SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Applied Mechanics

Journal homepage: https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

Evaluation of Assembly Time of Motorized Wheel Module for Hospital Bed using Boothroyd-Dewhurst Method

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ARTICLE INFO

Article history:
Received 11 April 2023
Received in revised form 15 June 2023
Accepted 23 June 2023
Available online 7 July 2023

Keywords:
Design for assembly; Boothroyd-Dewhurst; motorized wheel; hospital bed; assembly efficiency

ABSTRACT

Patient transfer using hospital beds often takes time and is inefficient. This activity also has negative impacts on the health of healthcare workers, such as musculoskeletal injuries. Our group of researchers previously developed a swerve drive motor wheel module, which will be implemented on existing hospital beds. The manual assembly process of the swerve drive wheel module presents its own challenges, especially in terms of manual assembly time. The time required to manually assemble the swerve drive wheel module can be evaluated through the Design for Assembly (DFA) approach using the Boothroyd-Dewhurst method. The previously designed swerve drive wheel module will be compared with an improved design based on this method, where the number of parts to be assembled is minimized. The manual assembly time for the swerve drive wheel module has been shown to decrease after the design improvement. In the previous design, the estimated manual assembly time was 1051.54 seconds, while in the improved design, the manual assembly time was 647.47 seconds, with manual assembly efficiencies of 5% and 9%, respectively. In addition, there is a decrease in the value of the manual assembly complexity index for each design applied to hospital bed legs. In the initial swerve drive module design, the manual assembly complexity index was 16.10, while in the improved swerve drive module design, the index was 15.74 Based on this, a complexity reduction value of 2% was obtained.

1. Introduction

Since the outbreak of the virus, hospitals have allocated many healthcare workers to serve patients who have been infected, but the medical staff handling these diseases are still considered to be lacking [1]. Healthcare workers who work daily are not exempt from the activity of pushing hospital beds, which is considered very tiring and inefficient in terms of hospital management because it requires at least two to three people to push the bed. The process of transferring patients from one room to another can also pose a risk of injury that can be experienced by healthcare workers, such as lower back pain, shoulder pain, and other musculoskeletal disorders [2]. Musculoskeletal pain is most common in healthcare workers working in the public service sector, with a proportion of

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https://doi.org/10.37934/aram.108.1.2746

musculoskeletal pain experienced being 45.8% [3]. One way to reduce the risk of musculoskeletal injuries is by using hospital beds equipped with motorized drives.

The motorized drive system employs speed and direction sensors, motor drivers, circuit board assemblies to integrate all utilized components and circuits, all managed by a microcontroller [4]. Adding motor drive modules to existing beds has a positive impact on reducing the risk of injury to healthcare workers and reduces the need for healthcare workers to move patients, allowing them to be allocated to other sectors. Dhelika *et al.,* [5] had previously developed a swerve drive motorized wheel module that can be implemented on existing hospital beds whose installation is done by only making slight modifications to the legs of the hospital bed. In the initial design, the swerve drive is produced using additive manufacturing methods, where the utilization of 3D printer is a common practice in healthcare sector research [6]. However, in the development of the swerve drive module, there are still issues regarding the swerve drive module as it is currently being produced using an FDM 3D printer with PLA material. This method results in structural strength that is directionally dependent and influenced by the inherent structure. This factor will impact the overall strength of the swerve drive module [7], as well as how the design evaluation of the module is conducted. This is important to be considered because the already made swerve drive module will be a reference for a designer in improving the design.

One approach that can be used to evaluate and determine the value of the design created is to review it based on the manual assembly process, which can be done using the Design for Assembly (DFA) approach [8]. Design for assembly is an important approach to consider because assembly contributes more than 50% of the total assembly time and 20% of the total production cost of a product [9]. Design for Assembly is a valuable tool for offering feedback to product designers. It aids in identifying critical parameters that must be considered during the development of future products to ensure they can be created using the minimum number of parts possible. This will have a positive impact on assembly time, production costs, and operational costs. In this context, the longer the time required for the assembly of a product, the higher the assembly cost, and there will also be a decrease in the efficiency of the design assembly [10-12]. The calculation model that can be used to determine the efficiency of product assembly design is using the Boothroyd and Dewhurst classification method, where the calculation model can estimate the assembly time of the product [13-15]. Boothroyd and Dewhurst have observed that to enhance product efficiency, it is essential to design the product using a minimal number of parts, while ensuring that its functional aspects are not compromised [16-18].

