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ARTICLE

An Ergonomics Study and Rapid Upper Limb Assessments (RULA) for a Car Interior to Support Limb Disabled Drivers

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ABSTRACT

The demanding market shows that the need for the disabled vehicles have been increasing over the recent years. However, these factory setting cars are pricey, and its buy-sell process is time-consuming. These cars also are not meant as a universal design or inclusion design type of car, so that when it is designed for the disabled, it can be beneficial for all. With the motivation to include limbs disabled drivers in designing a universally designed car, this study aims to determine the preferred ergonomics interior of the car which can improve features needed to meet the mobility of impaired individuals in most scenarios. 5 simulations were carried out to simulate these conditions using the RULA analysis, in order to simulate the ergonomics impact on the manikin. In the final analysis, the simulations showed a virtuous score, which was between 1 and 2 for the newly redesigned interior, compared to the score of 3 to 6 for current cars. Another verification made, post questionnaire delineates positive responses upon the redesigned parts scoring 70%~90% level of ergonomics rated. Therefore, this research has set forth the necessity of redesigning a car interior and improved its ergonomic features extensively, specifically for lower limb and combined limb disabled drivers.

1. Introduction

Today, inclusive designs have become a key approach for reducing the impact on the disabled, who are impaired and have reduced functional capabilities [1]. It also reduces the exclusion of the disabled from product use by making it much more accessible and easy to use [2]. Understanding the users and knowing their needs and requirements are vitally important for the success of an inclusive design [3]. Having inclusive design touches in a product or environ-

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ment results in making it usable regardless of age, gender, or disability [4].

However, in spite of the need for more inclusive design practices, the industry is not that keen to adopt this method. The main barriers in adopting inclusive designs include technical complexities, time-cost effectiveness, lack of knowledge, lack of guidelines, lack of awareness, lack of motivation, and a lack of appropriate design [5,6]. As a result, the more a product's design evolves, the more time and cost it will take to develop [7].

The cost and complexity of accommodating disabled people can be substantial [8,9]. In general, the cost of retrofitting (or vehicle modification) can reach 4 to 5 digits. Only certain models of automobiles, for example, can have their floor lowered to accommodate wheelchair users. The vehicle must then be installed with equipment for specialist instruments, or driving controls by specialized vendor [8].

The ability to make vehicle modifications with greater flexibility is beneficial, but it comes at a cost [10]. It is also costly to iterate that during the alteration procedure. Furthermore, getting the modification procedure right the first time is crucial, especially for individuals who purchase a new vehicle. They may be stuck with the vehicle for a long time, and repeating the process is costly [11].

Having modifications or adaptive equipment are said to be a proven step in maintaining the on-the-road freedom for the disabled [12]. With adaptations, it meets the needs of the user in a different way as well, as well as allowing the disabled who cannot drive before, to drive much more easily and independently [13]. A relevant and easily adapted technique is needed to transform a personal in-market car to enable it to be accessible to mobility-impaired groups, so as to ensure that their traveling experiences will be much more user-friendly and ergonomic. With the motivation to include limbs disabled drivers in designing a car with a universal design, this study is expected to determine the preferred interior of the car which can improve features needed to meet the mobility of impaired individuals in most scenarios, to benefit them in terms of reducing cost, time, long processing times.

2. Materials and Methods

Table 1 illustrates the current design and redesigned parts. This design has undergone few steps for the selection and decision from a previous paper which covered review papers, questionnaires, TRIZ solution methods, and the necessary concept design processes to help prevent a trial and error approach in the design [14-16]. Figure 1 (Red box indicated current step as presented in this paper) showcases this. Each design considered the capability of the parts to be able to suit the variations in the size of the disabled. Therefore, it was designed to be extendable and movable to cater for upper limbs, lower limbs, and both limbs of the disabled.

