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Design of Medical Self-Propelled Walking Tricycle as a Post-Stroke Rehabilitation Tool

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ABSTRACT

Patients recovering from a stroke may not be able to use all rehabilitation equipment due to their poor muscle strength and coordination. This study proposes to design a self-propelled walking tricycle that is a non-motorized three-wheel vehicle in a delta configuration without a pedal. This study was conducted by considering the post-stroke patient needs. It was done using two analysis methods, finite element analysis, and rapid upper limb analysis, to justify the reliability of the design. The results show that the maximum stress is 38.8 MPa in the connection area of the seat tube and down tube, while the maximum deformation is 0.399 mm in the seat post. The tricycle is constructed with 153 mm of ground clearance. Therefore, patients can lift their legs and drive the tricycle by swinging their legs repeatedly, like walking. The proposed self-propelled walking tricycle can be considered as a rehabilitation tool that can train the lower extremities. It could be used for strengthening the muscles and improve body coordination for the recovery process.

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1. INTRODUCTION

Difficulty walking due to neurological disorders is often experienced by people with a stroke (Beyaert et al., 2015; Kischka & Wade, 2004). As many as 70% of stroke patients frequently fall in their homes because they lose their balance while walking (Beyaert et al., 2015). In other words, they cannot do daily activities and need help from people surrounding them or walking aids such as walking canes and wheelchairs. There are 67% of stroke patients have restricted physical ability and declined mental health, which can cause depression (Mehrholz et al., 2017). Therefore, their quality of life is low, making it difficult to blend in with society due to their limited mobility (Beyaert et al., 2015; Lord et al., 2004).

Numerous rehabilitation techniques, such as light-intensity exercise and physical activity, have been researched and found effective in restoring the body's balance (Arienti et al., 2019). Post-stroke patients need to rehabilitate to re-cover muscle function at least 48 hours after recovering from a stroke (American College of Sports Medicine (ACSM), 2010). According to Jørgensen, patients with mild, moderate, and severe strokes need two, three, and four months for recovery, respectively. Patients with the most severe strokes need recovery for at least five months (Jørgensen HS, Nakayama H, Raaschou HO, 1999).

Rehabilitation equipment for post-stroke patients is still inadequate. When there is one, the rehabilitation medium is only intended for post-stroke patients who can walk independently or can stand without the help of people or walking canes. Meanwhile, patients who have just recovered from a stroke are not recommended to use the rehabilitation media and only do therapy with simple movements and light-intensity exercise because their body balance is weak, which makes them prefer to stay in their wheelchairs (Benaim et al., 1999; Huang et al., 2016).

Some researchers have developed rehabilitation media for poststroke patients, i.e., poststroke tricycles (Batan, I. M. L., Rodika, & Riva'i, 2015) and rehabilitation procedures (Febritasari & Batan, 2019a) until they gain benefits such as having fewer stiff muscles after pedaling for 10 minutes for one month. However, this tricycle is only intended for poststroke patients who have a muscle strength score of more than three based on the Stroke Postural Assessment Scale, which means that they can stand without aids (Batan et al., 2016; Londen Batan et al., 2019).

Researchers have been investigating tricycles with both tadpole and delta configurations specially designed for stroke sufferers (Kurniawan, 2020; Oktavian, 2016). Sandy designed a post-stroke tadpole tricycle with a hand pedal and foot pedal mechanism. The stroke sufferers can rotate and move the hand pedal independently. However, they could not move the hand steering on this bike because it was heavy and difficult to turn. Sulthoni (Kurniawan, 2020) designed a post-stroke delta tricycle without a hand pedal and repaired the driving mechanism to become lighter for paddling. Both tricycles were tested at Haji Hospital Surabaya, which showed an improvement in fitness and motor function in post-stroke patients (Febritasari & Batan, 2019b; Lutiawan, 2016). Besides, some companies have developed medical products for rehabilitation (Alinker USA, 2022; Bateni & Maki, 2005; Vanraam, n.d.). The Alinker walking bike, a non-pedaled tadpole tricycle, by Alinker Company has innovated the rehabilitation media for people with disabilities, Parkinson's, Cerebral Palsy, and stroke to implement an active culture of movement and support the muscle recovery process (Alinker USA, 2022). A city walking aid bike is a two-wheeled bike without pedals designed by VanRaam Company. It proved its benefits in helping people who have difficulty walking after surgery or are elderly (Vanraam, n.d.). A seat walker has been widely used for people with mobility problems because it helps them stand and walk easily by maintaining body balance and reducing the load on weak legs (Bateni & Maki, 2005).