The manual assembly process is divided into two separate parts that must be reviewed, namely the handling process and the insertion process. The handling process is the process of conditioning parts such as picking up, adjusting, and moving parts, while the insertion process is the process of combining parts with other parts or subassemblies [19]. The handling process involves the shape of the part such as the symmetry of the part with reference to the orientation of the part rotation direction that is in the same direction as its insertion axis, and the rotation of the part based on the axis perpendicular to its insertion axis, as well as the level of difficulty in manipulating the part. As for the insertion process, it refers to the level of difficulty of the part when inserted, such as the safety of the part after it is inserted, the need or not for holding the part when inserted, and the process of tightening the part in various ways.

In the context of developing a motorized hospital bed, it is important to examine the complexity of installing the swerve drive module onto the legs. To address this issue, Boothroyd and Dewhurst's classification method, along with the normalized average method weighting, can be utilized for further development. This approach enables the assessment of assembly process complexity and the percentage decrease in complexity achieved by the initial or improved product. Considering complexity is crucial in achieving optimal product designs and facilitating the assembly process [20].

The complexity index of the assembly process is a quantitative representation of the level of difficulty in assembling a product, where the complexity process of the assembly is influenced by the diversity, relative complexity of the assembly process, and also the total information available [21].

1.2 Research Question

A new design is proposed for the swerve drive module in order to optimize the existing module, which raises important questions such as the estimated assembly time for the original design and the improved version with fewer components, the level of complexity involved in the assembly process for mounting each module to a hospital bed frame, and the percentage reduction in complexity achieved after the design enhancement.

1.3 Research Objectives

The research objective is to evaluate the proposed new design for the swerve drive module and compare it with the existing module to determine the impact of the design enhancement on the estimated assembly time, complexity of the assembly process for mounting each module to a hospital bed frame, and the percentage reduction in complexity achieved.

2. Methodology

This research focuses to evaluate the improved design of the swerve drive module to determine whether the design modifications can reduce the estimated manual assembly time and decrease the complexity of the assembly process when installing each module to the hospital bed frame. The estimated assembly time is obtained using the Boothroyd-Dewhurst Classification System approach, while the complexity index of the assembly process is calculated using a previously developed model. The research process consists of several stages, including the evaluation of the first swerve drive module design, changes made and detail design to the improved module design, and calculation of the estimated assembly time and assembly complexity of each module when installing them to the hospital bed frame. The research flowchart is shown in Figure 1.

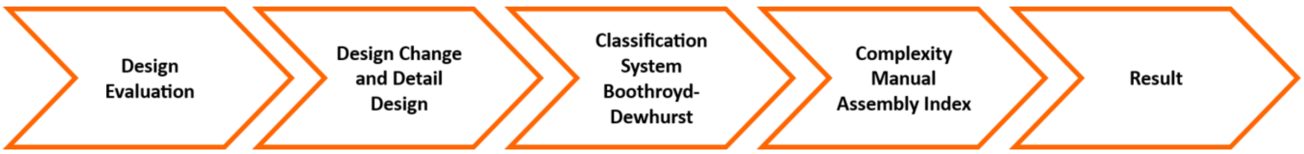

Fig. 1. Flowchart process

2.1 Design Evaluation

The first design for the swerve drive module had been developed by Dhelika *et al.,* [5] as shown in Figure 2. It was found that there are several areas where improvements could be made. It was discovered that the total number of parts was 97, some of which may not be necessary and could be eliminated by combining them with other parts. The use of washers for tightening and distributing loads was also identified as an inefficient design choice that could increase manual assembly time. Both bolts and nuts can be replaced with simpler commercial standard parts, such as flange head bolts and flange nuts. Mistakes made in selecting standard commercial components in the previous design had adverse effects on the assembly process, including prolonged assembly times and heightened assembly complexity for the swerve drive module itself.

