10^8$ MPa) | | Yield Strength ($2.750 \times 10^8$ MPa) | | Yield Strength ($8.74 \times 10^8$ MPa) | |
| | Von Mises ($N/m^2$) | | | | | |
| | Collapsed ($10^2$) | Extended ($10^8$) | Collapsed ($10^2$) | Extended ($10^8$) | Collapsed ($10^2$) | Extended ($10^8$) |
| 1 | 2.02 | 1.878 | 1.987 | 1.865 | 2.00 | 1.87 |
| 1.1 | 2.233 | 2.066 | 2.186 | 2.051 | 2.204 | 2.057 |
| 1.2 | 2.436 | 2.253 | 2.385 | 2.238 | 2.404 | 2.244 |
| 1.3 | 2.639 | 2.441 | 2.584 | 2.242 | 2.604 | 2.431 |
| 1.4 | 2.842 | 2.629 | 2.782 | 2.611 | 2.805 | 2.618 |
| 1.5 | 3.045 | 2.817 | 2.981 | 2.797 | 3.00 | 2.805 |




(a) (b) (c) (d)

**Figure 2.** Simulation results for AA 6061 Swivel plate: (**a**) von Mises when collapsed, (**b**) von Mises when extended, (**c**) displacement when collapsed, and (**d**) displacement when extended.