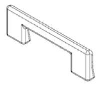
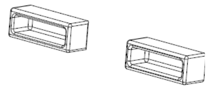
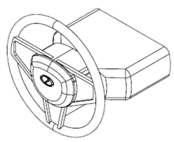
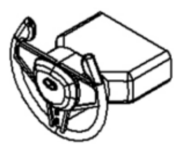
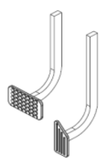
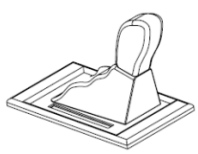
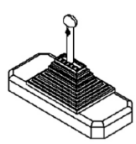
Current designs are based on a complete retracing of the original designed parts from the cockpit of the driver for a compact cars which is available on the market. It involved 8 highlighted parts, namely the handle (headliner), handle (door), steering, seat (upholstery bottom), seat (upholstery back), door, pedals, and gear knob. The redesigned parts involved parts that had undergone the process of conceptual design generation, development, and selection.

As discussed previously, with the generalization of the anthropometry of a disabled driver is virtually impossible due to the unique sizing and measurement of the limbs of the disabled. Consequently, this project adapted an average standard anthropometry from across the Malaysian population (Malays, Chinese, and Indians) in Malaysia [17].

Hence, the arithmetic mean or average of the male participant's height and weight were 172.02 cm and 67.35 kg. For the female participants, the average height and weight were 153.24 cm and 56.76 kg, respectively. Therefore, the final mean height and weight considered were 164.12 cm and 64.71 kg. Figure 3 shows the assigned dimensions in the standing position. In Figure 2(a) for height, and in Figure 2(b) for weight.

Figure 3 shows an example of the RULA analysis for a manikin in a driving position. A pop-up box on the right side in the figure lists the results of the analysis (right side of the box named Details), based on the selection (left side of the box named Parameters) of the driver's side, which lists the type of posture (static, intermittent, or repeated) and the checkbox of the driver's current posture, as well as the load the driver holds. For this study, the parameter analysis was set as an intermittent posture with a 0 kg load. Color codes as indicated in Figure 3 were based on the color associated with the score as shown in Figure 4, and the explanations of the scoring in Table 2.

Table 1. Current design versus Redesigned

Parts		Current Design	Redesigned
i	**Handle** (headliner)		
ii	**Handle** (door)	 Manual opening door (80degree opening)	 Sliding door
iii	**Door** (Ingress/ Egress)		
iv	**Seat** (upholstery back)		 Extra cushion attached on upholstery back and bottom
v	**Seat** (upholstery back)		
vi	**Steering**	 Movable steering (up and down - 2cm only)	 Movable steering (up and down, right and left, front and back)
vii	**Pedals**	 Fixed pedals.	 Combined brake & accelerator pedal, movable pedals (up and down, right and left, front and back)
viii	**Gear Knob**	 Fixed gear knob.	 Movable gear plate (up and down, right and left) Movable gear shaft (up and down)

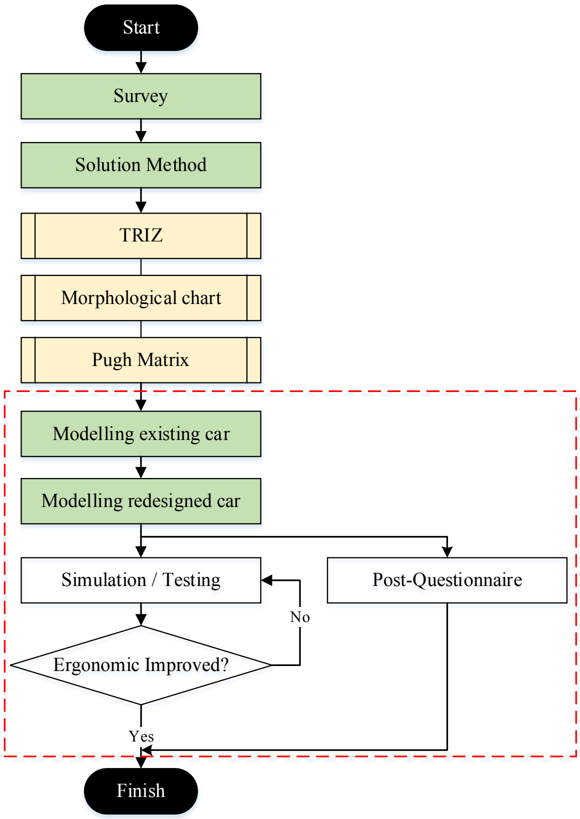
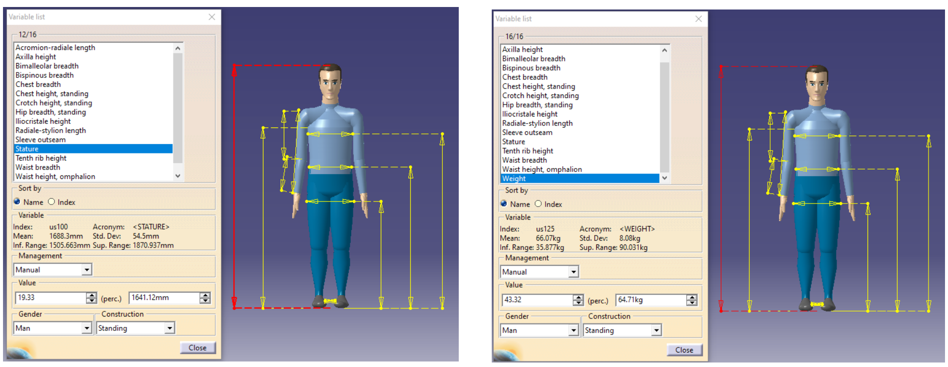


