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The Design and Development of a Foldable Wheelchair Stretcher

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Abstract: This study extends a previous research that conceptualised a foldable wheelchair stretcher (FWS) by furthering its design and development process. The material and component selections are accounted for in this study. Simulations are done using different loads to analyse the stress, displacement and safety factor of the stretcher design. Bending and maximum load analyses are used to inspect possibilities of deformation. The usability tests evaluated the (1) regular, (2) folding and (3) alternate functions of the stretcher. The data for tests 1 and 2 are analysed using *t*-tests, while test 3 data are analysed using an observational checklist. The FWS performed its regular function significantly slower than the normal stretcher by about 2 s due to its heavier weight. Its performance can still be considered akin to a regular stretcher's performance. The FWS's folding function performed significantly faster than the normal stretcher due to its simpler design. The angle increment test could not be executed due to technical constraints and the wheelchair function is tested without a seated user. However, the manoeuvrability of the FWS as a wheelchair was successfully verified. Finally, a cost analysis concluded that a commercial-ready FWS can be sold at 600 MYR, which is relatively cheaper compared to its competitors.

Keywords: stretcher; wheelchair; ergonomics; engineering design; usability

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1. Introduction

There are many kinds of medical transportation services to move patients effectively between facilities and rescue lives in the likelihood of an emergency. In the present day, an ambulance is a common medical transportation that moves patients who are seriously injured to treatment centres or hospitals [1]. Since there may be space-related challenges that render ambulances unable to reach the patient, the use of basic medical equipment such as stretchers might be needed.

A stretcher is a medical apparatus used by two or more healthcare workers to manually transport patients who need medical attention [2]. Its usage is common in emergency medical services (EMS). However, its basic design and functional limitations have also led to injuries occurring with both the patient and the medical workers during the transportation process [3–7].

A number of stretcher solutions such as the four-fold stretcher, compact foldable stretcher, foldable handle stretcher and portable stretcher have been designed and developed to resolve issues related to usability and portability [8–10]. Even so, limitations that involve patients sinking into the stretcher platform, lengthy setup time, lack of storage space and lack of alternate functions still prevail.

In a previous study, multiple design features have been synthesised through the investigation of ergonomic stretcher variants via patent literature, research literature and product reviews [11]. Through several levels of screening and scoring, this prior research finally conceptualised a novel stretcher variant that not only functions as a basic stretcher, but is also foldable and transformable into a wheelchair. Therefore, the aim of the present study is to extend from this previous research by designing and developing this foldable wheelchair stretcher (FWS).

In the above-stated previous study, it was also found that ergonomic stretcher designs have been patented since 1918, and the most updated patent relevant to this study was in 2014 [11]. Hence, there is a need to replace the existing ergonomic stretcher design variants and produce new ones with new advantages in usability and function.

The study commences with a brief literature review summarising the primary features of various stretchers and suitable components and materials for the development of the stretcher. Subsequently, the dimensions, wheel selection, material selection, simulation and analysis are established for the stretcher design. A usability test plan is also developed to test the functionality of the stretcher after its fabrication, followed by the presentation of the results and discussion. Before concluding the study, a cost analysis is also done to assess the potential of the stretcher for commercialisation and promotion in the market.

2. Literature Review

Stretchers are devices that healthcare workers use to move patients who require medical care. A review on stretcher designs identified the following stretchers to be common choices among modern stretchers.

- Simple stretcher: A basic type of stretcher carried by two or more people with no other feature or function besides moving a patient [12].
- Folding stretcher: A foldable stretcher consisting of two hinged bars, two poles and a cloth-like platform for improved portability and storage reduction [13].
- Litter (Rescue basket): A stretcher that firmly secures the patient while being transported through unsafe or uneven terrain (e.g., on a mountain) [14].
- Wheeled stretcher: A one-man operated stretcher where the medical person pushes and manoeuvres the stretcher with the help of the wheels [15].

Studies have also attempted to redesign or redevelop these common stretchers to be safer and more versatile. Table 1 shows a summary of primary features from various versatile stretcher designs extracted from Lim and Ng [11].

Table 1. Primary features of various stretchers [11].

Stretchers	Sources	Features	Pros	Cons
Four-fold stretcher	[16]	able to fold to four (4) segments	stretcher size is reduced once folded	none
		platform is soft	compressible or foldable for size reduction purpose	the user could still sink into the platform
Scoop stretcher	[17–20]	splits vertically	omits the need of carrying and placing the user onto the stretcher by scooping him/her up	none
		platform is hard	reduces possibility of undesirable movement	non-foldable
Multiutility wheelchair	[15,21]	transforms from stretcher to wheelchair and vice versa	user has the choice of sitting instead of lying down only one person needed to push wheelchair	size reduction not possible
Rubber shock absorbers	[22]	reduces vibrations and shock	avoids damages to internal organs	only needed when user is critically injured
				function only applies with soft platforms
Compact foldable stretcher	[8]	able to be folded into a bag	portable	complicated process of assembly

Table 1. *Cont.*

Stretchers	Sources	Features	Pros	Cons
Foldable handle	[9]	foldable handle	a small amount of space is saved	small space-saving benefit seems inconspicuous with heavy manufacturing effort
Portable stretcher	[10]	able to be folded into a luggage	portable	challenging to manufacture due to its complex parts
Rigid head and neck support	[23]	supports the neck and head	good for users with head and neck injuries	only needed when users have head or neck injuries
				supporting mechanisms reduce flexibility
Thermoplastic spine board	[24]	lightweight thermoplastic	portable	costly

These features have been screened by Lim and Ng [11] to be used for concept generation and selection purposes. The final concept selected in their research was the foldable wheelchair stretcher (FWS). This study emphasises on the design and development of this chosen stretcher, which means that the material and component selection also needs to be accounted for. In the next sections, the general details on wheels, steel, aluminium and wood are discussed.

2.1. Wheels

For wheeled stretchers, one of the important aspects to look at is the wheels. Researchers suggest that cleats, lugs and grousers are features of the wheel that play an important role in improving the wheel performance for lightweight vehicles [25]. Grousers in particular have an influence in wheel performance, especially when in contact with loose soil [26,27]. However, for some wheels, the performance is affected when impurities are present in the materials used to construct the wheels, causing the wheels to crack [28].

For this study, the important features to pay attention to when screening for appropriate wheels include smooth rolling, the ability to adapt to uneven surfaces, durability, stability, load capacity, cost and suitability of size.

2.2. Steel

Stainless steel is often used in construction due to its resistance to corrosion and aesthetic appearance [29]. In contrast to mild steel, stainless steel tends to possess a higher tensile strength. Even though the high cost of stainless steel is one of its disadvantages, it might still be a suitable choice in this study due to its resistance to corrosion, high tensile strength and ease of access. It also has good machinability and weldability.

2.3. Aluminium

Aluminium is one of the easiest metals to obtain since it occupies 8% of the Earth's surface by weight [30]. It has high strength, durability and ductility which makes it a popular choice for various industries. The demand for aluminium is increasing since it offers excellent corrosion resistance with superior strength and low density as contrasted with steel [31]. Generally, aluminium has many advantages such as high availability, good tensile strength and low cost. However, its material properties might change according to temperature. Overall, it might still be a good choice to consider in this study.

2.4. Wood

Wood is a widely used material in various industries as it is easy to obtain, easy to work on and durable with a variety of physical properties according to the species [32]. The advantages of wood include high specific strength, ease of processing, good aesthetics and its common use in various areas such as architecture and furniture design [33]. Some of the shortcomings of its use include its vulnerability to fire, inconsistency in properties and lack of stability [34]. Nonetheless, wood might still be a possible choice to consider for this study as it is easy to work on and has high availability. Though it is not as durable compared to metals, it is more lightweight and can be used for less critical parts.

3. Materials and Methods

3.1. Stretcher Concept

In a previous study, a multifunctional stretcher has been selected from several concepts based on the synthesisation of several key design features [11]. The final concept from that particular study is further developed in this research paper. The stretcher is made from 4 hard platforms which can be folded and transformed into a wheelchair.

Figure 1a shows the concept of the stretcher being fully stretched to be used as a normal stretcher. When the stretcher is not in use, the red sliders that hold the platforms can be moved up, and the stretcher can be folded and stored as illustrated in Figure 1b. By folding the platform into a suitable position, the stretcher can be transformed into a wheelchair for the patient to sit on as illustrated in Figure 1c. Since the stretcher can be folded and also transformed into a wheelchair, it is known as the foldable wheelchair stretcher (FWS) throughout this paper.

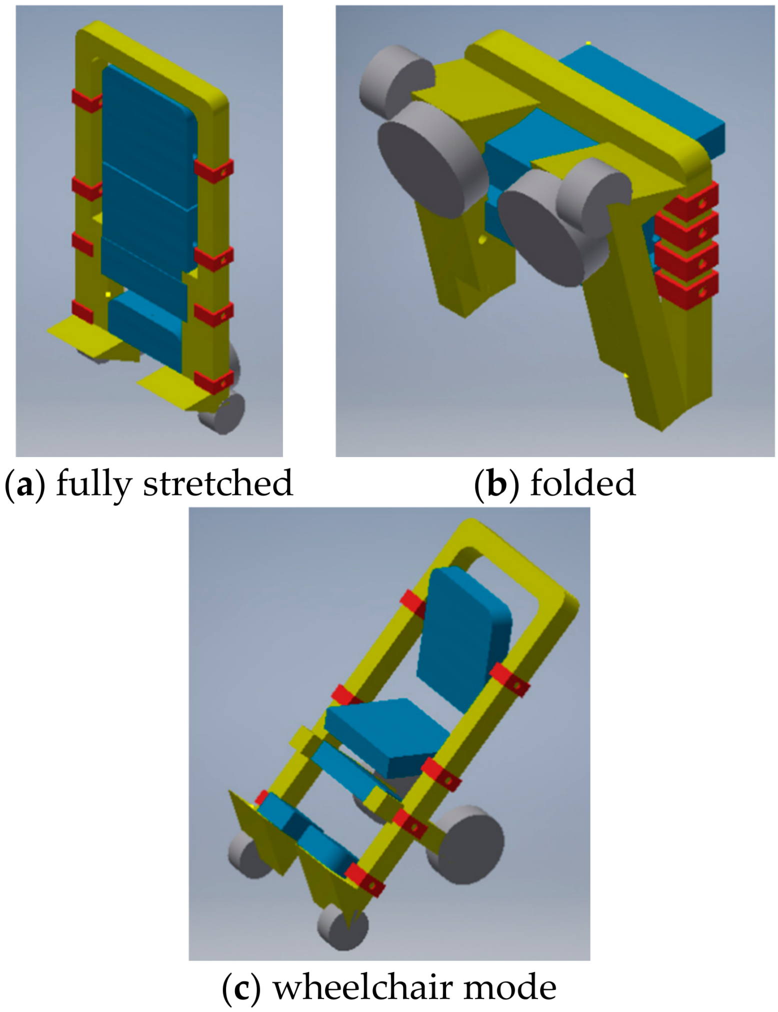

Figure 1. 3D models of the stretcher in its fully stretched, folded and wheelchair-transformed state [11].