Some researchers have tried to innovate conventional vehicles into electric vehicles. So, they have implemented electric components into medical tools like an electric tricycle for rehabilitation tools (Bulthuis et al., 2021; Febritasari et al., 2023; Febritasari & Batan, 2023). Electric tricycles can also be used for light-intensity exercise. They are perfect for people with disabilities and chronic diseases, making them stay active in motion instead of doing nothing on the chair (Bulthuis et al., 2021). In addition, they feel safe when walking without fear of falling. However, the use of a seat walker is not suitable for upper limbs as it can cause stress fractures in the hands, elbows, and shoulders in long-term use, which have been experienced by 64% of users (Bateni & Maki, 2005) so its design should be repaired to achieve safety and mobility (Laufer, 2003).

Therefore, it is necessary to have a tool to support the poststroke rehabilitation process for patients who have motor function weaknesses, muscle stiffness, and misalignment of muscle movements after recovering from a stroke attack. The design was based on customer needs and applied the science of product design and development (Batan, 2012; Karl Ulrich, 2019). This research was conducted to design a self-propelled walking tricycle without a pedal by modeling in 3D shape and then analyzing the material strength analysis on the frame using the finite element method. The novelty of this research is the non-pedaled tricycles. Compared to a conventional tricycle with a pedal, the non-pedaled tricycle will be good for lower extremities training because it adapts to walking movement. The walking movement can activate muscles such as the quadriceps, the hamstrings, the calf muscles, and the hip adductors (Liu et al., 2008). Meanwhile, the pedal-ling movement only activates the Quads, Glutes, and hamstring muscles (Lee, 2023). The self-propelled walking tricycle has a compact and rigid structure and no need for more space.

The self-propelled walking tricycle without a pedal can be an alternative to the poststroke rehabilitation tool. The advantage of this tricycle is to train balance and coordination, especially on the lower limbs. The frame is constructed with low ground clearance so that the patients can lift their legs on the ground onto the tricycle. The patients will give propulsion power to the tricycle through their legs by walking movement, and then their hands will drive the handlebar straight or turn. This research aims to design and simulate the self-propelled walking tricycle designed without a pedal to get the best performance of structural frame analysis.

2. RESEARCH METHODOLOGY

The design of a self-propelled tricycle was carried out in some steps. First, the list of requirements for a product was observed based on the needs of stroke sufferers. Second, the calculation of the propulsion power was required to run the tricycle. Third, the tricycle construction was designed based on the customer's needs. Fourth, an independent test grid from the variation of mesh element size was conducted to discover the optimal grid condition that has the smallest number of grids without generating a difference in the numerical results based on the evaluation of various grid conditions. Fifth, the strength of the material on the frame was analyzed to determine the safety of the frame. The parameters of the simulation outcome are Von Misses stress, displacement, and safety factor. Theoretically, the equation of strain and stress can be used as follows:

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \end{Bmatrix} = \frac{E}{(1+v\_(1-2v)} \begin{Bmatrix} (1-v)\varepsilon_x + v\varepsilon_y + v\varepsilon_z \\ v\varepsilon_x + (1-v)\varepsilon_y + v\varepsilon_z \\ v\varepsilon_z + \varepsilon_y + (1-v)\varepsilon_z \end{Bmatrix} \quad (1)$$

where σ is stress, ε is strain, υ is poison ratio, and E is modulus young of material. The safety factor's value can be counted using Equation 2 (Beaulieu, 2013a).

$$\text{SF} = \frac{\sigma_{max}}{\sigma_{max\,material}} \quad (2)$$

where SF is a safety factor, σ_{max} is allowable material stress, $\sigma_{\max material}$ is stress on the material. The analysis was carried out using open-source CAD Software, namely Ansys and Catia.

2.1 The List of Requirements

The list of requirements reflected the customer's needs for the self-propelled tricycle. The data was obtained by interviewing post-stroke patients about six aspects (Febritasari & Batan, 2023), such as product function, safety, geometry and dimensions, operational system, manufacturing, and maintenance (**Table 1**).

