Design of Locomotive Lower Limb Exoskeleton with Malaysian Anthropometric Characteristics

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***Abstract*—The lower limb exoskeleton (LLE) is a device used to assist paraplegics in regaining their ability to walk. The LLE is capable of providing paraplegics with a better degree of locomotion than a wheelchair. However, in LLE design, size is a critical issue that needs to be considered. The LLE should be small in package, compact, and portable. Therefore, this study presents a strategy to solve the issue with dimensions in LLE design to match the Malaysian anthropometric characteristics. The TRIZ (Russian acronym for "Teoriya Resheniya Izobreatatelskikh Zadatch") inventive principle method is used to generate the ideas discussed in this study. As a result, adjustable LLE designs that match the Malaysian anthropometric characteristics were developed, where the critical dimensions for LLE were obtained from previous anthropometric research in Malaysia.**

***Index Terms*—innovative design, lower limb exoskeleton, Pugh's total design process, product design specifications, TRIZ**

I. Introduction

The spinal cord is a bundle of nerves that carries motor and sensory information between the brain and the rest of the body. Injury can occur at any part of the spinal cord or nerves that can result in loss of or impaired function, which in turn reduces mobility or feeling. The literature has presented several causes of spinal cord injury (SCI) [1]. SCI can be divided into two categories, namely, trauma and nontrauma. The main cause of trauma is automobile accidents, followed by falls, gunshot wounds, motorcycle crashes, and driving incidents. Nontrauma is caused by ailments, such as cancer, tumor, tuberculosis, infection, and degenerative diseases, and the aging process.

A Malaysian epidemiological study conducted by Ibrahim et al. [2], from 2006 to 2009, showed that 57.2% of SCI was the result of traumatic causes, whereas 42.8% of SCI was the result of nontraumatic causes. This study also showed that 37% of the recorded cases was classified as quadriplegia, whereas the remaining 63% of the recorded cases was classified as paraplegia. Quadriplegia involves the loss of movement and sensation in all four limbs (arms and legs), whereas paraplegia involves the loss of movement and sensation in the lower half of the body (right and left legs) [3].

Patients suffering from paraplegia would lose mobility or would not be able to walk normally. Impaired mobility would significantly reduce the quality of life and increase the risk for secondary medical consequences, such as osteoporosis, muscle atrophy, obesity, and coronary heart disease [4]. Locomotive lower limb exoskeleton (LLE) is the most effective solution to assist paraplegics in regaining their ability to walk. The LLE provides paraplegics with a better degree of locomotion than a wheelchair, allowing them to regain their locomotive capability or recover their gait [5] and reduce the occurrences of secondary complications. Additionally, the LLE can provide movement assistance in daily activities.

LLE, such as WSE [6], BLERE [7], ATLAS [8], and Mina [9], was developed to help patients perform movements, such as walking, standing up, sitting, and walking up and down the stairs. However, the LLE is still in the research stage. Recently, LLE, such as Indego [10], ReWalk [11], Ekso [12], and HAL for Living Support [13], has been commercialized and used by patients in the society. Previous studies showed that many criteria are considered by users when they intend to use LLE. Size is a critical issue in LLE development as it should be compact and portable for ease of use. Thus, the structure of an LLE should be based on male and female anthropometric features. However, covering all dimensions and properties that match anthropometric characteristics is difficulty.

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Therefore, this study presents a strategy to solve the issue with dimensions in LLE design to match the Malaysian anthropometric characteristics. TRIZ (Russian acronym for "Teoriya Resheniya Izobreatatelskikh Zadatch") is equivalent to the theory of inventive problem solving [14], which was applied to generate this idea. Finally, a design that matches the Malaysian anthropometric characteristics was achieved.