3.2. Stretcher Dimensions

Table 2 presents some data on the dimensions and weight collected from different stretcher models. According to the data, most stretchers are designed with a length of 205 to 220 cm, and a width of 52 to 60 cm. However, these dimensions mostly accommodate the average height of Caucasian and American men, which is approximately 177 cm [35]. Since this research project is based in Malaysia, it is projected that its future progress and advancement to the commercialisation stage would extend to the nearest international market, namely in Southeast Asia. Hence, the present stretcher design in this study considers the anthropometric data of the population in Malaysia and Southeast Asia. All in all, the average height of approximately 166 cm needs to be considered [36]. Hence, for this study, a different set of dimensions is used.

Table 2. Dimensions and weight of different stretcher models.

Brand	Model	Dimensions (L × W × H) cm	Weight (kg)
Dragon	DW-F002	205 × 52 × 14	4.0
Medisave	Code Red	206 × 52 × 14	n/a
FirstAid4Sport	A901	220 × 54 × 13	n/a
PatrolQuip	WSX-D1C-P	205 × 53.5 × 13.5	7.6
IB BASICS	IB-3243	210 × 60 × 11	6.0

Note: L—Length; W—Weight; H—Height.

The total space that the platform occupies is estimated to be at a length of 185 cm, width of 50 cm and thickness of 2 cm. There is a gap between the outer frame and the platform, measuring at 1 cm in width and 4 cm in length, for both sides, respectively. With a 3 by 3 cm square cross section, the outer frame occupies a space of 199 × 58 × 3 cm. Figure 2 illustrates the overall dimensions of the stretcher. The shaded area represents the platform and outer frame.

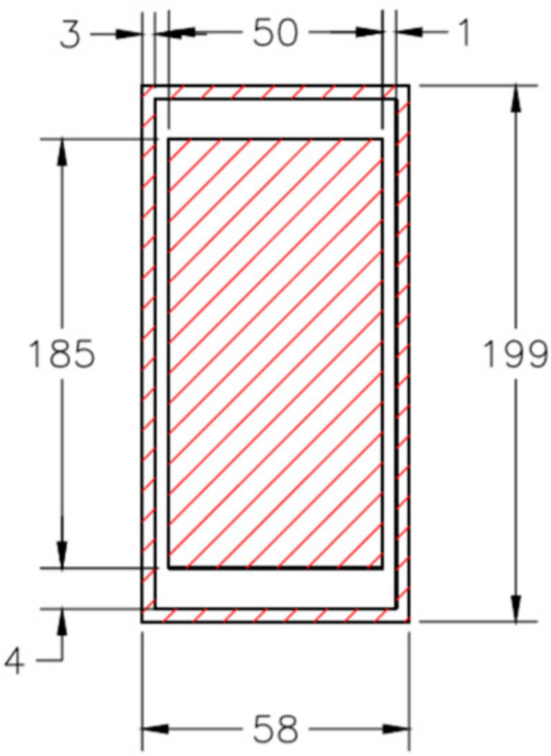

Figure 2. Illustration of the overall dimensions of the stretcher (in cm).

3.3. Component Selection: Wheels

Several types of wheels that are commonly used in the industry are selected for the stretcher. The appropriate choices of wheels include the puncture proof pneumatic wheels, polyurethane tyred cast iron centre wheels, polyurethane tyred nylon centre wheels and cushion tyred steel centred trolley wheels [37,38].

A component selection is performed to select the most suitable wheel for the stretcher. Ratings were given to the wheels according to the criteria. The following list defines the scale of each rating.

0: Unacceptable fulfilment of criteria.
1: Extremely poor fulfilment of criteria.
2: Very poor fulfilment of criteria.
3: Poor fulfilment of criteria.
4: Somewhat poor fulfilment of criteria.
5: Satisfactory fulfilment of criteria.
6: Somewhat good fulfilment of criteria.
7: Good fulfilment of criteria.
8: Very good fulfilment of criteria.
9: Extremely good fulfilment of criteria.
10: Exceptional fulfilment of criteria.

Each criterion is given a weight (W). In order to ascertain the weighted score (WS) of the criterion, the rating (R) is multiplied by the weight (WS = R × W). Table 3 shows the scoring of the wheels. The scoring results show that the polyurethane tyred cast iron centre wheel obtained the highest rank and is hence chosen for this study.

Table 3. Scoring of wheels.

Selection Criteria	Weight (%)	Wheel							
		A		B		C		D	
		R	WS	R	WS	R	WS	R	WS
Smooth rolling	5	6	0.30	9	0.45	8	0.40	6	0.30
Adapting to uneven surfaces	10	8	0.80	6	0.60	6	0.60	9	0.90
Durability	15	7	1.05	8	1.20	5	0.75	8	1.20
Stability	15	8	1.20	5	0.75	4	0.60	4	0.60
Cost	15	5	0.75	4	0.60	8	1.20	8	1.20
Suitability of size	20	2	0.40	10	2.00	10	2.00	6	1.20
Load capacity	20	2	0.40	10	2.00	6	1.20	3	0.60
Total score			4.90		7.60		6.75		6.00
Rank			4		1		2		3

Notes: R—Rating; WS—Weighted score; A—Puncture proof pneumatic wheels; B—Polyurethane tyred cast iron centre wheels; C—Polyurethane tyred nylon centre wheels; D—Cushion tyred steel centred trolley wheels.

Similar to the practice in the study of Lim and Ng [11], the scoring and ranking process is done by the main author of this study with some advice from his co-author. The weightage and ratings are first proposed by the main author based on his specific experience and knowledge on various stretcher designs. The main author is also in the forefront of the design work and has a good grasp of the prototyping requirements, cost and ergonomics aspects of this study. Approximately 14 stretcher solutions were explored by the main author who also has about 4 years of research experience in this area of study. Therefore, in reference to the main author's superior design sense in the specific area of stretcher designs, the co-author of this study concurred to the ratings and rankings provided by the main author.

3.4. Material Selection: Frame

Since the frame of the stretcher needs to undergo welding and bending, metal would be a suitable material for the frame. A few types of metal are deliberated for the stretcher.

Steel is widely used and has outstanding ductility and toughness. It is machinable, weldable and cheaper compared to other metals. Aluminium has a relatively low density (2.7 g/cm^3) compared to steel (7.9 g/cm^3). It has high electrical and thermal conductivities, which means that it can easily heat up when the wheelchair is moving, causing its strength to decrease. It also has high resistance to corrosion in an ambient atmosphere [39]. Brass contains a combination of copper and a small amount of zinc. It has greater strength than copper. However, it has poor corrosion resistance, which means that it would not be a sustainable choice for the stretcher.

Table 4 shows the comparison of the material properties for steel, aluminium and brass. Steel is chosen to be the material for the frame since it has the highest durability among the 3 metals.

Table 4. Comparison of material properties.

Material	Yield Strength (MPa)	Tensile Strength (MPa)	Density (g/cm^3)	Durability
Steel	580	830	7.90	durable
Aluminium	55	120	2.70	not durable
Brass	135	345	8.73	moderate

3.5. Material Selection: Platform

In order to minimise the weight of the stretcher, the platform material should possess a small density. With reference to the Ashby chart in Figure 3, wood appears to be the best option as foam would be too fragile for the platform. Thus, wood is chosen as the material for the platform.

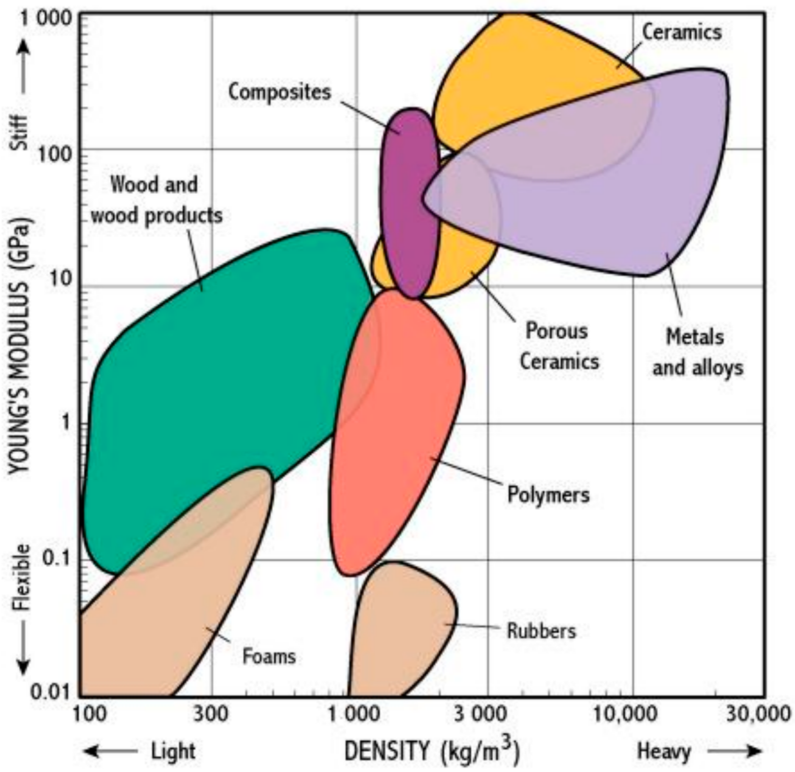

Figure 3. Ashby chart [40].