Figure 1. Process Flow



(a) **(b)**

Figure 2. (a). Manikin dimension (height); **(b).** Manikin dimension (weight)

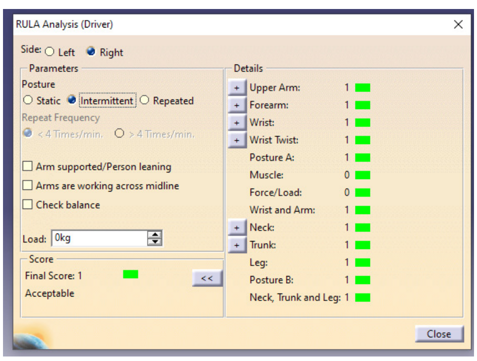


Figure 3. RULA analysis example

Segment	Score Range	Color associated to the score					
		1	2	3	4	5	6
Upper arm	1 to 6						
Forearm	1 to 3						
Wrist	1 to 4						
Wrist twist	1 to 2						
Neck	1 to 6						
Trunk	1 to 6						

Figure 4. RULA Score Range

The RULA analysis examined the following risk factors: number of movements, static muscle work, force, working posture, and time worked without a break. All these factors combined to provide a final score which ranged from 1 to 7, as mapped in Table 2.

Table 2. RULA scoring details

Score	Color	Risk level and details	
1,2		Negligible risk	No action required. Posture is acceptable if it is not maintained or repeated for long periods of time.
3, 4		Low risk	Indicates that further investigation is needed and changes may be required.
5,6		Medium risk	Indicates that investigation and changes are required soon
7,8		High risk	Indicates that investigation and changes are required immediately.

As pictured in Figure 1, besides the simulation, a simultaneous post questionnaire was also carried out. The post-questionnaire proved to be an effective assessment and feedback tool [18]. It also worked as a platform for gathering and recording data on certain topics of interest based on earlier works (questionnaire) [18]. In this study, post-questionnaires act as verification aid to strengthen the verification made using CATiA. It was answered by disabled drivers with the same criteria from the questionnaire. A technical briefing will be made to demonstrate work done on the redesigned process. Figure 5 depicts the questionnaire's focus area.

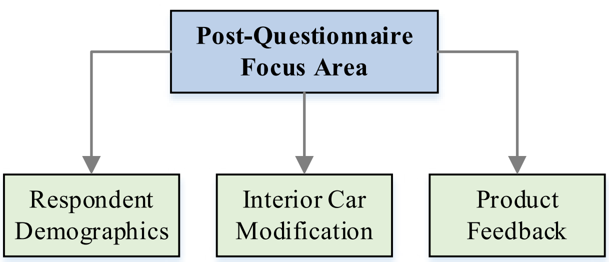


Figure 5. Post-Questionnaire focus area

3. Results and Discussions

There were five positions for the RULA testing, as illustrated in Table 3 to Table 7. The positions covered the involvement and usage of certain parts of the listed components. Each table consisted of two parts, namely the current design and redesigned part. All tests analyzed the right and left body parts individually based on the selection in the checkbox.