II. TRIZ Method

TRIZ is the theory of inventive problem solving or, in other words, a systematic and algorithmic approach to creativity based on logic, data, and research rather than through intuition or spontaneity. TRIZ was developed in Russia in the late 1940s by Genrich Altshuller. The TRIZ inventive principles were abstracted from 40,000 patterns. On the basis of these patterns, Altshuller summarized 1,201 standard engineering problems called contradictions. Hence, 40 fundamental solutions called inventive principles were developed [15].

In TRIZ, at least 12 techniques can be used in idea generation [16]. Among these techniques are the TRIZ inventive principles, which were used in previous work [14]. Fig. 1 shows the general process of problem or conflict solving using the TRIZ inventive principles.

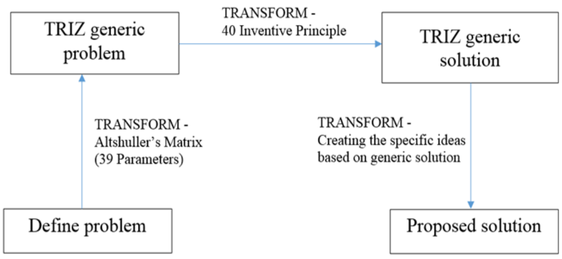


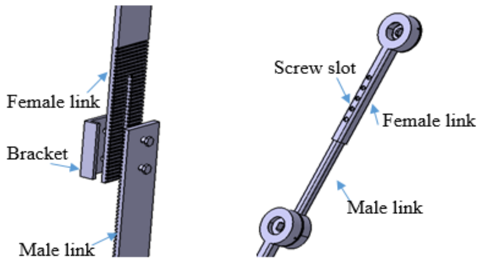
Figure 1. General process of the TRIZ inventive principles

The inventive principles start with improving any characteristic (called specific improvement factor) that causes the worsening of another characteristic (called specific worsening factor). These characteristics can be described as contradictions, which correspond to the definition of the generic problem. The 40 inventive principles were used to remove the contradictions that exist in the system. Therefore, 39 parameters were extracted to describe all contradictions in the invention or patterns.

The contradictions in the invention were solved by linking two contradiction parameters using Altshuller's matrix. The specific worsening factor had precise TRIZ inventive principle solutions. Hence, the 40 TRIZ inventive principles generated solutions as a universal principle of the invention to overcome the contradiction parameters that emerged [17]. Finally, specific ideas for the contradictions were proposed on the basis of the universal principle from TRIZ-generated solutions.

III. Design Methodology

As discussed previously, this study presents a strategy to solve the issue with dimensions in LLE design to match the Malaysian anthropometric characteristics. The TRIZ engineering parameter related to the improvement factor was described as inventive principle 4—length of a stationary object, whereas that related to the worsening factor was described as inventive principle 36—device complexity. The suggestions in the TRIZ contradiction matrix led to inventive principles 1 and 26. The analysis of inventive principle 1—segmentation led to the development of an adjustable structure based on human anthropometric features to match human limbs. Two conceptual designs were proposed. The first conceptual design (shown in Fig. 2(a)) uses a link plate, which consists of three main parts, namely, male and female links and bracket. A slot on the connecting link between male and female links can be adjusted based on the size of the user's limb. The second conceptual design (shown in Fig. 2(b)) consists of male and female rod bars as the main LLE structure. This structure has slots and two links that are fixed using screws to link them together. Additionally, inventive principle 1—segmentation also suggested that if the adjustable link did not cover all dimensions of human anthropometric features, then the group size should be considered. Furthermore, the design was targeted to be simple and easy to assemble and disassemble. Inventive principle 26—copying led to the solution that all of the adjustable link sizes use the same concept to look structurally uniform.