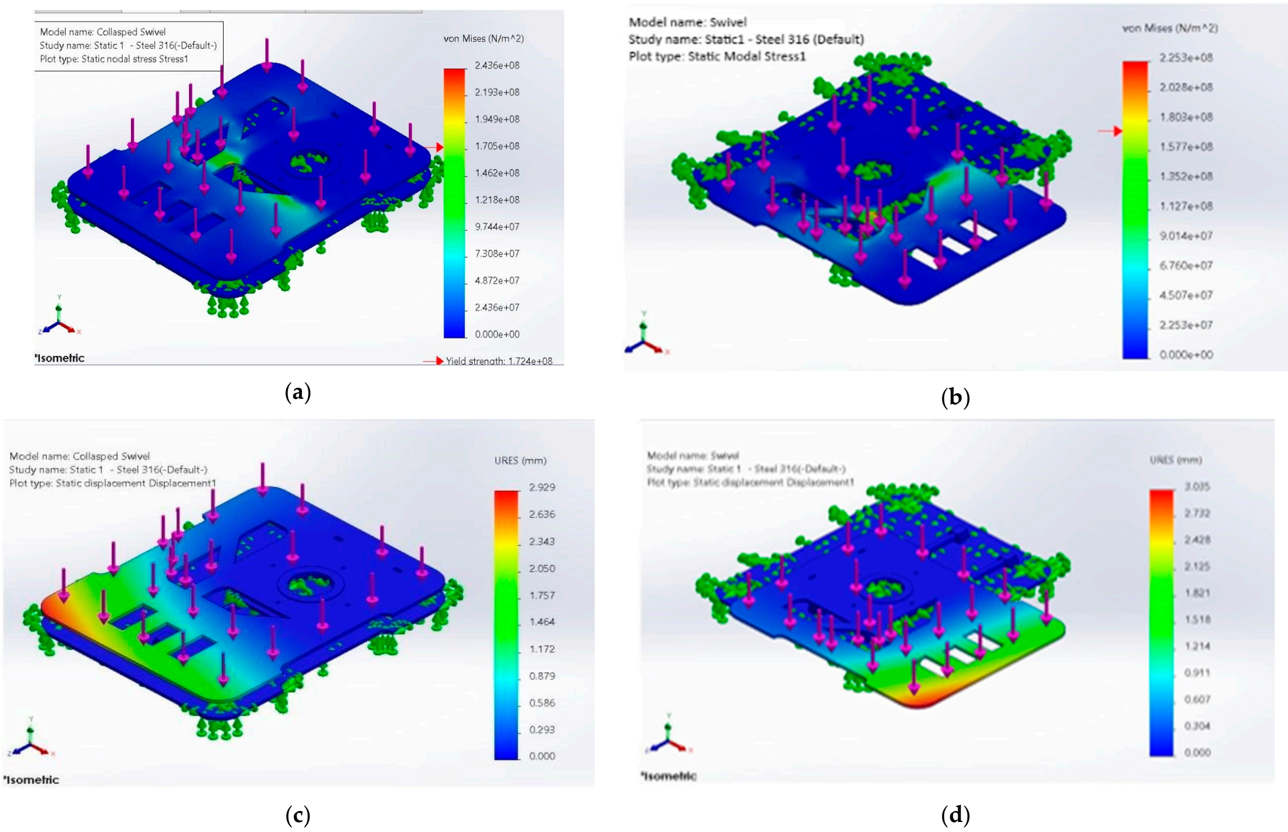



**Figure 3.** Simulation results for SS 316L Swivel plate: (**a**) von Mises when collapsed, (**b**) von Mises when extended, (**c**) displacement when collapsed, and (**d**) displacement when extended.

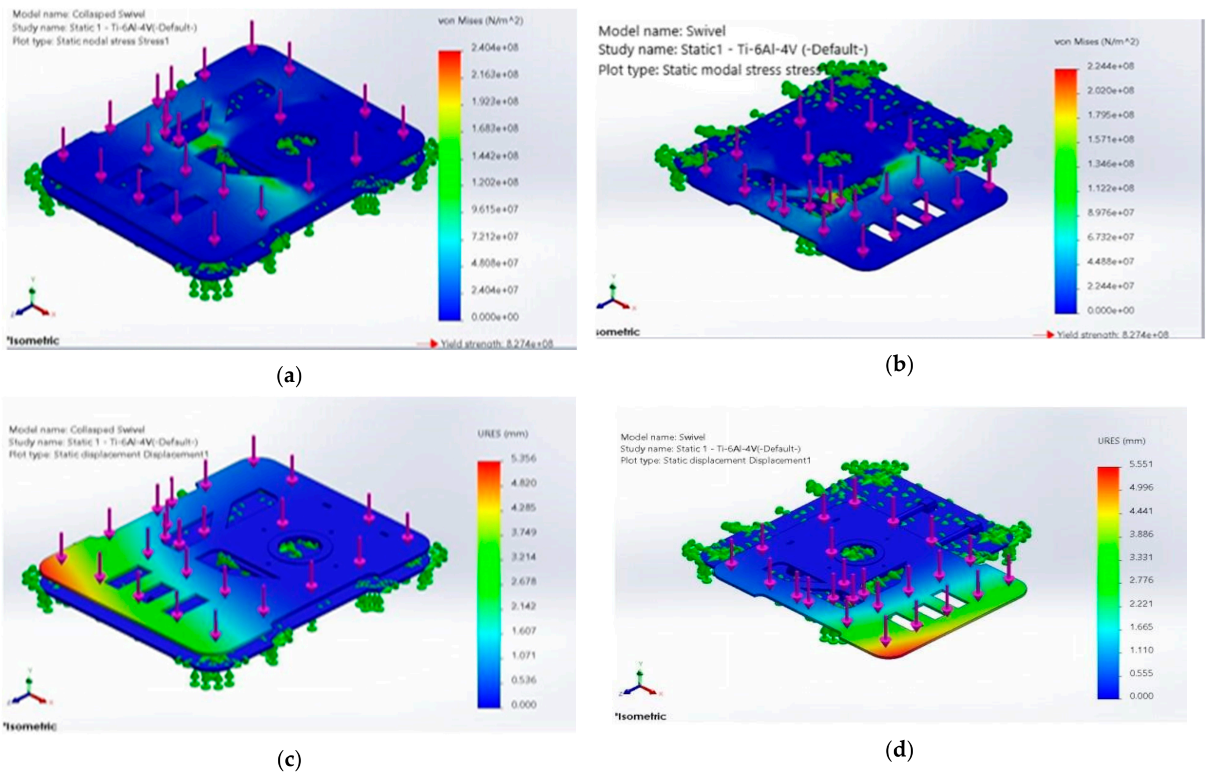



**Figure 4.** Simulation results for Ti6Al4V Swivel plate: (**a**) von Mises when collapsed, (**b**) von Mises when extended, (**c**) displacement when collapsed, and (**d**) displacement when extended.