Table 1 declared that the post-stroke patient requires a medical tricycle that can fulfill their needs, such as (1) the down tube was set with a lower ground clearance of 153 mm so that the post-stroke patient can lift his foot and (2) non-pedal driving that means the driver does not use the pedal to propel the tricycle but use their foot and move it by stepping the leg on the ground like walking.

2.2 The tricycle frame modeling

The tricycle frame was modeled using open-source CAD software. The tricycle was designed without pedals, so there was no bottom bracket. The dimensions of this tricycle frame design can be seen in **Figure 1**.

The topology of the frame uses The Alinker walking bike, a non-pedaled tricycle tadpole configuration, as a reference. This study modified the frame on the configuration that is delta configuration. So, there are two axle mounts on the rear frame to put the rear wheels. There was no bracket for pedal mounting like a conventional bike because it was built without a pedal. Its purpose was focused on walking movement, not pedal movement. The frame tube was the same as other bikes, such as the head tube, down tube, bottom tube, seat tube, seat stay, chain stay tube, and axle tube.

Table 1. The list of requirements

ASPECTS OF NEEDS	DESCRIPTION OF THE SELF-PROPELLED TRICYCLE REQUIREMENT
1. Function	a. The tricycle is driven by the foot, without pedals for training the leg muscle strength (Janssen et al., 2008a) b. The rider can support his body and sit on the saddle to improve balance performance (Janssen et al., 2008b), (De Athayde Costa E Silva et al., 2020) c. Feet step on the ground for improving coordination performance (Janssen et al., 2008b) d. The saddle and handlebar can be adjusted for ergonomics (Gordon et al., 2004a)
2. Safety	a. Maximum rider weight is 100 kg (Febritasari & Batan, 2023) b. Front-wheel and rear-wheel braking systems (Febritasari & Batan, 2023) c. A three-wheel vehicle with a delta configuration to minimize the risk of falling (Gordon et al., 2004b)
3. Geometry and Dimensions	a. The tricycle has three wheels in delta configuration (Febritasari & Batan, 2023) b. The tricycle frame resembles a feminine bike (Febritasari & Batan, 2023) c. The tricycle frame weight does not exceed 15 kg (Febritasari & Batan, 2023) d. Total height does not reach 800 cm (Febritasari & Batan, 2023) e. The weight of other components does not exceed 10 kg (Febritasari & Batan, 2023) f. The down tube frame is constructed with lower ground clearance (Febritasari & Batan, 2023)
4. Operational System	a. Easy and comfortable to drive (Ada et al., 2003a) b. Easy to drive from human propulsion by stepping legs on the ground (Ada et al., 2003b) c. The operation of the tricycle targeted leg muscle movements (Ada et al., 2003b)
5. Manufacturing	a. The tricycle frame can be manufactured (Febritasari & Batan, 2023) b. The tricycle components can be assembled with standard tools (Febritasari & Batan, 2023)
6. Maintenance	a. Easy to clean and maintain (Febritasari & Batan, 2023)

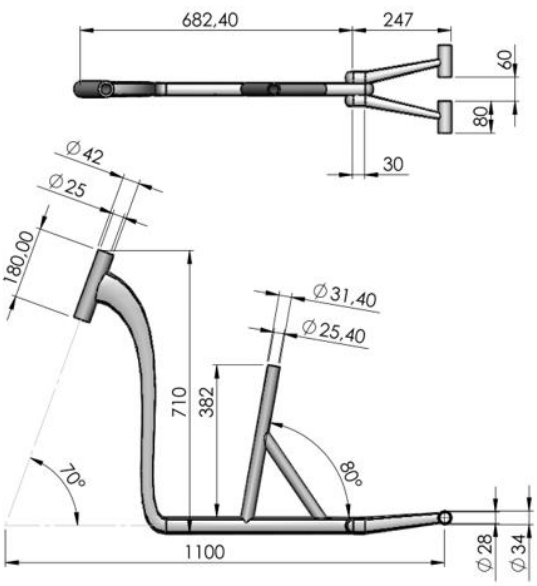

Figure 1. The self-propelled tricycle design

The tricycle frame was built in 2 parts, namely the Front Frame Sub Assembly (FFSA) and the Rear Frame Sub Assembly (RFSA). The FFSA and RFSA were combined with the welding process.