(a) (b)

Figure 2. Flexible link joint (a) using a link plate and (b) using a rod bar

IV. Dimensions of the LLE Design

The dimensions of the LLE design were obtained from the standard properties of Malaysian male and female anthropometrics as reported by Nor et al. [18], Karmegam et al. [19], S. Dawal et al. [20], Dawal et al. [21], D. Mohamad et al. [22], and Rosnah et al. [23]. The potential limb dimensions for LLE are illustrated in detail in Fig. 3, and the anthropometric data collected are shown in Table I. The design considers a population between the ages of 20 and 70 years old with the minimum of 5th percentile (male and female) and maximum of 95th percentile (male and female) of the anthropometric data extracted. On the basis of the anthropometric data, the related limb dimensions for Malaysian LLE are illustrated in detail in Fig. 4, and the design features for Malaysian LLE are developed through the formulations shown in Table II. Finally, the detailed dimensions of LLE based on Malaysian anthropometric characteristics are shown in Fig. 5.

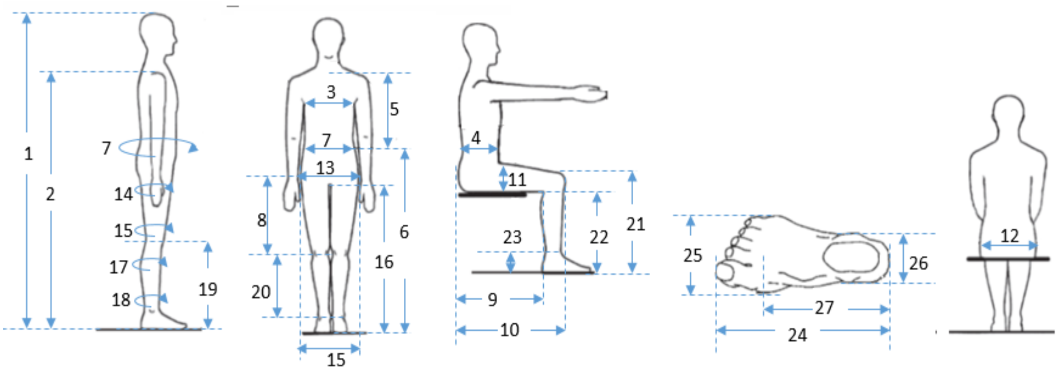


Figure 3. Limb measurements obtained from Nor et al. [18], Karmegam et al. [19], S. Dawal et al. [20], Dawal et al. [21], D. Mohamad et al. [22], and Rosnah et al. [23]

TABLE I. THE MAXIMUM–MINIMUM, MINIMUM 5TH PERCENTILE (MALE OR FEMALE), AND MAXIMUM 95TH PERCENTILE (MALE OR FEMALE) ANTHROPOMETRIC DATA FOR MALAYSIANS.

No.	Dimension	Nor et al. [18]		Karmegam et al. [19]		S. Dawal et al. [20]		Dawal et al. [21]		D. Mohamad et al. [22]		Rosnah et al. [23]		Design Consideration	
		N = 100 Aged: 20–90		*N* = 1,032 Aged: 18–24		*N* = 143 Aged: 17–28		*N* = 107 Aged: 55–70		*N* = 1,216 Aged: 15–80		*N* = 230 Aged: 60–84			
		Min	Max	Min 5P	Max 95P	Min 5P	Max 95P	Min 5P	Max 95P	Min 5P	Max 95P	Min 5P	Max 95P	Min	Max
–	Weight (kg)			41.00	99.00	41.63	95.00	32.71	99.50	13.59	142.25	35.8	85.0		142.25
1	Stature	140	186	146.49	178.34	150.38	179.10	134.97	169.95	149.43	177.87	138.2	172.6	134.97	179.10
2	Shoulder height, standing			119.70	150.00			109.62	142.15	118.50	150.36	111.9	143.1	109.62	150.36
	Shoulder height, sitting			44.49	61.42	48.58	67.24	45.48	94.23			43.1	62.3	43.1	94.23
3	Chest breadth									25.5	42.17			25.5	42.17
4	Abdominal depth, sitting			13.50	27.60									13.50	27.60
5	Back waist length					32.92	53.55	34.49	53.88					32.92	53.88
6	Waist height, standing							78.00	98.26	56.82	137.82	81.7	103.3	56.82	137.82
7	Waist circumference							67.62	115.62	56.68	100.28			56.68	115.62
8	Thigh length	35.4	54.0											35.4	54.0
9	Buttock–popliteal length (seat depth)			40.30	54.40	34.27	49.71	36.60	49.00	38.40	54.14	37.7	50.5	34.27	54.40
10	Buttock to front knee length (sitting)			48.30	65.82	46.65	59.94	40.40	57.47			47.4	58.6	40.40	65.82
11	Thigh clearance			9.99	19.30			8.00	17.4	11.06	26.12	8.6	18.3	8.00	26.12
12	Hip breadth, sitting					25.69	40.91	29.06	51.93	26.23	48.26	27.3	40.4	25.69	51.93
13	Hip breadth, standing			26.49	39.00			27.41	38.22					26.49	39.00
14	Hip circumference							72.81	126.09					72.81	126.09
15	Lower thigh circumference							31.82	53.60	40.76	63.17			31.82	63.17