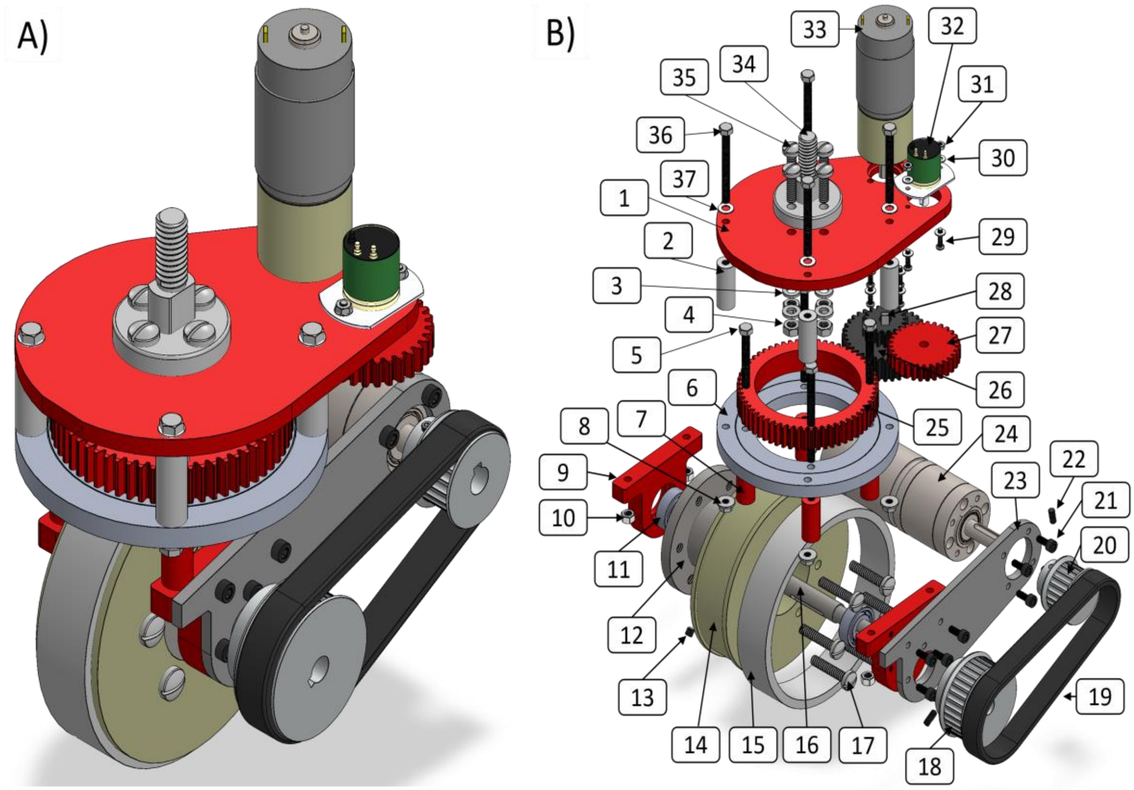

Fig. 2. (a) Initial design of swerve drive module (b) exploded view of an initial design

2.2 Design Change and Detail Design

Design changes were made to improve the swerve drive module using CAD modeling. CAD modeling can help designers visualize the model accurately and precisely, accelerate development time, facilitate changes or design revisions, and easily optimize the ongoing design. After observing the initial swerve drive module design, there were several limitations in improving the swerve drive module design. Some parts such as the DC motor for direction control, DC motor for speed control, turntable bearing, and gear used cannot be replaced or eliminated, so no changes can be made to those parts. The changes made did not alter the important function of using the swerve drive module for hospital beds. One way to reduce manual assembly time is by reducing the use of parts by combining them with related parts but using the same material conditions, changing part designs without eliminating their function. In the improved swerve drive design, parts were combined, such as four upper spacer parts combined with the top plate part, four lower spacer parts with two each combined with the right and left bearing housing, combining the side plate of the speed control DC motor mount with the bearing housing, combining the fastener on the 60T gear (steering gear) into a single unit, combining the wheel shaft with the wheel cylinder, replacing commercial standard parts such as hexagonal bolts, hex nuts, and washers with flange head bolts and flange nuts. Additionally, the model change on the swerve drive module adapter was made because the use of threaded shaft in the first swerve drive module was considered inefficient in terms of installation to the hospital bed frame. Figure 3 below shows an improved swerve drive module design. The changes made to the swerve drive module show a significant decrease in the number of parts used. The total usage in the improved swerve drive module is 56 parts, and the comparison of parts used can be seen in Table 1. Reducing the number of parts used has a significant influence on the assembly time of the module under construction, potentially resulting in a shorter assembly duration for the module. Additionally, it can lead to cost savings in the production of the swerve drive module.