The front frame was built using several pipes, including a head tube with a diameter of 2.5 cm and a length of 18 cm, a rectangular profile down tube with dimensions of 7 cm and 2.8 cm, a rectangular bottom tube with dimensions of 2.8 cm and 2.8 cm, a seat tube with a diameter of 2.54 cm and a length of 38.2 cm, and a seat stay tube with dimensions of 2.8 cm. The FFSA was composed of 5 pipes, namely FFSA -1, FFSA -2, FFSA -3, FFSA -4, and SRD-5.

The RFSA was constructed using two different pipe sizes, namely, a chain stay tube (RFSA -1) and a rear axle tube (RFSA -2). Both RFSA -1 and RFSA -2 have a diameter of 3 cm. The details can be seen in **Figure 2**.

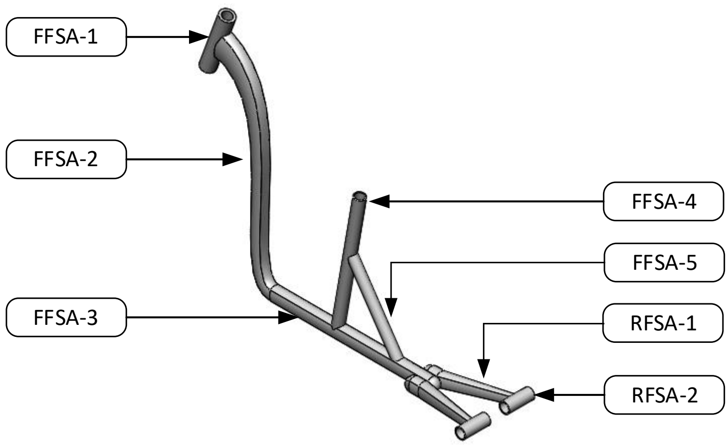

Figure 2. The Front and Rear Frame Sub Assembly

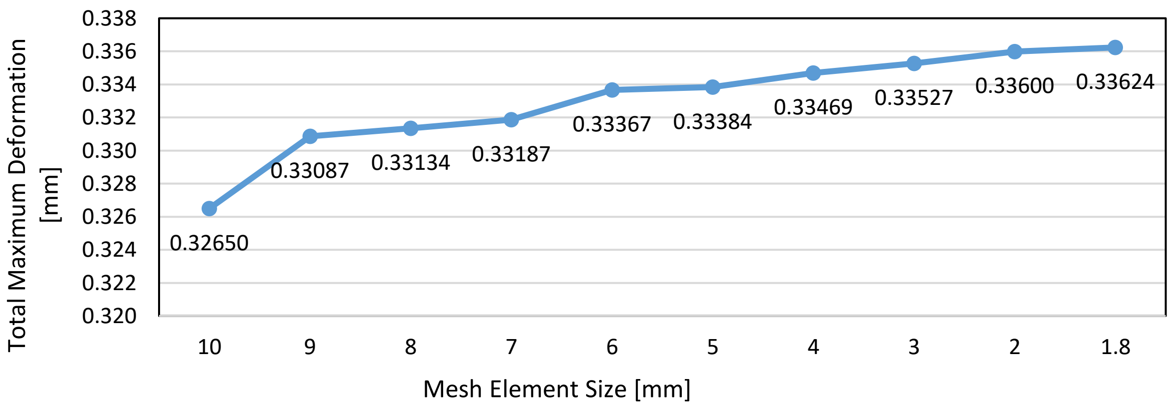

Figure 3. Comparison of total maximum deformation for mesh element size

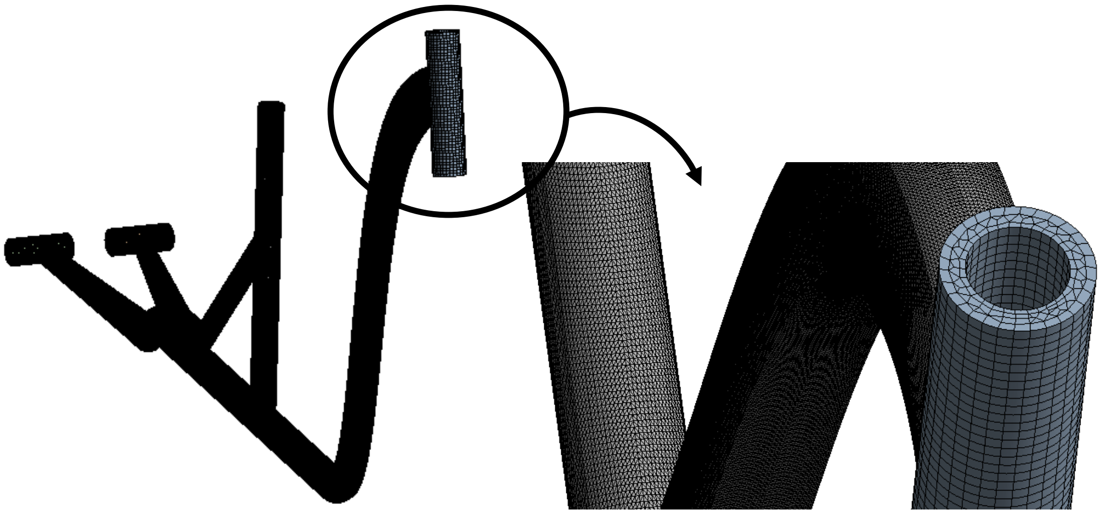

Figure 4. Mesh on the tricycle frame

2.3 *Mesh Generation*

The tricycle frame was analyzed by structural analysis to determine the effect of the load on the frame, which represents the actual condition. The grid independence test was carried out on a tricycle frame with various element sizes to discover the optimum grid size and the effect on total maximum deformation. It has been found that there is no significant change in total maximum deformation beyond the element size of 1.8 mm, which is shown in **Figure 3**. The element size of 1.8 mm with tetra and hex mesh types was applied to the frame (see **Figure 4**). The total meshes were 1,348,906 nodes and 733,261 elements. The skewness test showed 0.42034.

2.4 Boundary Conditions