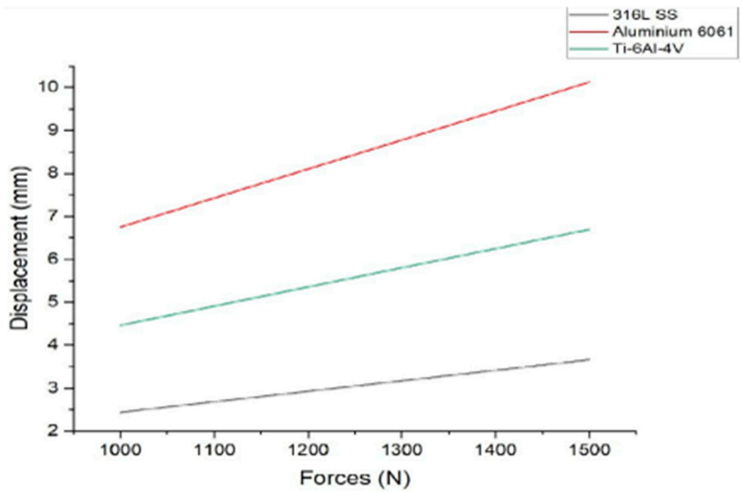



**Figure 5.** Displacement plot when the swivel plate is collapsed.

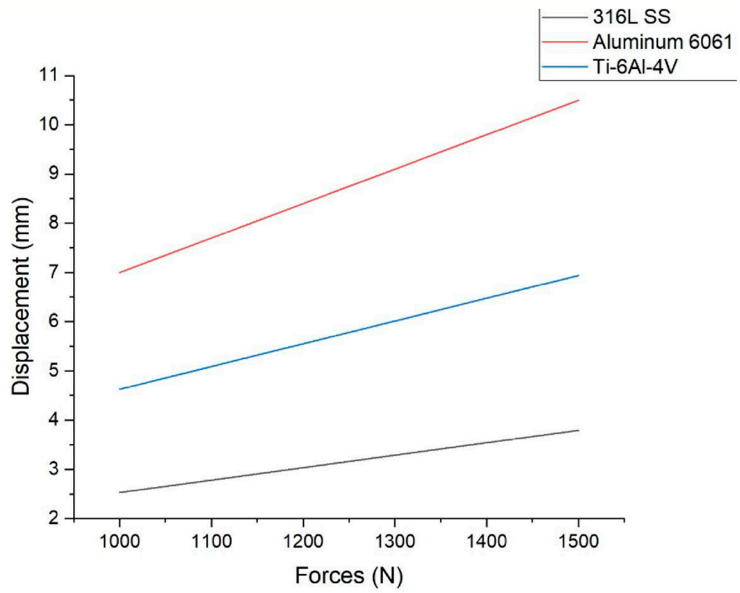



**Figure 6.** Displacement plot when the swivel plate is fully extended.

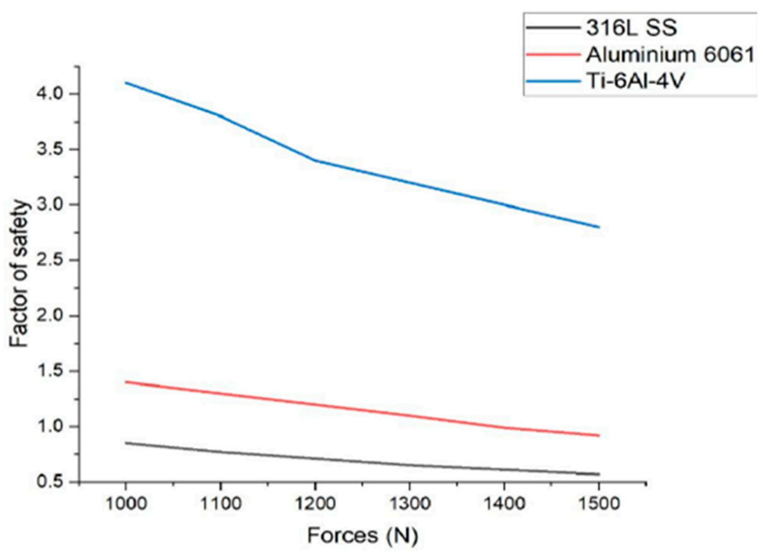



**Figure 7.** The factor of safety when the swivel plate is fully collapsed.

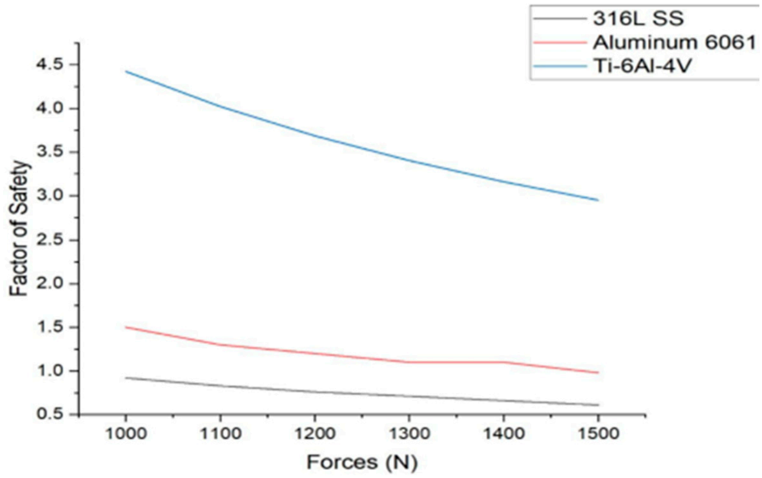



**Figure 8.** The factor of safety when the swivel plate is fully extended.

*3.2. Discussions*

From Figures 2–8, the range of the von Mises stress for the collapsed plate is lower than that of the extended one. This pattern applies to all of the materials. This is justifiable because, at the collapsed position, the two plates are placed on each other; hence, they support each other. The properties measured here are important because the safety of the patient depends on the durability of the plates in various conditions. These plates assist in patient transfer from one platform to another, sometimes from the wheelchair to the car or the bed. The swivel works as a sideways slider, making the patient turn without having to lift their bodies or be lifted by others. The sliding speed and rotation area are very important, hence the kinematic analysis, which provides the operating conditions for the plate. This also takes into consideration the weight of the patient as it affects the movement of the plate. All these considerations call for a diligent selection of the materials of the swivel plate. The mechanical properties of each of these materials determine their suitability, among other considerations such as cost, availability, weight, and aesthetics.