As shown in Figure 4 of the RULA score sheet, the scores and colors were used to determine the outcome of the RULA analysis. The color was auto-generated in the RULA Analysis using CATIA, which was intertwined. There were seven different scores and four different colors. Green, yellow, orange, and red were the primary colors. The green hue signified a healthy posture, whereas the red color indicated a poor posture which had to be corrected quickly. For example, score 3 for the upper arm gave a yellow color, while score 3 for the arm gave a red color.

Position 1 involved both hands of the manikin holding the steering wheel. Table 3 presents the results of the RULA analysis for the first position. This table clearly shows that the manikin driving the current car design experienced high impact on its legs and medium impact on its arms. The position recorded a final score of 5 for the right side, and 6 for the left side based on the RULA scoring recommendations. Thus, further investigation is needed, and changes need to be carried out. Despite the manikin being positioned at its best posture, it still experienced impact on certain parts. Unlike the current design, the manikin in the redesigned car interior had a better environment as shown in the results (Final score =1, color score =green; for both sides), because the redesigned parts were adjustable. Therefore, the seat, steering wheel, and pedals were adjusted accordingly to achieve the best positioning.

Position 2 depicts the right hand holding the steering wheel, and the left hand holding the gear. The right hand maneuvering the steering wheel and the left hand handling the gear is another common position for a driver. Similar to Table 3, Table 4 highlighted that the driver had a negative impact, as the driver tried hard to reach the gear knob, resulting in the final score of 6. Positive scoring recorded in the redesigned position 3 setup resulted in a final score =1 and 2, and a color score =green for both sides.

Position 3 depicts the driver opening the door from the inside (egress). Table 5 indicates the results for the egress positioning. The manikin is trying to exit the car by opening the door manually. The wrist posture is twisted to the maximum degree, contributing to the final score of 6. Thus, further changes need to be made. Nevertheless, for the redesigned egress, the manikin only needs to press a button at the steering wheel, as illustrated in Figure 6, to automatically open the door (Final score =1, colour score = green; for both sides).

Position 4 depicts the manikin closing the door from the inside (ingress). The driver faces much more significant issues for the ingress, including reach, force, and pressure problems. Table 6 indicates a final score of 6 for

Table 3. RULA analysis scores for both hands holding the steering wheel

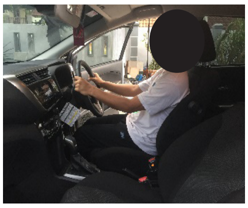
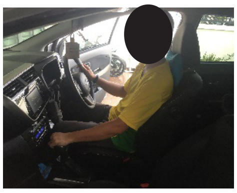
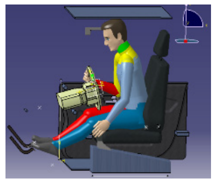
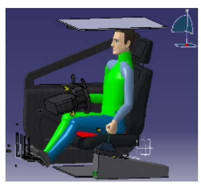
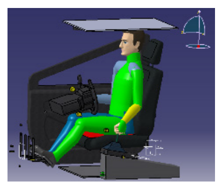
CURRENT DESIGN			
		Right body 	Left body 
1.	Upper Arm	3	3
2.	Forearm	2	2
3.	Wrist	3	4
4.	Wrist Twist	2	2
5.	Posture A	4	5
6.	Muscle	1	1
7.	Force/Load	0	0
8.	Wrist and Arm	5	6
9.	Neck	1	1
10.	Trunk	2	2
11.	Leg	2	2
12.	Posture B	3	3
13.	Neck, Trunk, and Leg	4	4
14.	Final Score	5	6
REDESIGNED			
Criteria		Right body 	Left body 
1.	Upper Arm	1	1
2.	Forearm	1	1
3.	Wrist	1	1
4.	Wrist Twist	1	1
5.	Posture A	1	1
6.	Muscle	0	0
7.	Force/Load	0	0
8.	Wrist and Arm	1	1
9.	Neck	1	1
10.	Trunk	1	1
11.	Leg	1	1
12.	Posture B	1	1
13.	Neck, Trunk, and Leg	1	1
14.	Final Score	1	1