A specific type of wood also needs to be chosen. Table 5 compares the tensile strength, density, durability ratio, common usage and advantages of different types of wood. Tensile strength refers to the ultimate tensile strength acting perpendicularly to the grain of the wood. Durability ratio is the ratio of tensile strength to density.

Table 5. Comparison of common types of wood.

Type	Tensile Strength (MPa)	Density (kg/m^3)	Durability Ratio ($\times 10^{-3}$)	Common Usage	Advantages
Cedar	1.50	335	4.48	outdoor projects	resistant to moisture
Fir	2.30	530	4.34	buildings	common, easy to purchase
Pine	2.10	410	5.12	furniture	easy to be carved
Redwood	1.70	450	3.78	outdoor projects	resistant to moisture
Maple	4.00	675	5.93	decorations, baseball bats, charcoal	stable (consistent) due to fine, straight grain
Oak	5.50	750	7.33	outdoor furniture	strong, easy to work on

A scoring is then performed to select the most suitable wood for the platform. Similar to the scoring and ranking process done for the wheels, this process is also conducted solely by the main author of the study due to his superior design sense, specific knowledge and experience in various stretcher designs. The same 10-point rating scale is also used. The ratings are given to the wood types according to the criteria. Table 6 shows the scoring of the wood types. Cedar wood turned out to be the best choice for the material of the platform.

Table 6. Scoring of wood types.

Selection Criteria	Weight (%)	Wood											
		Cedar		Fir		Pine		Redwood		Maple		Oak	
		R	WS	R	WS	R	WS	R	WS	R	WS	R	WS
Weight	15	9	1.35	6	0.90	8	1.20	7	1.05	5	0.75	3	0.45
Durability	20	5	1.00	5	1.00	6	1.20	4	0.80	7	1.40	8	1.60
Moist Resistance	25	8	2.00	3	0.75	3	0.75	7	1.75	3	0.75	7	1.75
Cost	10	5	0.50	8	0.80	7	0.70	5	0.50	7	0.70	6	0.60
Ease of purchase	10	7	0.70	8	0.80	6	0.60	7	0.70	5	0.50	6	0.60
Ease of fabrication	10	7	0.70	4	0.40	9	0.90	6	0.60	8	0.80	6	0.60
Comfortability	10	7	0.70	8	0.80	7	0.70	6	0.60	7	0.70	4	0.40
Total score			6.95		5.45		6.05		6.00		5.60		6.00
Rank			1		6		2		3		5		3

Notes: R—Rating; WS—Weighted Score.

3.6. Simulation and Analysis

A stress analysis is performed on the individual parts of the stretcher to verify whether the design is structurally safe and would not fail when in use. The Autodesk Inventor Pro 2016 software is used for the simulation.

Females from Southeast Asia have an average weight of 54.7 kg (536.61 N), while the men have an average weight of 61.0 kg (598.41 N) [41]. However, when observed specifically in Malaysia, females weigh 63.5 kg (622.94 N) on average, and men weigh an average of 71.1 kg (697.49 N). These values are used in the simulation exercise when applying the forces to the stretcher.

3.6.1. Platform Simulation

Figure 4 shows the location of the force applied on the platform. Table 7 shows the simulations of the von Mises stress, displacement and safety factor for the platform while applying forces of 536.61 N, 598.41 N, 622.84 N and 697.49 N.

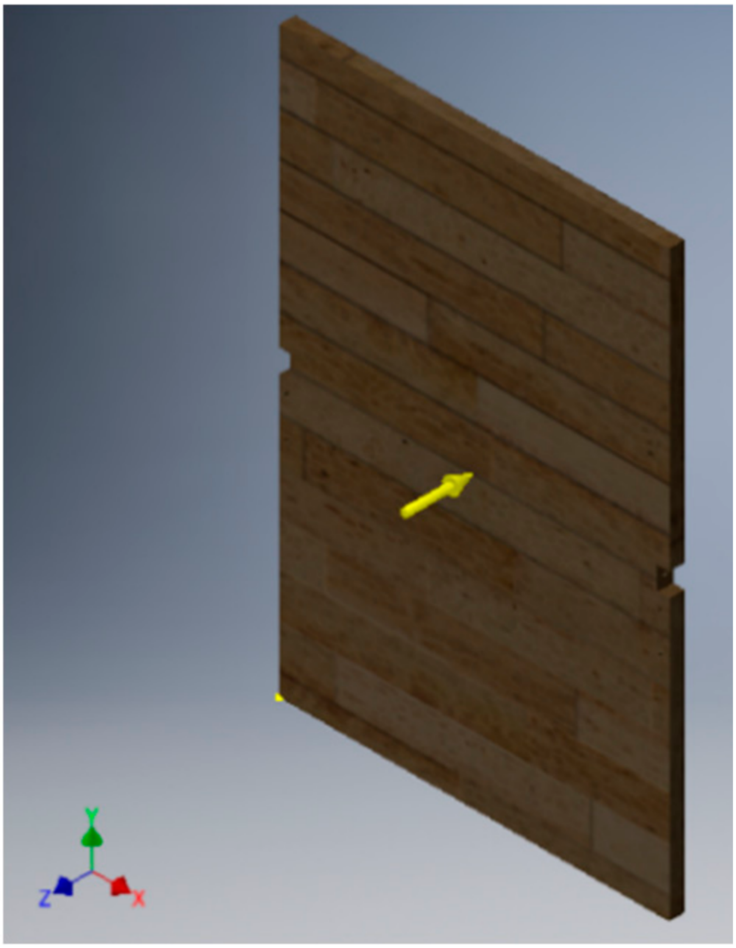

Figure 4. Overview of the force applied on the platform.

The force is applied at the centre of the platform. From the simulation, it can be observed that the maximum stress is accumulated at the drilled hole where the platform is fixed. By observing the colour indicators for all four conditions, it is found that the stress ranges from 8 to 12 MPa, which actually exceeds the tensile strength of Cedar wood. However, apart from this small region, the stress across the entire platform is close to zero and negligible. Referring to load condition (d) where the highest force is applied, the maximum displacement is 1.447 mm, which is a relatively small value when the size of the platform is considered. The minimum safety factor is shown to be 2.38. Hence, the design of the platform is still considered structurally safe.

Table 7. Von Mises stress, displacement and safety factor for the platform when applying loads of (a) 536.61 N, (b) 598.41 N, (c) 622.94 N and (d) 697.49 N.

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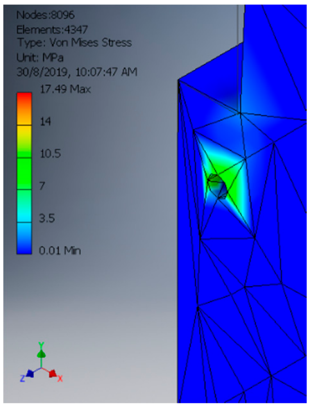
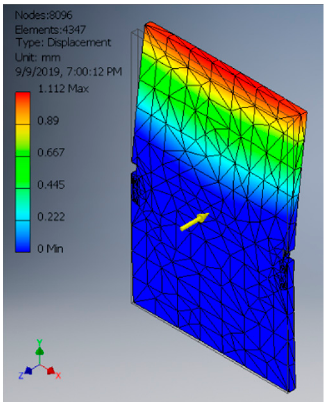
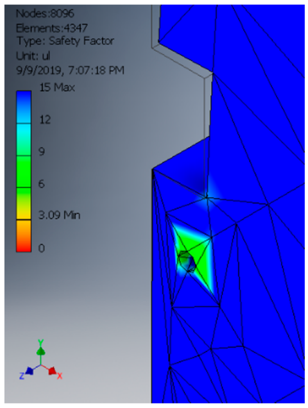
<tr><td>(a)</td><td>
</td><td>
</td><td>
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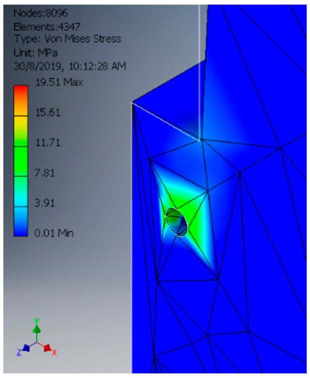
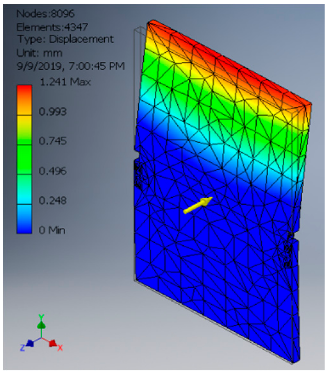
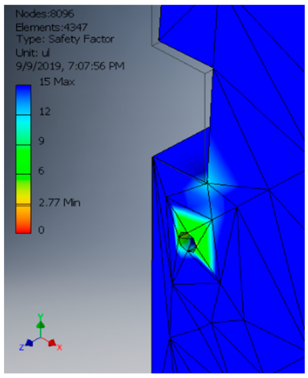
<tr><td>(b)</td><td>
</td><td>
</td><td>
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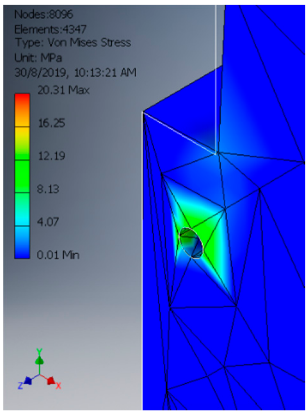
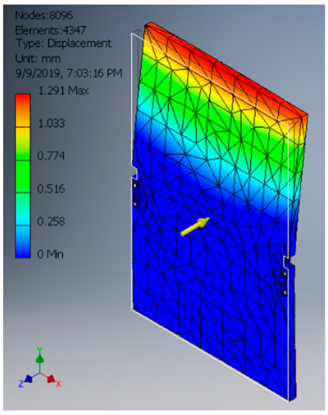
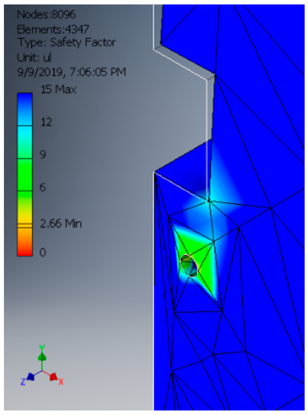
<tr><td>(c)</td><td>
</td><td>
</td><td>
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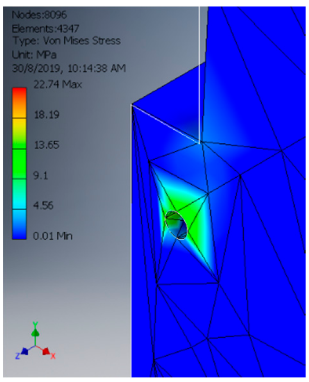
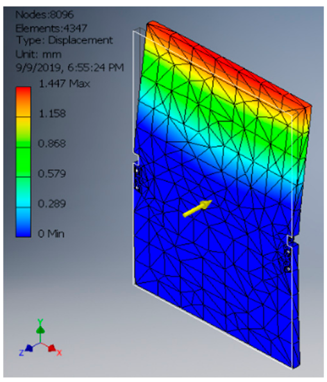
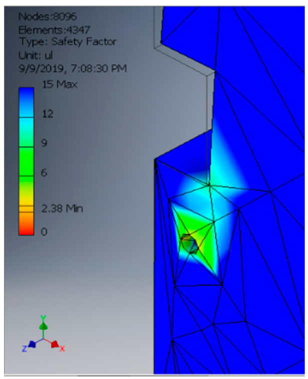
<tr><td>(d)</td><td>
</td><td>
</td><td>
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Notes: F—Force.