In this study, the material of the self-propelled tricycle frame was Aluminum 6061-T6. It was chosen over other alloys because the Aluminum 6061-T6 offers greater strength than other alloys in the 6xxx series. It has good toughness and light, is easy to work, and is corrosion resistant. The properties of the material are shown in **Table 3.**

Table 3. Material properties of Aluminum 6061-T6

Properties	Value
Density	2.7 g/cm^3
Poisson Ratio	0.33
Yield strength	278 MPa
Tensile strength	310 MPa
Fatigue strength	96.5 MPa

The load was given to the frame based on the mass segment of the human body (Karl Ulrich, 2019). In this simulation, there were 2 forces, and the rider’s weight was assumed W = 100 kg for the maximum body weight.

a. Force F_1 is the rider's heavy force on the tube head and is subjected to the total arm force (0.0505W + 0.01) (Karl Ulrich, 2019) :

$$F_1 = 9.81(0.0505W + 0.01) \quad (1)$$

$$F_1 = 49.6386\ \mathrm{N}$$

b. Force F_2 is the rider's heavy force on the seat post and is subjected to head, neck and torso force (0.5940W - 2.20) added with upper arm (0.0274W - 0.01) (Karl Ulrich, 2019):

$$F_2 = 9.81((0.5940W - 2.2) + (0.0274W - 0.01)) \quad (2)$$

$F_2 = 587.9133\text{ N}$

There were 4 boundary conditions set to the tricycle frame that can be seen in **Figure 5**. These boundary conditions are:

a. Fixed Support on the head tube: Fixed boundary conditions are given to frames that are mounted with the front fork.

b. Fixed Support on the rear shaft: Fixed boundary conditions are given to frames that are mounted with the rear axle.

c. Seat tube force: the rider sits on the tricycle applying the load $\text{F}_2 = 587{,}9133\text{ N}$ on the seat tube.

d. Head tube force: the rider put their hand on the handlebar applying load $\text{F}_1 = 49{,}6386\text{ N}$ on the head tube.