Table 1
List of swerve drive module parts

No	Part name (initial module)	Qty	No	Part name (improved module)	Qty
1	Top plate	1	1	Top plate	1
2	Upper spacer	4	2	Gear 60 T	1
3	Washer (M6)	4	3	Dc motor PG45	1
4	Nut (M6)	4	4	Bearing housing (right side)	1
5	Hex bolt (M5x65mm)	4	5	Flange nut M5	4
6	Turntable bearing	1	6	Ball bearing	2
7	Bottom spacer	4	7	Countersunk bolt M6x30mm	2
8	Flange Nut (M5)	4	8	Tire	1
9	Bearing housing	2	9	Rim	1
10	Nut (M5)	4	10	Wheel axle	1
11	Bearing 6000zz	2	11	Bearing housing (left side)	1
12	Wheel cylinder	1	12	Stopper	1
13	Socket set screw (M5x10mm)	1	13	Driven sprocket	1
14	Rim	1	14	Chain connecting link plate	1
15	Tire	1	15	Chain spring clip	1
16	Wheel axle	1	16	Chain press fit	1
17	Slot head bolt (M6x30mm)	6	17	Chain	1
18	Pulley (driven)	1	18	Driver sprocket	1
19	Timing belt	1	19	Allen bolt M4x10mm	4
20	Pulley (driver)	1	20	Socket set screw M5x8mm	2
21	Allen bolt (M4x10mm)	10	21	Flange nut M5	4
22	Socket set screw (M5x8mm)	2	22	Turntable bearing	1
23	Side plate	1	23	Gear 36T and 18 T	1
24	DC Motor PG46	1	24	Gear 30T	1
25	Gear 60T	1	25	Socket set screw M3x5mm	2
26	Gear 36T and 18 T	1	26	Flange button head hex socket bolt M3x10mm	4
27	Gear 30T	1	27	DC motor PG36	1
28	Woodruff key	1	28	Flange button head hex socket bolt M3x6mm	2
29	Phillip bolt (M3x12mm)	6	29	Angle hall sensor	1
30	Washer (M3)	8	30	Hospital bed adaptor	1
31	Nut (M3)	2	31	Flange button head hex socket bolt M5x10mm	4
32	Angle hall sensor	1	32	Flange button head hex socket bolt M5x40mm	4
33	DC Motor PG36	1	Total		55
34	Hospital bed adaptor	1			
35	Slot head bolt (M6x20mm)	4			
36	Hex bolt (M5x50mm)	4			
37	Washer (M5)	4			
Total		97			