Table 4. RULA analysis scores for the right hand holding the steering wheel and the left hand holding the gear

	CURRENT DESIGN		
		Right body 	Left body 
1.	Upper Arm	4	4
2.	Forearm	3	3
3.	Wrist	3	2
4.	Wrist Twist	2	2
5.	Posture A	5	5
6.	Muscle	1	1
7.	Force/Load	0	0
8.	Wrist and Arm	6	6
9.	Neck	1	1
10.	Trunk	3	3
11.	Leg	2	2
12.	Posture B	4	4
13.	Neck, Trunk, and Leg	5	5
14.	Final Score	6	6
	REDESIGNED		
Criteria		Right body 	Left body 
1.	Upper Arm	1	1
2.	Forearm	1	2
3.	Wrist	1	1
4.	Wrist Twist	1	1
5.	Posture A	1	2
6.	Muscle	0	0
7.	Force/Load	0	0
8.	Wrist and Arm	1	2
9.	Neck	1	1
10.	Trunk	1	1
11.	Leg	1	1
12.	Posture B	1	1
13.	Neck, Trunk, and Leg	1	1
14.	Final Score	1	2

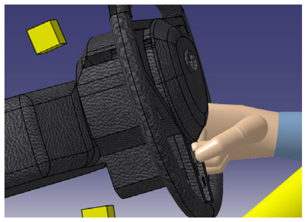
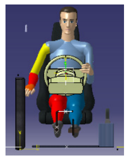


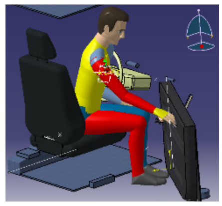
Figure 6. Automatic door button located at the steering wheel

Table 5. RULA analysis scores for opening the door from the inside (egress)

CURRENT DESIGN			
		Right body 	Left body 
1.	Upper Arm	3	3
2.	Forearm	2	2
3.	Wrist	3	4
4.	Wrist Twist	2	2
5.	Posture A	4	5
6.	Muscle	1	1
7.	Force/Load	0	0
8.	Wrist and Arm	5	6
9.	Neck	1	1
10.	Trunk	2	2
11.	Leg	2	2
12.	Posture B	3	3
13.	Neck, Trunk, and Leg	4	4
14.	Final Score	6	6
REDESIGNED			
Criteria		Right body 	Left body 
1.	Upper Arm	1	1
2.	Forearm	1	2
3.	Wrist	1	1
4.	Wrist Twist	1	1
5.	Posture A	1	2
6.	Muscle	0	0
7.	Force/Load	0	0
8.	Wrist and Arm	1	2
9.	Neck	1	1
10.	Trunk	1	1
11.	Leg	1	1
12.	Posture B	1	1
13.	Neck, Trunk, and Leg	1	1
14.	Final Score	1	2

the left body, and 4 for the right body of the current design, and a final score of 1 for both left and right body of the redesigned model. For the redesigned Position 3 and Position 4, it resulted in the same score, as these two positions only allowed the manikin to use an automatic button (Final score =1, colour score =green for both sides).

Table 6. RULA analysis scores for closing the door from the inside (ingress)

CURRENT DESIGN			
		Right body 	Left body 
1.	Upper Arm	5	3
2.	Forearm	3	2
3.	Wrist	2	2
4.	Wrist Twist	2	2
5.	Posture A	7	4
6.	Muscle	0	0
7.	Force/Load	0	0
8.	Wrist and Arm	7	4
9.	Neck	1	1
10.	Trunk	3	3
11.	Leg	2	2
12.	Posture B	4	4
13.	Neck, Trunk, and Leg	4	4
14.	Final Score	6	4
REDESIGNED			
Criteria		Right body 	Left body 
1.	Upper Arm	1	1
2.	Forearm	1	2
3.	Wrist	1	1
4.	Wrist Twist	1	2
5.	Posture A	1	0
6.	Muscle	0	0
7.	Force/Load	0	0
8.	Wrist and Arm	1	2
9.	Neck	1	1
10.	Trunk	1	1
11.	Leg	1	1
12.	Posture B	1	1
13.	Neck, Trunk, and Leg	1	1
14.	Final Score	1	1