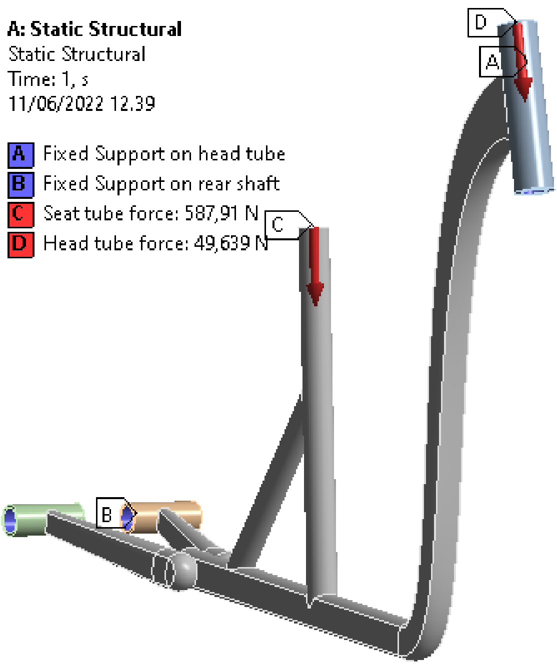

Figure 5. Boundary conditions on the frame

3. RESULTS AND DISCUSSION

3.1 Von Mises Stress

Von Mises testing was carried out on the tricycle frame to see the maximum tensile strength response the frame could receive before fracture. Equivalent (von Mises) Stress represents the distribution of equivalent stress levels, combining different types of stresses to assess a material's potential for yielding or failure (Park et al., 2023). **Figure 6** shows the simulation results on the tricycle frame run by the open-source software Ansys Workbench. Equivalent (von Mises) Stress test shows the contours of the vertical loading distribution after F_1 and F_2 forces are applied to the tricycle frame. Maximum equivalent stress of 38,806 Mpa occurred in the connection area of the seat and the down tube. Therefore, the tricycle frame will fail under 38,806 Mpa of received stress.

3.2 Deformation

Deformation is a physical alteration to an object caused by a load or force. The physical alteration can be categorized as elastic and plastic deformation (Prasetiyo & Sekarjati, 2022). A total deformation response determines how much deformation the tricycle frame will get the maximum load (see Figure 7). The total deformation test demonstrates that the maximum deformation on the saddle area is 0.399 mm, which is marked in red. It means that the component can be deformed in 0.399 mm by the applied load.

3.3 Safety Factor

One of the parameters used when performing stress testing on a model of an object is the safety factor (FoS) (Beaulieu, 2013b). FoS can be used to find the safety value of the tricycle frame, as shown in **Figure 8**. The higher the number of FoS, the safer the product or structure is. The simulation results showed the number of FoS is 11,031 on average, which means that the frame structure is safe to use. This is in line with the frame's purpose to ensure the safety of stroke survivors when using this tricycle.