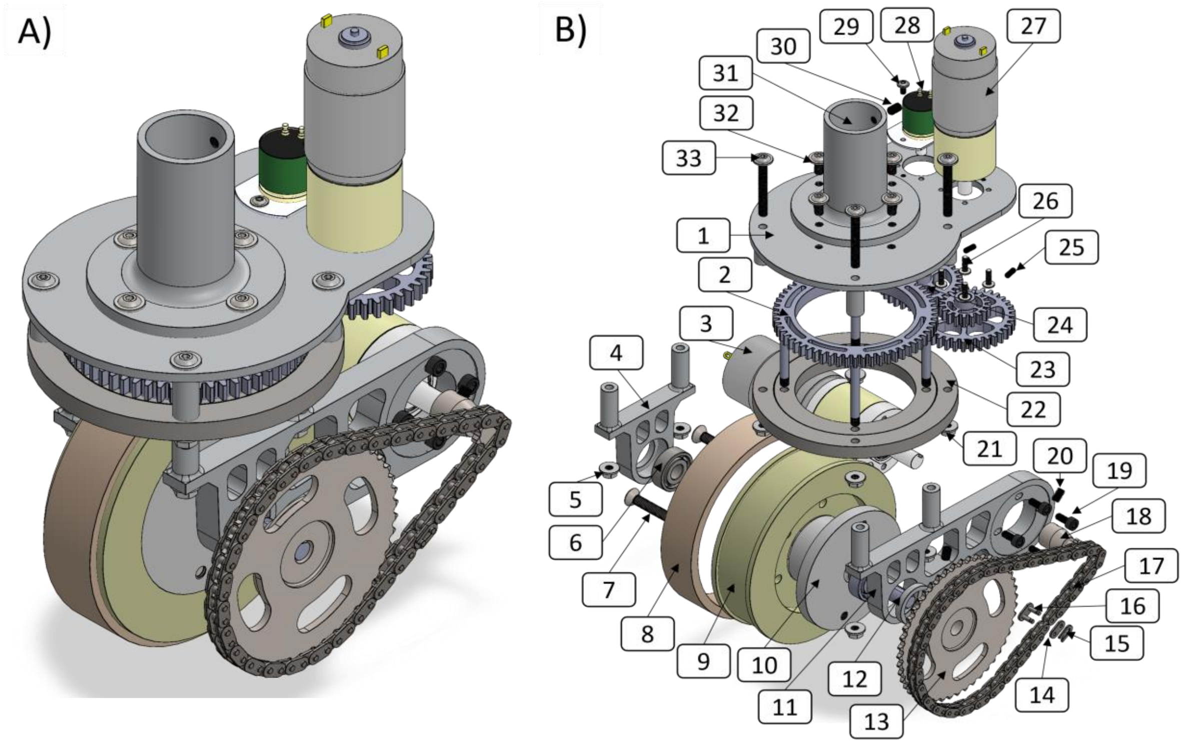

Fig. 3. (a) Improved design of swerve drive module (b) exploded view of an improved design

2.3 Boothroyd-Dewhurst Classification System

The method developed by Boothroyd-Dewhurst is useful to determine the estimated time required in the manual assembly process as well as the assembly efficiency obtained from the changes made to the swerve drive module. There are two aspects that are considered in the use of Boothroyd-Dewhurst classification system, namely the handling process and the insertion and fastening process.

In the handling process, parts are handled such as gripping, placing, and moving parts or sub-assemblies. Factors such as part symmetry, thickness, size, weight, curvature, twist, brittleness, flexibility, slipperiness, stickiness, one-handed or two-handed use, use of holding tools, use of magnifying tools (as a visual aid), and the need for mechanical equipment or energy affect the criteria for manual part handling. The symmetry of a part in the handling process can be determined based on the angle α and β formed by the part, wherein,

i. The α angle represents the rotation of the part about an axis perpendicular to the insertion axis.
ii. The β angle represents the rotation of the part about an axis parallel to the insertion axis.

The thickness and size of the part in the handling process can be determined based on two categories, namely "cylindrical" parts and "non-cylindrical" parts, wherein,

i. For cylindrical parts: parts that have a cylindrical shape or parts that have a cross-section with five or more sides. The thickness is measured based on the radius of the part.
ii. For non-cylindrical parts: the maximum height of a part with its smallest dimension that extends from a flat surface or has a diameter greater than or equal to its length.

In the insertion and fastening process, a part is joined with other parts or subassemblies. The insertion process is the meeting process between two parts or subassemblies, while the fastening process is the tightening process that is carried out. Aspects that are considered during the insertion and fastening process are accessibility and vision, holding down, alignment, insertion resistance, mechanical fastening processes, non-mechanical fastening processes, and non-fastening processes. These are aspects that need to be considered when using the estimation time classification table created by Boothroyd and Dewhurst for assembly.

These are aspects that need to be considered when using the estimation time classification table created by Boothroyd and Dewhurst for assembly. After obtaining the assembly time estimation for the initial swerve drive module and the updated swerve drive module, the DFA index or assembly efficiency of the swerve drive module being assessed can be calculated using Eq. (1) [19].

$$E_{ma} = \frac{N_{min} t_a}{t_{ma}} \tag{1}$$

where N_{min} represents the theoretical minimum number of parts, t_a represents the basic assembly time of each part (3 seconds), t_{ma} represents time estimation to complete the assembly process. Aspects in determining the theoretical minimum number of parts are based on three questions that need to be considered. First, regarding the movement of the part, does the part move relative to all other parts? Then, the isolation of the part, does the part have to be made of different material from other parts? And adjustment/replacement of the part, does the part need to be separated from other parts? A part is not included in the theoretical minimum number of parts if all three aspects have a "no" answer. If there is at least one aspect in the part being reviewed, then the reviewed part is included in the theoretical minimum number of parts [22].