From the results in Table 3, AA 6061 has the highest yield strength, and SS 316L has the lowest value of yield strength. The yield strength for SS 316L is 1.724 ($10^8$) MPa, AA 6061 is 2.750 ($10^8$) MPa, and Ti6Al4V is 8.274 ($10^8$) MPa. In terms of the factor of safety, the difference between the values of collapsed and extended plates varied between 6–10%. From Figures 7 and 8, the range of values for the factors of safety for the materials are SS 316L (0.61–0.92), AA 6061 (0.98–1.5), and Ti6Al4V (2.95–4.424). For the elastic modulus, SS 316L has a higher value (4.7 GPa) compared to the AA 6061 and Ti6Al4V with 1.71 GPa and 1.8 GPa, respectively, when the mechanism is fully extended. Similarly, Figures 5 and 6 show that AA 6061 and Ti6Al4V outperformed SS 316L in terms of displacement because of higher yield strength and the factor of safety values. From Figures 5 and 6, the values of displacement covering both collapsed and extended scenarios varied between 2.441–3.794 mm for SS 316L and 6.751–10.491 mm for AA 6061 and 4.463–6.939 mm for Ti6Al4V. From these values, the range of the displacement values when force was applied from 1 kN to 1.5 kN is 0.241–0.37 mm for AA 6061, 0.088–0.133 mm for SS 316L, and 0.103–0.244 mm for Ti6Al4V. These values are all less than 1 mm for all the scenarios. Hence, each of these materials is safe to use, and AA 6061 or Ti6Al4V is suitable for replacing SS 316L as material for the swivel mechanism on this basis.