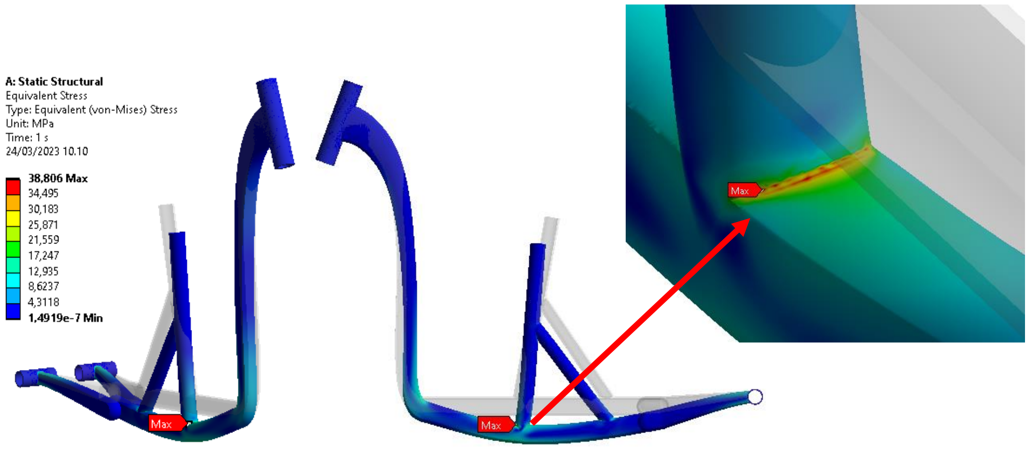

Figure 6. Equivalent (von Mises) Stress result

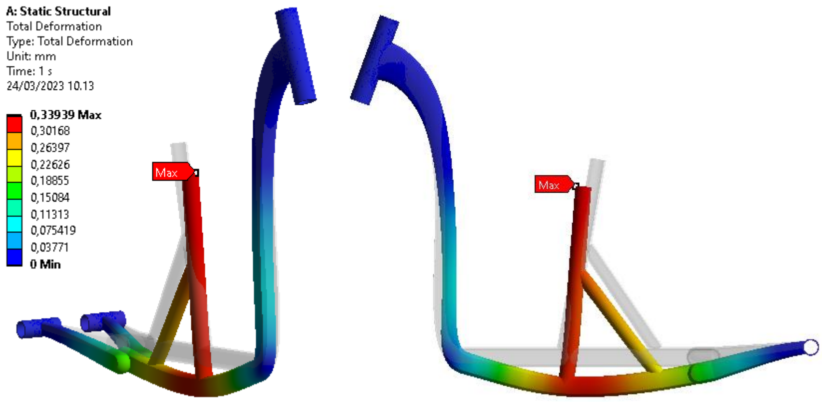

Figure 7. Total Deformation result

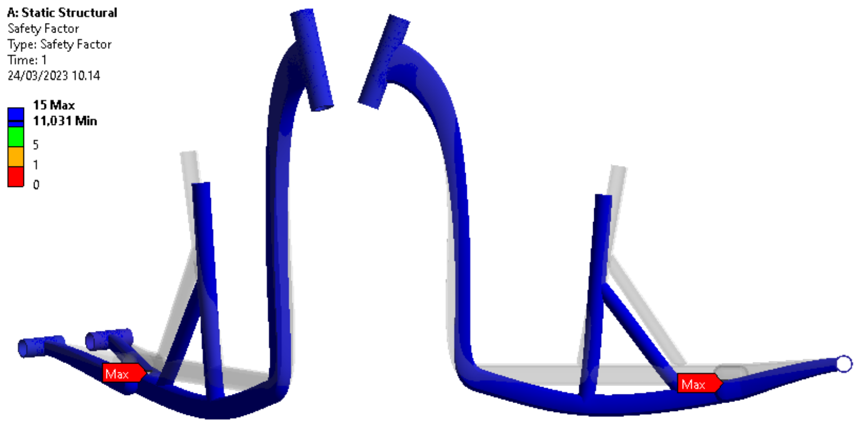

Figure 8. Safety Factor

3.4 Discussion

Finally, the final design of the tricycle is the frame equipped with a handlebar, a saddle with a backrest, brakes on both hands, and three wheels in delta configuration to give balance. The design of this tricycle has a length of 1478 mm, a height of 732 mm, and a width of 358 mm, which can be seen in **Figure 9**.

Figure 9. Self-Propelled Tricycle design

An analysis of the simulation results with various variations was carried out and compared with the results of the previous research. A similar study related to FEA analysis on mountain bike frames with aluminum 6061-T6 material was conducted by Sarath P (Sarath et al., 2021). A load of 2250 N given to the mountain bike frame vertically indicates the occurrence of maximum voltage on the intersection seat tube and bottom bracket of 33.72 Mpa, and maximum deformation occurred in the saddle area of 0.52604 mm (Sarath et al., 2021). Derek Covill conducted finite element analysis on the bicycle frame and showed its maximum displacement of 0.342 mm on the seat tube (Covill et al., 2014).

No consideration was given regarding the strength requirements of the bicycle frame, whether it uses materials such as aluminum, titanium, and carbon fiber. Hamzah Ibnu Yasin stated that the frame tube bike composite occurred deformation at the end of the seat tube, and the maximum stress due to loading is the connection (node) of the seat tube to the seat stays (Ibnu et al., 2021). This results from the loading angle direction colliding with the direction of gravity.

4. CONCLUSION

The self-propelled tricycle for post-stroke rehabilitation has been designed according to the post-stroke patient's requirements who have muscle weakness, body imbalances, and lack of coordination of limbs. This tricycle is designed for 100 kg of maximum rider weight with a ground clearance of 153 mm so that post-stroke patients can lift their legs. In finite element analysis, the tricycle is loaded with 49,638 N of total arm force on the tube head tube and 587,913 N of head, neck, torso, and upper arm force on the seat post. Fixed boundary conditions are given to frames mounted with the rear axle and front fork. Analysis of finite elements on the tricycle frame shows that the maximum strength of 38.8 MPa in the connection area of the seat tube and down tube causes an emphasis toward the negative y-axis. The maximum deformation occurs in the saddle area of 0.399 mm. According to the analysis, this tricycle provides comfort without the risk of injury when riding straight or turning.

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