3.6.2. Slider Simulation

Figure 5 shows the location of the force applied on the slider which is used along the frame of the stretcher. Table 8 shows the simulations of the von Mises stress, displacement and safety factor for the slider while applying forces of 536.61 N, 598.41 N, 622.84 N and 697.49 N.

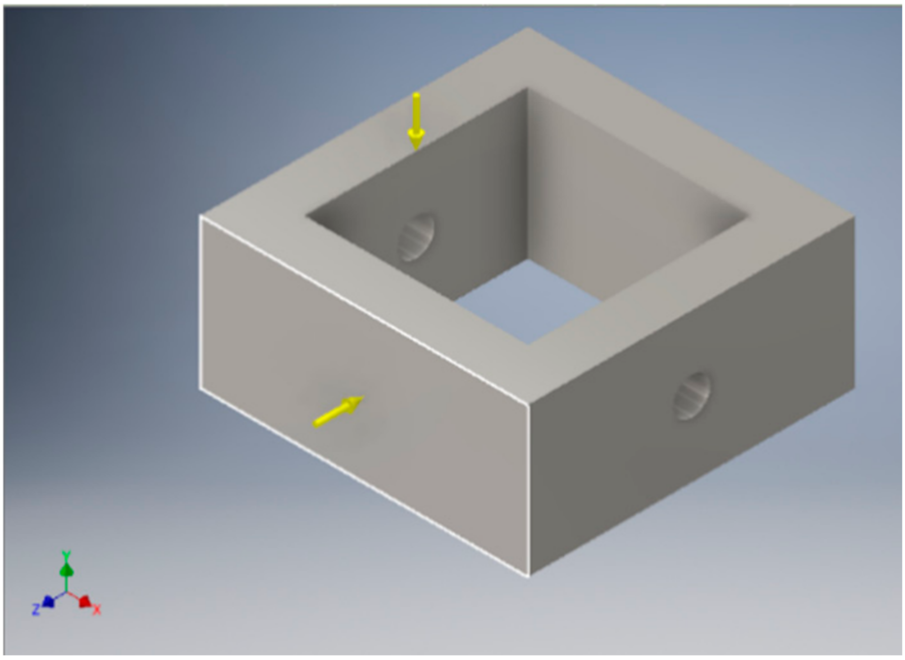


Figure 5. Overview of the force applied on the slider.

The forces are applied at the top and front faces of the slider. From the simulation, it is observed that the maximum stress is accumulated at the drilled hole where the slider is fixed. The maximum stress is observed to be at 16.32 MPa, which does not exceed the tensile strength of steel. Based on load condition (d), the maximum displacement is 0.001726 mm, which is negligible in comparison with the size of the slider. The minimum safety factor is 12.68. Hence, the slider design is considered to be structurally safe with regard to its von Mises stress, displacement and safety factor.

Table 8. Von Mises stress, displacement and safety factor for the slider when applying loads of (a) 536.61 N, (b) 598.41 N, (c) 622.94 N and (d) 697.49 N.

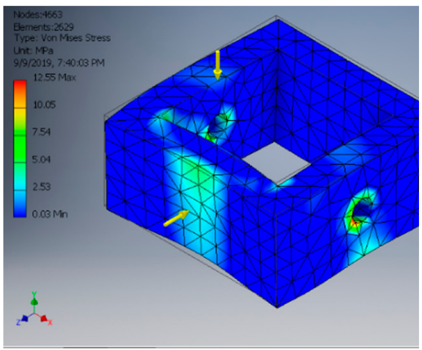
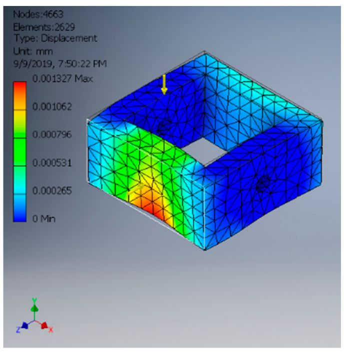
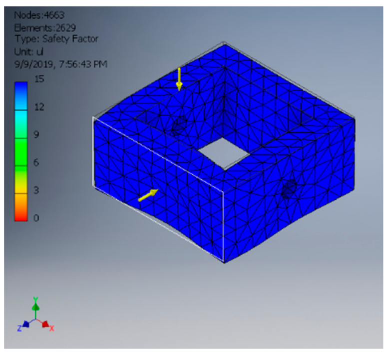
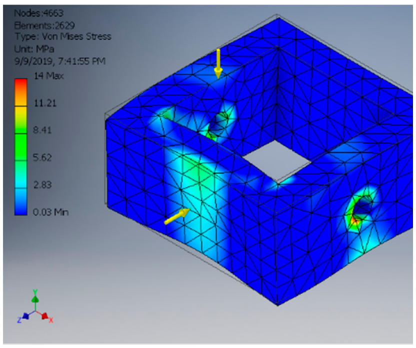
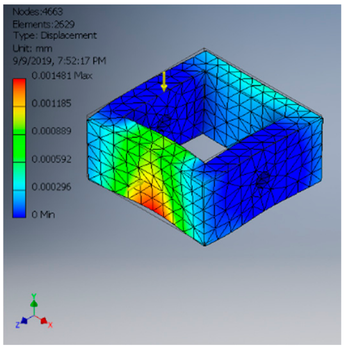
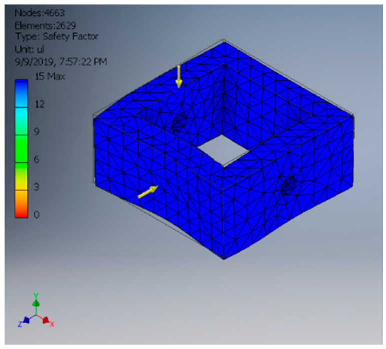
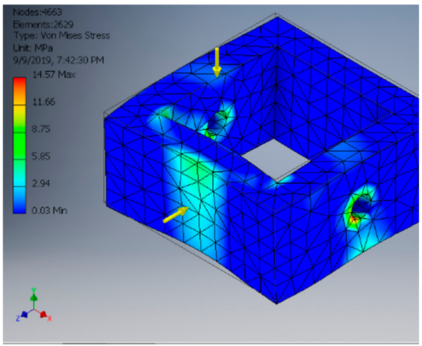
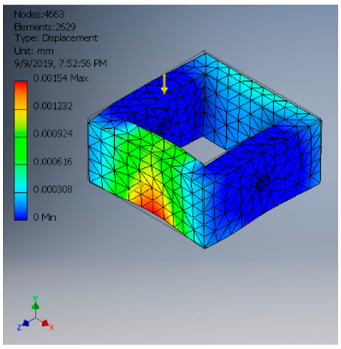
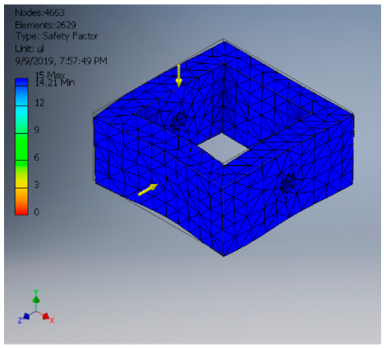
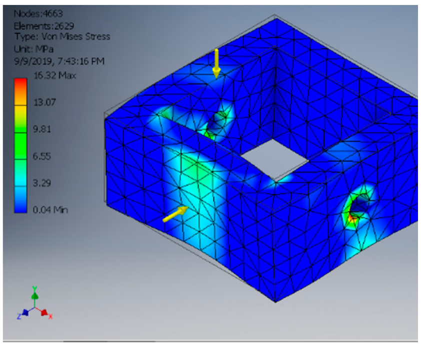
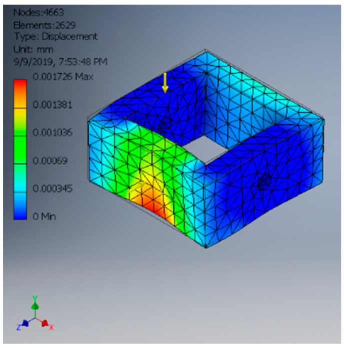
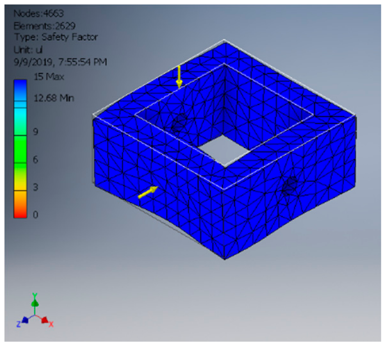
F (N)	Von Mises Stress	Displacement	Safety Factor
(a)			

Table 8. *Cont.*

F (N)	Von Mises Stress	Displacement	Safety Factor
(b)			
(c)			
(d)			

Notes: F—Force.