TABLE I. CONTINUE. THE MINIMUM 5TH PERCENTILE (MALE OR FEMALE) AND MAXIMUM 95TH PERCENTILE (MALE OR FEMALE) ANTHROPOMETRIC DATA FOR MALAYSIANS (MALE AND FEMALE).

No.	Dimension	Nor et al. [18]		Karmegam et al. [19]		S. Dawal et al. [20]		Dawal et al. [21]		D. Mohamad et al. [22]		Rosnah et al. [23]		Design Consideration	
		N = 100 Aged: 20–90		*N* = 1,032 Aged: 18–24		*N* = 143 Aged: 17–28		*N* = 107 Aged: 55–70		*N* = 1,216 Aged: 15–80		*N* = 230 Aged: 60–84			
		Min	Min	Min 5P	Max 95P	Min 5P	Max 95P	Min 5P	Max 95P	Min 5P	Max 95P	Min 5P	Max 95P	Min 5P	Max 95P
16	Crotch height, standing							57.50	78.37	62.45	99.40	60.4	77.6	57.50	99.40
17	Calf circumference							26.03	40.71	27.75	43.78			26.03	43.78
18	Ankle circumference							18.72	27.95					18.72	27.95
19	Knee height, standing	38.8	56.4					35.29	53.43	37.16	55.90	40.1	56.6	35.29	56.6
20	Knee to ankle (shank) height	33.4	49.7											33.4	49.7
21	Knee height (sitting)					39.73	57.18	21.71	54.39	37.58	61.44	41.3	54.8	21.71	61.44
22	Popliteal tendon height			34.4	44.00	33.83	47.07	38.20	52.82	37.48	50.21	33.9	43.1	33.83	50.21
23	Foot height	3.2	10.6					4.80	9.98					3.2	10.6
24	Foot length	20.1	28.0	20.1	26.90			19.52	25.80	19.73	28.71	20.1	26.8	19.52	28.71
25	Foot breadth	7.4	10.5	7.20	10.60			7.70	10.95			7.8	11.2	7.2	11.2
26	Heel breadth							4.50	7.00			5.3	7.6	4.50	7.6
27	Instep length							13.33	19.90			14.4	20.6	13.33	20.6