Position 5 depicts the manikin standing with the support of the handle (headliner). The headliner handle is essential as a support system for the disabled, especially for lifting their body to exit the car. Table 7 presents the results of using the current design versus the redesigned handle at the headliner. The final score after further investigation only recorded one medium risk recommendation for the left body of the current design. This was due to the RULA rules, whereby if the manikin was forced to lift an arm from 45° to 60°, it would result in a +3 (colour

Table 7. RULA analysis scores for standing with the support of the handle (headliner)

CURRENT DESIGN			
		**Right** 	**Left body** 
1.	Upper Arm	2	5
2.	Forearm	1	2
3.	Wrist	1	3
4.	Wrist Twist	1	2
5.	Posture A	2	7
6.	Muscle	0	0
7.	Force/Load	0	0
8.	Wrist and Arm	3	7
9.	Neck	1	1
10.	Trunk	1	1
11.	Leg	1	1
12.	Posture B	1	1
13.	Neck, Trunk, and Leg	2	1
14.	Final Score	3	5
REDESIGNED			
Criteria		Right body 	Left body 
1.	Upper Arm	3	3
2.	Forearm	1	1
3.	Wrist	1	1
4.	Wrist Twist	1	1
5.	Posture A	3	3
6.	Muscle	0	0
7.	Force/Load	0	0
8.	Wrist and Arm	3	3
9.	Neck	1	1
10.	Trunk	1	1
11.	Leg	1	1
12.	Posture B	1	1
13.	Neck, Trunk, and Leg	1	1
14.	Final Score	3	3

score =green for both sides) on the scoreboards.

A total of 10 respondents responded to the post questionnaire. Technical presentations were given to the respondents on the study flow, solution methods used, and redesigns made to comprehensively explain the studies before the questionnaire was answered. Figure 7 shows a balanced gender involvement, with men at 50% and women also at 50% in terms of contributions. All respondents were volunteers who were licensed independent disabled drivers with lower limbs and combined limbs disability. They were also working and driving to the workplace as part of their primary daily routine.

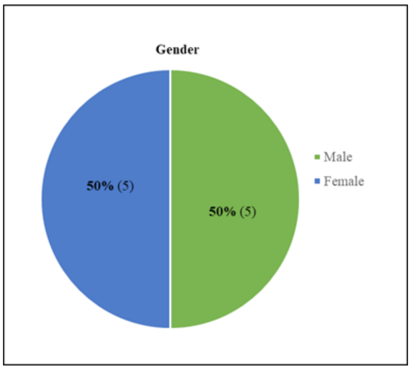


Figure 7. Gender

The Likert scale was used to cater for the level of the score in post questionnaire. However, the post questionnaire only compared responses on the ergonomics scoring for the current interior versus redesigned interior. Table 8 shows the results for the level of ergonomics scoring form key, in which it uses the top two box (T2B) method. The key combination indicator is listed below:

Ergonomic = (Very ergonomics + Ergonomics)

Not ergonomics = (Neutral+ Less ergonomics + Not ergonomics)

From Table 8, it is clearly shown that respondents found that driving the current car without modification was less ergonomic and not ergonomic for disabled drivers with a 70%~90% score. A similar question was asked to rate the level of ergonomics controls in the redesigned car as shown in 9. In the top two box percentage analyses as summarized in Table 9, it is shown that a 70%~90% score fell under the ergonomics column. It showed a positive feedback toward newly redesigned features.

Additionally, positive feedback with a 100% 'yes' was recorded for all questions in the Product Feedback section. It showed an acceptance and support towards the improvement introduced, as summarized in Table 10.

Table 8. How do you find level of ergonomics in following controls in current vehicle?

Answer Option		Ergonomics (%)	Not ergonomics (%)
Pedals	Most	30.0	70.0
Gear knob	↓	30.0	70.0
Seat (upholstery back)		30.0	70.0
Handle (headliner)		30.0	70.0
Handle (door)		20.0	80.0
Seat (upholstery bottom)		20.0	80.0
Door		10.0	90.0
Steering	Least	10.0	90.0

Table 9. How do you find level of ergonomics in following controls in redesigned vehicle?