3.6.3. Frame Simulation

Figure 6 shows the location of the force applied on the frame. Table 9 shows simulations of the von Mises stress, displacement and safety factor while applying forces of 536.61 N, 598.41 N, 622.84 N and 697.49 N on the frame.

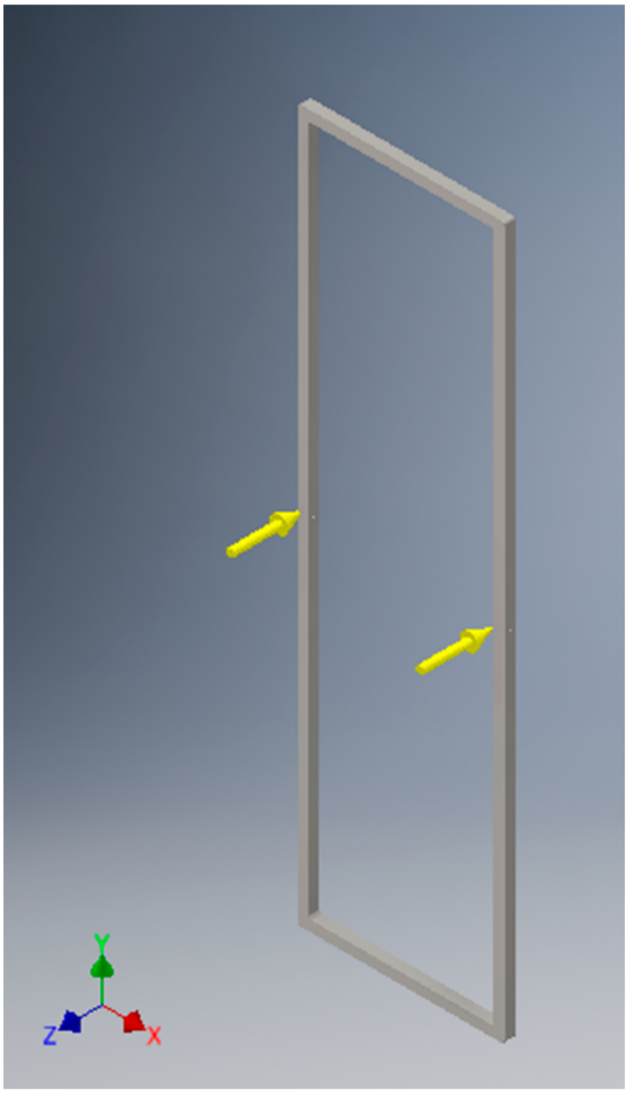


Figure 6. Overview of the force applied on the frame.

Table 9. Von Mises stress, displacement and safety factor for the frame when applying loads of (a) 536.61 N, (b) 598.41 N, (c) 622.94 N and (d) 697.49 N.

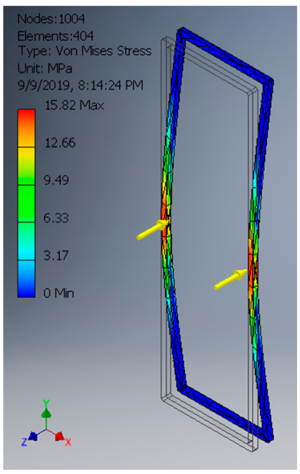
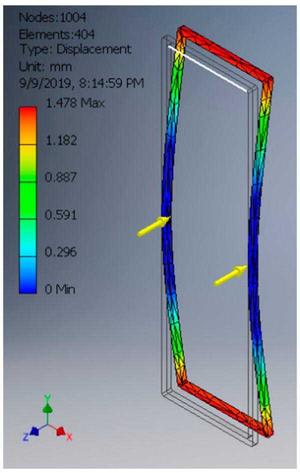
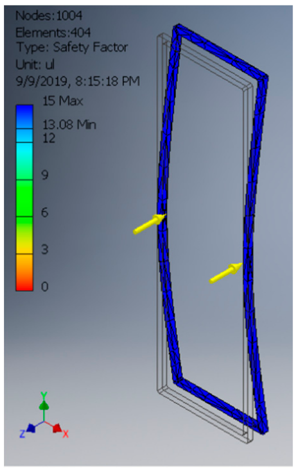
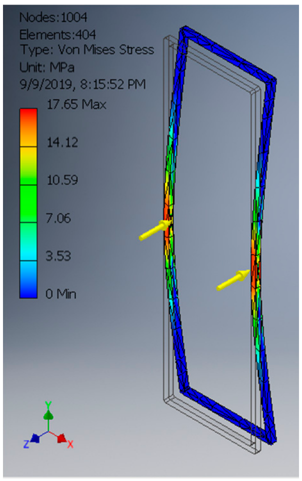
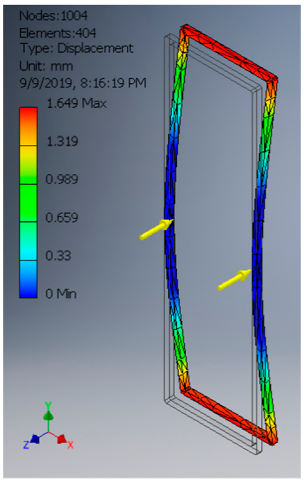
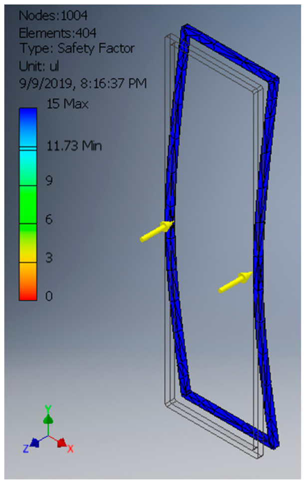
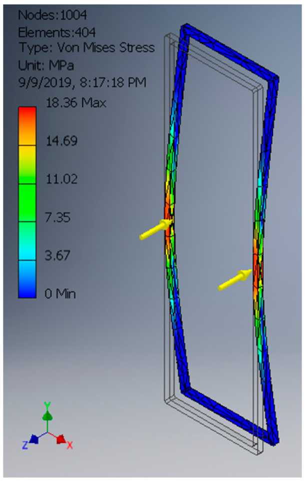
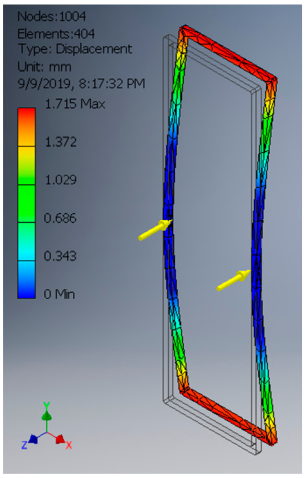
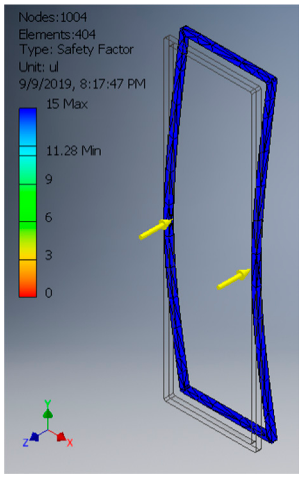
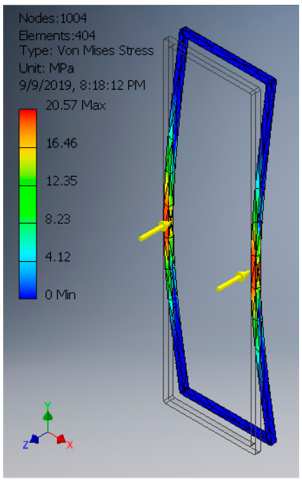
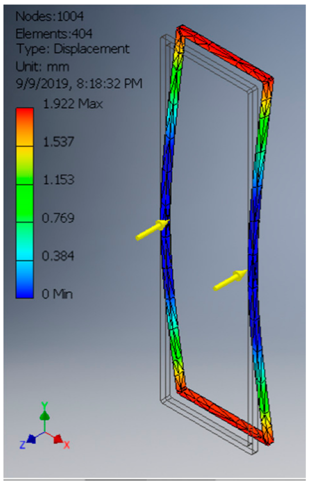
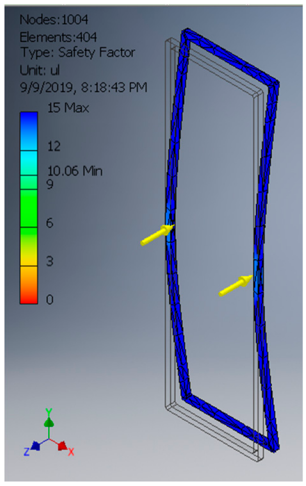
F (N)	Von Mises Stress	Displacement	Safety Factor
(a)			

Table 9. *Cont.*

<table>
<tr><th>F (N)</th><th>Von Mises Stress</th><th>Displacement</th><th>Safety Factor</th></tr>
<tr><td>(b)</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>(c)</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>(d)</td><td>
</td><td>
</td><td>
</td></tr>
</table>

Notes: F—Force.