Note: All units in centimeters (cm)
P = Percentile

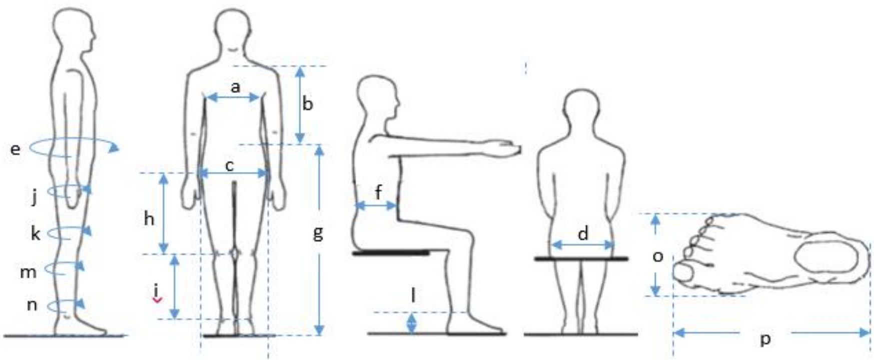


Figure 4. Related anthropometric measurements for Malaysian LLE

TABLE II. THE MALAYSIAN LLE DIMENSIONS, MINIMUM 5TH PERCENTILE (MALE AND FEMALE), AND MAXIMUM 95TH PERCENTILE (MALE AND FEMALE) ANTHROPOMETRIC DATA.

LLE dimensions (Refer to Fig. 5)	LLE part description	Anthropometric measurement (refer to Table I)	Description (dimension number, refer to Fig. 3)	Anthropometric dimensions (from Table I)		Malaysian LLE dimensions	
				Min (5P)	Max (95P)	Min (5P)	Max (95P)
A	Power supply and controller box size	Back waist length × chest breadth	a × b	25.5 × 32.92	–	–	20 × 25
B	Back waist with adjustable length	Hip breadth (standing)	c	26.49	39.00	25	52
		Hip breadth (sitting)	D	25.69	51.93		
C	Waist fastener	Waist circumference	e	56.68	115.62	56	116
D	Left- and right-side waist lengths	Abdominal depth, sitting	f	13.50	27.60	10	–
		Middle point of 95P to 5P of abdominal depth, sitting	(f(5P)/2 + f(95P)/2)/2	10.28	-		
E	Waist–hip length	Difference between waist height—standing and hip joint height (thigh length + shank length + foot height)	g − (h + i + l)	–	23.52	–	23
F	Exoskeleton thigh length	Thigh length	h	35.4	54.0	35	55
G	Exoskeleton shank length	Difference between knee height (standing) and foot height	i	33.4	49.7	30	50
H	Upper hip fastener circumference	Hip circumference	j	72.81	126.09	71	127
I	Lower hip fastener circumference	Lower thigh circumference	k	31.82	63.17	30	64
J	Ankle link (height)	Foot height	l	3.2	10.6	3	11
K	Upper calf fastener circumference	Calf circumference	m	26.03	43.78	25	44
L	Lower calf fastener circumference	Ankle circumference	n	18.72	27.95	18	30
M	Shoe sole breadth	Foot breadth	o	–	11.2	–	12
N	Shoe sole length	Foot length	p	–	28.78	–	30

Note: All units in centimeters (cm)
P = Percentile

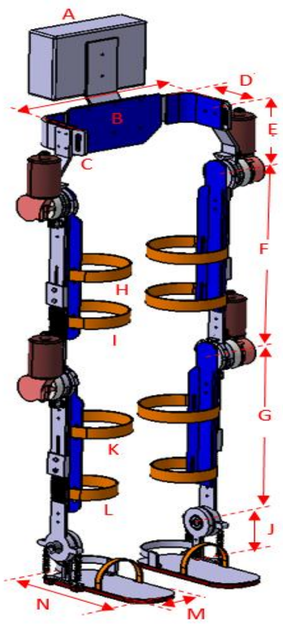


Figure 5. The LLE with Malaysian anthropometric dimensions

V. CONCLUSIONS

This study presented a strategy to solve the issue with dimensions in LLE design to match the Malaysian anthropometric characteristics. The use of TRIZ to generate a problem solution can help designers or inventors design LLE and come up with ideas in a short time. The conceptual design was developed with the Malaysian anthropometric characteristics, where the critical design dimensions for the LLE were obtained from the anthropometric dimensions of previous research conducted in Malaysia. The anthropometric dimensions were an important guide before proceeding to the detailed design concept to ensure that the LLE can be adapted to suit the majority of Malaysian users (the 5th percentile to the 99th percentile).

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