The change in modulus when 1.5 kN forces were applied for fully collapsed and fully extended are 3. 658% and 3.653% for AA 6061, 3.479% and 3.5% for SS 316L, and 3.52% and 3.516% for Ti6Al4V. The yield strength of the titanium alloy is 4.8 times that of steel alloy, whereas aluminum alloy is 1.6 times that of steel alloy. In addition, the elastic modulus of SS 316L is approximately 2.7 times that of Ti6Al4V and AA 6061. Because the yield strength and elastic modulus values have a relative proportionality, the mechanism's dimensions are appropriate for any material. Furthermore, the yield strength property of the alternative materials shows that they will perform well as a replacement for SS 316L when considering performance within the elastic zone. Looking at the properties of the three materials, Ti6Al4V gave better yield strength and is therefore preferred. Given that the values obtained for Ti6Al4V and AA 6061 are very close, and it is common knowledge that aluminum is cheaper than titanium and most steel materials, AA 6061 can be a choice when cost implication is a major consideration. However, considering the strength-to-weight ratio and yield strength, Ti6Al4V is preferable.

When patients are assisted in the operation of the swivel mechanism, the patient's weight contributes to the operation. This makes it tedious work for the person assisting; hence, a lighter mechanism will be preferred. Though the patient's body does not directly interact with the mechanism, there is a touch sensation felt in terms of the hardness of the surface. The harder the surface, the higher the tendency for patient discomfort, especially for a long period of sitting.

### *3.3. Manufacturability*

The swivel plate mechanism is best manufactured using computer numeric control (CNC) machines to ensure the accuracy of the dimensions and to preserve the mechanical properties. The 3D model of each of the parts (swivel base, pivot point, locking mechanism, actuator integrator, and other structural elements) is carefully drafted with the appropriate clearances, fits, and tolerance. CNC method of machining helps to achieve accurate parts, especially those parts that move relative to one another, as in the case of the swivel mechanism. A combination of CNC methods may be required, such as laser cutting, milling, and turning operations, to produce precision cutting, drilling, and shaping for surface finish. In addition, for smooth operation, aesthetics, and durability of the swivel mechanism, surface finish such as polishing, powder coating, anodizing, or electroplating can be performed. However, there is the liberty to choose from the available options based on interest and personal choices.

## 4. Conclusions

In this study, a swivel mechanism for paraplegic patients made with stainless steel 316L was examined to compare its properties with suggested alternatives. AA 6061 and Ti6Al4V were chosen as alternatives regarding their strength-to-weight ratio and cost. A 3D model of the swivel plate was developed with SolidWorks software 2023, and the three materials were simulated to investigate their performance when in operation. The investigation was conducted when the swivel was in its collapsed state and when it was fully extended. The two alternatives had higher yield strength and factor of safety, which puts them in the position of substitutes for the SS 316L. From this analysis and known knowledge of the cost of these materials, the optimal replacement considering cost is AA 6061. Although SS 316L has better surface aesthetics, further treatment may be needed to achieve better surface aesthetics for AA 6061 by anodizing [29,30] and laser treatment for Ti6Al4V [30]. The machining operations suitable for these materials are CNC milling, 3D printing, and laser cutting operations. These methods will ensure accuracy and proper heat distribution within the grains of the structure.

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