Two forces are applied at the front face of the frame. The simulation reveals that the maximum stress is accumulated at the centre of the frame. The maximum stress is observed to be at 20.57 MPa, which is still lower than the tensile strength of steel. When the highest force is applied, the maximum displacement is 1.922 mm, which is negligible in comparison with the size of the frame. The minimum safety factor is 10.06. Hence, the design of the frame is considered to be structurally safe in terms of its von Mises stress, displacement and safety factor.

3.6.4. Bending Analysis

For this analysis, the stretcher is assumed to take the form of a beam structure in order to calculate the amount of bending (deflection) that would occur. When the patient lies on top of the stretcher, the load is assumed to be uniformly distributed. The load of 697.49 N (the highest load used in the simulation) is used for this analysis. The following equation is used to calculate the deflection.

$$\delta = \frac{5qL^4}{384EI} \tag{1}$$

where moment of inertia, $I = \frac{a^4}{12} = \frac{(0.03)^4}{12} = 6.75 \times 10^{-8}$ kg.m^2
Load of intensity, $q = \frac{W}{L} = \frac{697.49}{1.99} = 350.50$ N/m
Young's modulus of steel, E_{steel} = 210 GPa
Using Equation (1), the deflection, δ = 5.049 mm.

From the calculation, it is observed that the maximum deflection is 5.049 mm, which is higher than the 1.922 mm deflection from the frame simulation. Both of these values indicate that the bending is inconsequential in comparison to the size of the stretcher and the stretcher should not experience deformation.

3.6.5. Maximum Load Analysis

In order to calculate the maximum sustainable load of the stretcher, the following equation is used.

$$Yield\ strength,\ \sigma = \frac{Mc}{I} \tag{2}$$

where the bending moment, $M = WL/8$
Perpendicular distance to the neutral axis, $c = \delta$
By substituting the variables from Equation (1), Equation (2) becomes:

$$\sigma = \left(\frac{WL}{8}\right)\left(\frac{5\frac{W}{L}L^4}{384EI}\right)\left(\frac{1}{I}\right) = \frac{5W^2L^4}{3072EI^2} \tag{3}$$

Using the yield strength of steel (σ_{steel} = 250 MPa) in Equation (3), it is possible to calculate the load at yield, W = 1178.29 N. According to this analysis, the stretcher would yield if the load is greater than 1178.29 N (or 120.11 kg), which means that it would experience permanent deformation at the point of this load application. The highest load applied for the simulation (697.49 N) is considered far from this value.

3.7. Usability Test Plan

Since this project involves developing a foldable and multifunctional stretcher, its basic, foldable and alternate functions need to be tested. This project does not involve collaborations from any medical health institutions or centres. The project also does not include the participation of actual patients that have conditions requiring them to use a stretcher or wheelchair. Hence, there is no medical ethics clearance required. Instead, the study involves the participation of normal and healthy adults aged 18–25 years old. It is important to note that the participants of the experiment had no prior experience in using the FWS or normal stretcher.

All participants gave their written informed consent prior to the experiments. All procedures and protocols have been approved by the Research Ethics Committee (REC) from the Technology Transfer Office (TTO) of Multimedia University. The research ethics approval for the project has been granted with the approval number EA0032021, and the approval letter has been endorsed by the TTO Director cum REC Secretariat of the university. The following procedures are drafted solely for experimentation purposes.

3.7.1. Test 1: Normal Stretcher Use

1. Six (6) people are assigned to act on behalf of the medical person, while one (1) person is assigned to act on behalf of the patient. Since they are not actual medical workers and patients, they will be known throughout the experiment as transporting users (the medical workers) and the transported user (the patient). The users are indicated as A, B, C, D, E and F.
2. Two transporting users are to form a group with one of them carrying the front handle and the other carrying the back handle of the stretcher. The groupings are shown in Table 10.
3. The normal stretcher is placed on the floor, and the transported user lies down on the stretcher. The group formed in step 2 has to standby beside the transported user.
4. When the timer starts, both members of the transporting user group are to lift the stretcher up at their assigned positions.
5. Upon lifting the stretcher, both transporting users are to travel through a distance of 10 m at the fastest speed possible without dropping the patient.
6. The stretcher is placed down and the timer stopped. The total duration is recorded.
7. If at any point in steps 4, 5 and 6, an error occurs, the test is to be repeated from steps 3 to 6.
8. Steps 3 to 7 are repeated with groups 2 to 30.
9. Steps 3 to 8 are repeated using the FWS.

Table 10. Groupings and data recording for test 1.

Group	Position of User		Time Taken to Complete the Test (s)	
	Front	**Back**	**Normal Stretcher**	**FWS**
1	A	B		
2	A	C		
3	A	D		
4	A	E		
5	A	F		
6	B	A		
7	B	C		
8	B	D		
9	B	E		
10	B	F		
11	C	A		
12	C	B		
13	C	D		
14	C	E		
15	C	F		
16	D	A		
17	D	B		
18	D	C		
19	D	E		
20	D	F		
21	E	A		

Table 10. *Cont.*

Group	Position of User		Time Taken to Complete the Test (s)	
	Front	Back	Normal Stretcher	FWS
22	E	B		
23	E	C		
24	E	D		
25	E	F		
26	F	A		
27	F	B		
28	F	C		
29	F	D		
30	F	E		

3.7.2. Test 2: Folding Stretcher

1. The normal stretcher is placed on the floor in a fully stretched mode.
2. When the timer starts, person A commences folding the stretcher.
3. The timer stops when the stretcher is completely folded. The total duration is then recorded (See Table 11).
4. When the timer starts again, person A begins to unfold the stretcher.
5. The timer is stopped when the stretcher is fully stretched. The total duration is recorded again.
6. Steps 1 to 5 are repeated for person B, C, D, E and F.
7. Steps 1 to 6 are repeated 5 times.
8. Steps 1 to 7 are repeated using the FWS.

Table 11. Data recording for test 2.

Person	Attempt (5 Attempts per Person)	Total Time Taken to Complete the Test (s)			
		Normal Stretcher		FWS	
		Fold	Unfold	Fold	Unfold
A					
B					
C					
D					
E					
F					

3.7.3. Test 3: Alternate Function

1. The stretcher is folded into a wheelchair. The platform of the seat is adjusted to be parallel to the ground (45° to the frame).
2. Person A sits on the wheelchair and slowly adjusts the angle of the platform just before he/she begins to slide off the seat. The increment of the angle is recorded (See Table 12 for the data collection method).
3. Steps 1 and 2 are repeated for persons B, C, D, E and F.
4. The platform of the seat is adjusted back to be parallel to the ground and the transported user sits on it before the subsequent tasks are carried out.
5. All transporting members then try to complete the following tasks:
    (a) Push the transported user on the wheelchair to move a distance of 10 m
    (b) Zero radius left turn
    (c) Zero radius right turn

6. If the task is able to be completed, a checkmark is granted (✓). If not, a cross mark is given (×) (See Table 13 for the data collection method).

Table 12. Data recording for angle increment.

Person	Angle Increment (°)
A	
B	
C	
D	
E	
F	

Table 13. Preparation of checklist for testing of the wheelchair function.

Person	Task Checklist (✓/×)		
	a	b	c
A			
B			
C			
D			
E			
F			

Note: a—push the wheelchair to move a distance of 10 m; b—zero radius left turn; c—zero radius right turn.

3.8. Analysis Planning

The data collected for test 1 and test 2 are analysed using two-sample *t*-tests. The Minitab 19 software is used to complete the test. The hypotheses are formulated according to the different scenarios in test 1 and 2. Since only nominal data are available in test 3, simple descriptive analyses are used.

3.8.1. Analysis Planning for Test 1 and 2

With the significance value, α, set at 0.05, the hypotheses for test 1 and test 2 are formulated as such:

H_{o1}: The FWS does not significantly differ from the normal stretcher with regard to the time taken to complete test 1.

H_{a1}: The FWS significantly differs from the normal stretcher with regard to the time taken to complete test 1.

H_{o2}: The FWS does not significantly differ from the normal stretcher in terms of the time taken to fully fold and unfold in test 2.

H_{a2}: The FWS significantly differs from the normal stretcher in terms of the time taken to fully fold and unfold in test 2.

Once the data are entered into Minitab 19, the mean value, *t*-value and *p*-value are generated. If the *p*-value is less than 0.05 ($p < \alpha$), the null hypothesis (H_{o1} or H_{o2}) is rejected, and the alternate hypothesis (H_{a1} or H_{a2}) is supported. If the *p*-value is more than 0.05 ($p > \alpha$), the null hypothesis is supported, and the alternate hypothesis is rejected.

3.8.2. Analyses Planning for Test 3

For the analysis of angle increment, the mean value and the standard deviation is calculated from the data collected. If the standard deviation is more than 30 degrees ($\sigma > 30°$), then the average adjustable seat angle is $x°$, but it differs according to the person adjusting it. If the standard deviation is less than 30 degrees ($\sigma < 30°$), then the average adjustable seat angle is $x°$, and it is consistent regardless of the person adjusting it. In the preceding statements, $x°$ refers to the actual value of the seat angle.

For the analysis of the wheelchair function, the number of checkmarks is used to judge if the stretcher can function properly as a wheelchair. The following are the definition of the outcomes.

If 100% of the data consist of ✓: This model can function properly as a wheelchair.