Answer Option		Ergonomics (%)	Not ergonomics (%)
Handle (door)	Most	90.0	10.0
Handle (headliner)	↓	90.0	10.0
Seat (upholstery back)		90.0	10.0
Seat (upholstery bottom)		80.0	20.0
Steering		80.0	20.0
Door		80.0	20.0
Gear knob		70.0	30.0
Pedal	Least	70.0	30.0

Table 10. Customer feedback section

Questions	Percentage (%)	
	Yes	No
Do you think our product is easy to use?	100	0
Do you think features of our product are important to limbs disabled drivers?	100	0
Do you think features of our product are usable for normal driver?	100	0
Do you think features of our product could improve drivers' ergonomics?	100	0
Are you happy if our product will be in market in future?	100	0
Do you think our product is good?	100	0
Would you recommend our product to a friend or colleague?	100	0

4. Discussion

Table 11 summarizes the verification results for RULA by comparing the current design and the redesigned model. The final three columns indicate improved, same, or worsen outcomes, allowing a clear comparison of the results. From all 5 positions sets for the human model, all captured an improvements of RULA scores except of position 5, right body which carries the same score before and after. This is due to similar RULA scores for both position in before and after redesign of interior.

Also, Table 12 compared the space (in respective dimensions or direction) of the current design and the redesigned parts based on the extendibility, movability, and usability of the parts.

Table 11. Summary of the results for human analysis verification

Analysis	Model	Current Design		Redesigned		Improved	Same	Worsen
		Right Body	Left Body	Right Body	Left Body			
RULA	Position 1	5	6	1	1			
	Position 2	6	6	1	2			
	Position 3	6	6	1	1			
	Position 4	6	4	1	1			
	Position 5	3	5	3	3			

Table 12. Space comparison

Part		Dimension/ Direction	Current Design (mm)	Redesigned (mm)	Improved	Same	Worsen
i	**Handle** (headliner)	X	20.60 (holder)	50.00 (outer) 47.63 (inner)			
		Y	205.00 (outer) 115.00 (inner)	410.00 (outer) 110.00 (inner)			
ii	**Handle** (door)	Reach (min)	398.45	140.95			
iii	**Door** (Ingress/ Egress)	Y	n/a	1254.73 (front/back)			
		Angle (°)	80.00	n/a			
iv	**Seat** (upholstery back)	Y	150.00 (front/back)	400.00 (front/back)			
v	**Seat** (upholstery back)	Z	30.00 (up) 30.00 (down)	50.00 (up) 50.00 (down)			
vi	**Steering**	X	n/a	100.00 (right/left)			
		Y	n/a	50.00 (front) 100.00 (back)			
		Z	20.00 (up) 20.00 (down)	80.00 (up/down)			
vii	**Pedals**	X	n/a	160.00 (right/left)			
		Y	n/a	160.00 (front/back)			
		Z	n/a	350.00 (up/down)			
viii	**Gear Knob**	X	n/a	100.00 (right/left)			
		Y	n/a	100.00 (front/back)			
		Z	n/a	70.00 (up/down)			

5. Conclusions

Conclusively, the results from the questionnaire conducted in the previous study among Malaysian limb disabled drivers concluded that certain major changes were needed to redesign the interior part of the driver's area in order to achieve an ergonomically friendly car for limb disabled drivers, at the same time adaptable to be used by other users without raising other ergonomic issues. This included handles at the door and surrounding area, pedals, egress, upholstery (back), and upholstery (bottom). With that, the TRIZ, morphological chart, and Pugh matrix were used as conceptual design frames, solution methods, and decision making tools to resolve problems which arose.

In this paper, a redesign of an interior compact car for limbs disabled drivers was presented. By applying CAD in the design and verification of the study, it reduced the tendency of repetitive reworks and reengineered the future, as it showed valid calculations and imitated the design closely. Hence, this study showed that an improvement was made by comparing the ergonomics aspects of the current design, and the redesigned model based on the compilation of both postures (position 1-5) using the RULA scores in CATIA. Another verification was made (sequel verification of this study) via post questionnaires which delineated the positive responses for the redesigned parts. Experts favoured five out of six proposed redesigned parts for the improvement of the mobility of the limbs of the disabled drivers.

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Conflict of Interest

The authors declare no conflicts of interest.

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