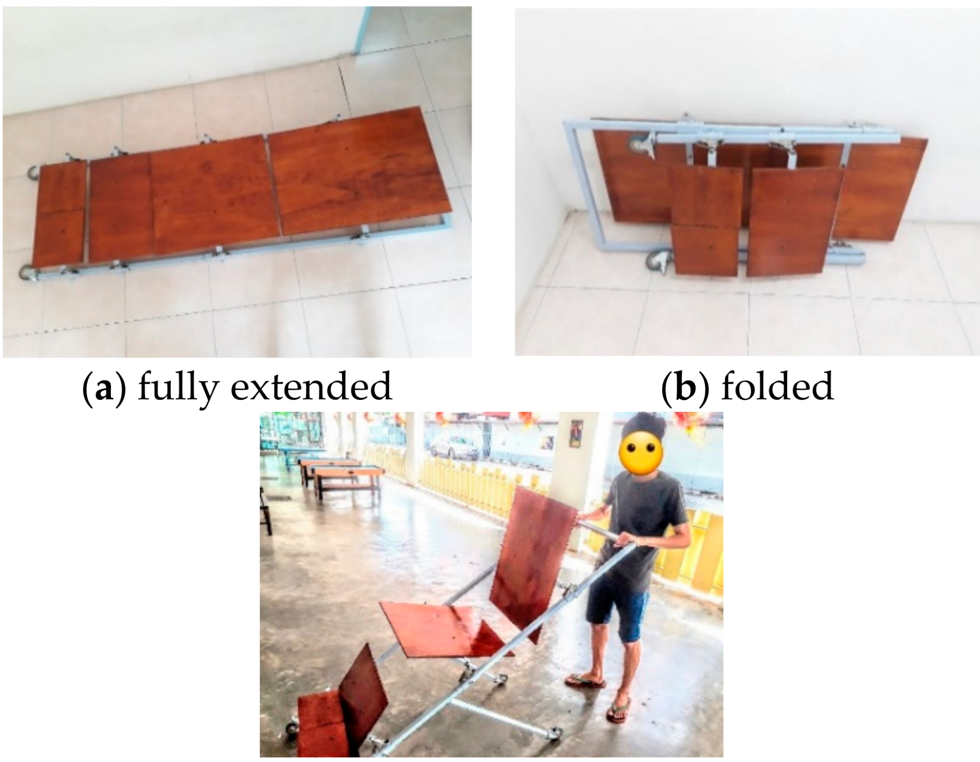
If more than 80% of the data consist of ✓: This model can function properly as a wheelchair, but the performance is not the same for every single person.

If less than 80% of the data consist of ✓: This model cannot function properly as a wheelchair.

4. Results and Discussion

4.1. Final Product

The final product is able to fully extend into a stretcher as shown in Figure 7a. It can also be folded in half as shown in Figure 7b for ease of storage and improved portability. By adjusting the platforms and fixing the positions with the customised slider hinge, the stretcher transforms into a wheelchair as shown in Figure 7c. The frame was painted and the wooden platforms were coated with shellac with the intention to protect the material from stains and contamination (e.g., an injured patient's blood).



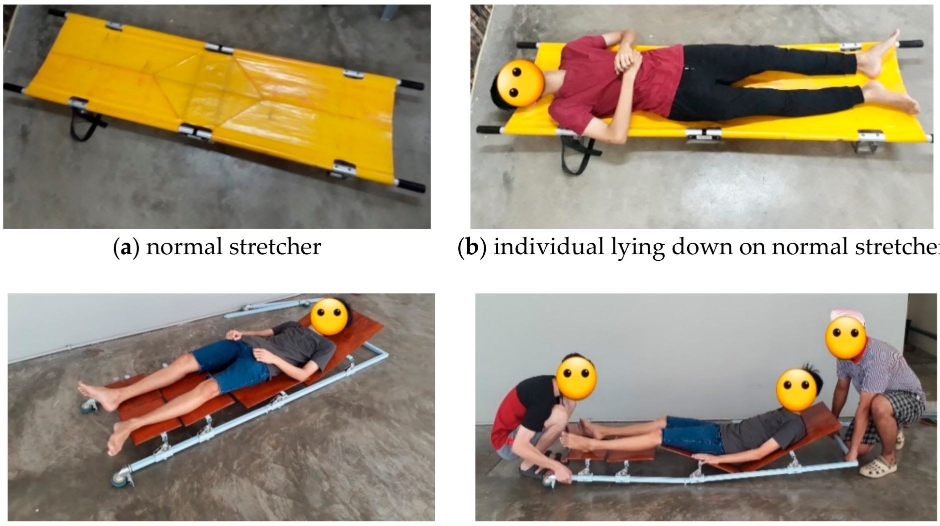
(**a**) fully extended (**b**) folded

(**c**) wheelchair mode

Figure 7. Final product in stretcher, folded and wheelchair modes.

4.2. Results for Test 1

Test 1 compared the FWS's transporting function with a normal stretcher's transporting function. Figure 8a shows the photo of the normal stretcher used in this test and Figure 8b shows an example of an individual (who is not an actual patient) lying down on the stretcher. Figure 8c shows an example of an individual lying down on the FWS while Figure 8d shows an example of transporting users (who are not actual medical workers) attempting to lift the FWS with the transported user on top.



(**a**) normal stretcher (**b**) individual lying down on normal stretcher

(**c**) individual lying down on FWS (**d**) users transporting individual with FWS

Figure 8. Test 1—comparison between the normal stretcher and FWS.

It was noticeable in Figure 8c,d that the platforms were not parallel as in Figure 7. This issue occurred because the fasteners connecting the support bars for the platforms with hinges were not strong enough to hold and prevent the platform from tilting when a person lies down on the stretcher. Even though the platforms could not maintain a straightened position, the person could still lie down on the stretcher securely. Hence, the test was carried out as planned.

The paired sample *t*-test was used for the analysis. The significance level for the test was set at 0.05 ($\alpha = 0.05$). Table 14 shows the results of the paired sample *t*-test for test 1. The average time taken to complete test 1 for the FWS appeared to be approximately close with the one for the normal stretcher (M_{FWS} = 31.25 s; M_N = 29.41 s). However, according to the *t*-test, the two groups differed significantly from each other [$t(29) = -2.128$, $p < 0.05$]. Hence, H_{a1} was not rejected.

Table 14. Paired sample *t*-test for test 1.

Stretcher	Mean	SD	t	df	*p*-Value
Normal (N)	29.41	3.499	−2.128	29	0.04196
Foldable Wheelchair Stretcher (FWS)	31.25	3.193			

Note: N = 30; SD—Standard Deviation.

However, the FWS's mean time to complete test 1 was more than the normal stretcher's mean time by only 1.84 s (about 6% difference). Even though the final product might not be exceptionally better than the existing product, the authors believe that its performance at least marginally matched the performance of the normal stretcher for test 1.

4.3. Results for Test 2

Test 2 compared the FWS's folding function with the normal stretcher's folding function. Figure 9 shows the completely folded normal stretcher used in this test.

Figure 9. Completely folded normal stretcher used for test 2.

According to the results in Table 15, the two groups differed significantly from each other [$t(29) = 6.669$, $p < 0.05$], with the FWS requiring a lower average time to completely fold and unfold as compared to the normal stretcher ($M_{FWS} = 49.92$ s, $M_N = 88.97$ s). Hence, H_{a2} was not rejected.

Table 15. Paired sample *t*-test for test 2.

Stretcher	Mean	SD	t	df	*p*-Value
Normal (N)	88.97	31.124	6.669	29	0.00001
Foldable Wheelchair Stretcher (FWS)	49.92	7.762			

Note: N = 30; SD—Standard Deviation.

Even though the FWS was capable of being folded at almost double the speed of the normal stretcher, the storage space required for the FWS ($L \times W \times H$: 120 × 60 × 30 cm) was still larger than the space required for the normal stretcher ($L \times W \times H$: 58 × 21 × 14 cm) [42]. While it exceled in terms of setup or preparation time, the FWS took up more space and was less convenient to bring around as compared to the normal stretcher.

4.4. Results for Test 3

Test 3 evaluated the wheelchair function of the FWS. In test 3, it was found that the fasteners connecting the support bars for platforms with hinges were not strong enough to hold and prevent the platform from tilting when a person lies down on the stretcher. For the angle increment test, the platforms were made to be adjustable to any angle without additional weight. However, it was found that the platforms were still unable to sustain the full weight of a person when the stretcher was in its wheelchair mode. Hence, the angle increment part of test 3 could not be performed, and the wheelchair function validation in test 3 was completed without a seated user. Table 16 shows the checklist for the wheelchair function test.

Table 16. Checklist for the wheelchair function test.

Person	Task Checklist (✓/×)		
	a	**b**	**c**
A	✓	✓	✓
B	✓	✓	✓
C	✓	✓	✓
D	✓	✓	✓
E	✓	✓	✓
F	✓	✓	✓

Note: a—push the wheelchair to move a distance of 10 m; b—zero radius left turn; c—zero radius right turn.

Throughout the test, each person was able to complete the tasks with one or two tries. No difficulties were found when manoeuvring the wheelchair. If there was a way to fix the position of the platform, the FWS should be able to function properly as a wheelchair as demonstrated by its structural integrity analyses.

4.5. Key Findings and Discussion

Several key findings were concluded from this project.

4.5.1. The Weight of the FWS Very Much Affects Its Performance

From the results of test 1, it was found that in terms of stretcher usage, the FWS was slightly more time-consuming to use compared to a normal stretcher. This shortcoming, albeit a slight one, was probably because the FWS was heavier than the normal stretcher. The performance would probably improve significantly if it were designed to be lighter in weight. It was often observed in studies on medical innovations that fulfilling the lightweight attribute would also allow for improved portability [43–46].

4.5.2. Simple Designs Are More User Friendly

Test 2 proved that the FWS's folding function was better than a normal stretcher's folding function. The average time required to completely fold and unfold the FWS was about 44% lesser than the time required for the normal stretcher. This difference was probably due to the simplicity of the FWS's design. In principle, normal stretcher designs highly emphasise on the space-saving attribute, and hence tend to be more complex since segmentations are required for the design to be more modular [16]. In this project, the FWS only needed two steps to be folded or unfolded.

4.5.3. The Design of the Prototype Should Be Flexible

Before arriving to the finalised version, the design of the prototype was amended a few times as the fabrication process was faced with some challenges. Some of these challenges were not noticed during the design stage, and only discovered during the usability test stage. Therefore, designing a solution with the aim of having a more flexible design from the start would allow the amendments to be easier and reduce major changes. Methods that could be used include the design for manufacturing and assembly (DFMA) and TRIZ (the theory of inventive problem solving) approaches [47–49]. However, due to the cost and time constraint, the researchers decided to complete the research project at this stage.

4.6. Cost Analysis

A cost analysis was performed on this FWS to estimate its potential to be commercialised and promoted in the market. Different scenarios were used for this analysis.

Case 1: No discounts received. The first case involved a scenario where no discounts or price reductions were available. Table 17 shows the material cost for each unit of FWS produced for case 1. Table 18 shows the fixed cost per month required to maintain the production. The selling price per unit was set as 450 MYR for this case, which was about 50% higher than the total material cost for a single unit.

Table 17. Material cost per unit (case 1).

Variable Cost Per Unit (Malaysian Ringgit, MYR)	
Wood	80
Steel	115
Slider	50
Hinge	45
Consumables (screws, lubricants, paint)	10
Total	300

Table 18. Fixed cost per month for production (case 1).

Fixed Cost Per Month (Malaysian Ringgit, MYR)	
Labour (3 technicians with wage of 2500 MYR per month)	7500
Maintenance of tools and equipment per month	1000
Total	8500

Figure 10 shows the break-even analysis graph for case 1. The break-even quantity was determined by the intersecting point between the total cost and sales line. The break-even point was observed to be at 57 units. Hence, in order to make profit for case 1, more than 57 units need to be sold per month.

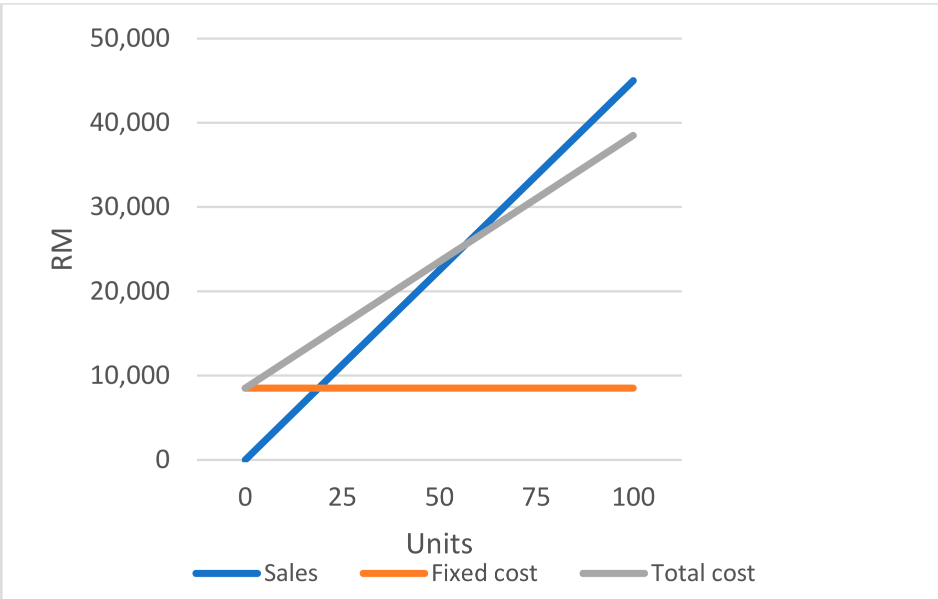


Figure 10. Break-even analysis graph for case 1.

Case 2: Reduced cost from bulk purchasing of materials. For this case, the materials were obtained from bulk purchasing. Hence, the overall cost would be much lower. The quality of these cheaper materials was assumed to be the same as the materials in case 1. Table 19 shows the material cost for a single unit of FWS produced for case 2. The fixed cost per month required to maintain the production was assumed to be the same as case 1. In this case, the selling price could also maintain at 450 MYR.

Table 19. Material cost per unit (case 2).

Variable Cost Per Unit (Malaysian Ringgit, MYR)	
Wood	60
Steel	85
Slider	35
Hinge	30
Consumables (screws, lubricants, paint)	5
Total	215

Figure 11 shows the break-even analysis graph for case 2. It was found that the break-even point was at 36 units. Therefore, in order to make profit for case 2, more than 36 units need to be sold per month.

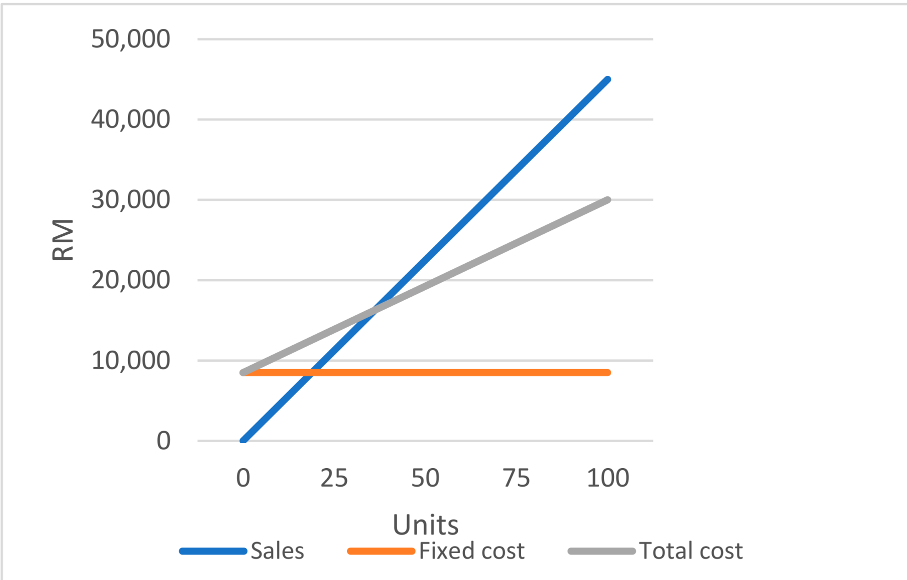


Figure 11. Break-even analysis graph for case 2.

Case 3: Increase the selling price while promoting the product. While placing emphasis on promoting the advantages of this product through advertisements, the selling price of this product could also be increased for higher profit. The material cost for a single unit of FWS produced was assumed to be the same as case 2. Since this case considers promotions, the selling price was estimated to be 50% higher than the original selling price in case 1 and 2. Therefore, the selling price could be set at 600 MYR. Table 20 shows the fixed cost per month required to maintain the production and advertisements.

Table 20. Fixed cost per month for production and advertisements (case 3).

Fixed Cost Per Month (Malaysian Ringgit, MYR)	
Labour (3 technicians with wage of 2500 MYR per month)	7500
Maintenance of tools and equipment per month	1000
Advertisements	2000
Total	10,500

Figure 12 shows the break-even analysis graph for case 3. The break-even point was observed to be at 27 units. Thus, in order to make profit for case 3, more than 27 units need to be sold per month.

Figure 12. Break-even analysis graph for case 3.

From the analysis, case 3 was concluded as the best-case scenario if the prototype were to undergo production, as it only required 27 units of sales to break-even. Every unit sold for the price of 600 MYR would then have a profit of 385 MYR. This price is considered reasonable seeing as the selling price of other similar stretcher variants is about 2000 MYR, which is much higher as compared to this FWS.

5. Conclusions

The primary objective of this study was to design and develop a foldable wheelchair stretcher conceptualised from a previous research. Upon completion of this project, several key findings were found. During the fabrication stage, it was found that several design changes were required. Hence, the initial design of the prototype should be made flexible to allow for future changes. For this purpose, methods such as DFMA or TRIZ could be used.

After analysing the test results, it was found that the weight of the stretcher very much affected its performance, since using a heavier FWS would delay the user in completing the task. In principle, simple designs are more user-friendly. With a much simpler design than the normal stretcher, the FWS was much easier to fold and unfold.

In conclusion, the FWS is around the third or fourth technology readiness level, and requires further experimentation and lab-scale validation to reach the level of an actual product. Nevertheless, this study is still useful since it uncovers ways for other researchers to adopt in improving the comfortability and usability of stretchers for better medical care. With an enhanced and commercial-ready FWS in the future, medical workers would be able to carry out their manual transportation duties with ease and prevent injuries to themselves and the patient.

5.1. Limitations of Study

One substantial limitation in the design aspect was the hinge used. During the first stage of the design, a type of hinge was identified to fit the design well. However, it was later found that it could only sustain a weight of approximately 2 kg. Therefore, another hinge was used, and a supporting bar had to be added into the design.

The next limitation involved the failure to perform the angle increment test. In association with the previous limitation, the supporting bar was secured to the hinge with fasteners and it was found to be unable to sustain a person's full body weight. While welding the parts together might have been able to solve this problem, there was not enough time left in the project to do so.

Another limitation involved the limitation in including professional medical workers as participants of the tests. Stretchers are mostly handled by professional medical personnel. However, the people participating in the test had almost no experience in EMS. Hence, the data collected might have differed from how it could have been with professional medical workers as participants.

5.2. Directions for Future Research

There are several possible directions for future research to extend from this study. One of them includes making the stretcher lighter in weight. The frame can be made with a lighter material, such as plastic. With some changes in the design, the wooden platform can be substituted with a soft platform, or possibly a thermoplastic spine board.

In order to improve the portability aspect, more folding features or mechanisms can be integrated into the design, making it at least similar to a 4-fold stretcher. This improvement would make it easier for the stretcher to be stored as it would occupy less space due to its reduction in size.

Furthermore, due to mobility and tourism development in the last decade, considering the anthropometric data of isolated communities for the stretcher design may be appropriate apart from the generic population data from Malaysia and Southeast Asia. Accommodating the design for remote, rural, poor and homeless communities for instance would allow for a more inclusive stretcher design to be developed.

Lastly, with a few additions to the current design, the FWS can have another function similar to a scoop stretcher's function. If the platforms are divided vertically by half and a hinge is added at the top of the frame, the medical person would be able to use the stretcher to scoop the patients up from the ground.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: This project contains the following underlying data: Data Availability Sheet.docx (dataset used for the analyses of Test 1, 2 and 3). The data can be found at Figshare: doi:10.6084/m9.figshare.14587881. Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

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