2.4 Complexity Index of Manual Assembly Processes

A model has been developed through a classification system to calculate the complexity index of manual assembly processes, with the aim of determining the complexity index value of the assembly process and the complexity reduction value resulting from design changes. The manual assembly complexity index refers to the level of difficulty in handling individual parts or sub-assemblies during the assembly process. The calculation is carried out to determine the complexity level of each design of the swerve drive, both the initial swerve drive module and the improved swerve drive module, when attached to a hospital bed frame. The complexity index of the manual assembly process, $C_{ma,x}$, can be obtained by following the equation steps.

Calculate the average complexity value of handling, C_h

$$C_h = \frac{\sum_1^J C_{h,f}}{J} \tag{2}$$

Calculate the average complexity value of insertion, C_i

$$C_i = \frac{\sum_1^K C_{i,f}}{K} \tag{3}$$

wherein, $C_{h,f}$ represents the complexity level value for handling attributes, $C_{i,f}$ represents the complexity level value for insertion attributes, J represents the number of handling attributes, and K represents the number of insertion attributes. The calculation of $C_{h,f}$ and $C_{i,f}$ is based on the development of the Boothroyd-Dewhurst classification system. The weighting of $C_{h,f}$ and $C_{i,f}$values is achieved using the normalized average method, and the resulting values are simplified and presented in Table 2 and 3.

Calculate the average weighting value of part complexity factor during assembly, C_{part}

$$C_{part} = \frac{C_h \sum_1^J C_{h,f} + C_i \sum_1^K C_{i,f}}{\sum_1^J C_{h,f} + \sum_1^K C_{i,f}} \tag{4}$$

Calculate the coefficient of relative complexity for the assembly process, $C_{apc,x}$

$$C_{apc,x} = \sum_{p=1}^{n} x_p C_{part} \tag{5}$$

$$x_p = \left(\frac{Number\ of\ parts}{Total\ number\ of\ parts}\right) \times 100\% \tag{6}$$

where, x_p represents the percentage of each part to the total number of parts, and n is the number of unique parts.

Calculate the complexity index of manual assembly process, $C_{ma,x}$

$$C_{ma,x} = \left[\frac{n_p}{N_p} + C_{ap,x}\right] [log_2(N_p + 1)] + \left[\frac{n_s}{N_s}\right] [log_2(N_s + 1)] \tag{7}$$

where, $n_p$represent the number of unique parts, N_p represent the total number of parts, $n_s$represent the number of unique fasteners, and N_s represent the total number of fasteners that are assembled.

After obtaining the manual assembly complexity index values for each module under review, in order to determine the success of the design updates, the next step is to calculate the complexity reduction value. The complexity reduction value is the percentage of how much the assembly process complexity index value is reduced. By using Eq. (8), the complexity reduction value can be calculated.

Calculate the complexity reduction

$$Complexity\ reduction = \left[\frac{C_{ma,1} - C_{ma,2}}{C_{ma,1}} + \right] \times 100\% \tag{8}$$

where, $C_{ma,1}$ represent the complexity index of manual assembly in the design of the first module, and $C_{ma,2}$ represent the complexity index of manual assembly in the design of improved module.

Table 2
Manual assembly handling attributes, C_{hf} [20]

Group	Attribute	Description	C_{hf}
Handling attributes	Symmetry	α+β < 360	0.70
		360 ≤ α+β ≤ 540	0.84
		540 ≤ α+β < 720	0.94
		α+β = 720	1.00
	Size	> 15 mm	0.74
		6 mm < x < 15 mm	0.81
		< 6 mm	1.00
	Thickness	> 2 mm	0.27
		0.25 mm < x ≤ 2 mm	0.50
		≤ 0.25 mm	1.00
	Weight	< 10 lb (light)	0.50
		> 10 lb	1.00
	Grasping and manipulation	Easy to grasp and manipulate	0.91
		Not easy to grasp and manipulate	1.00
	Assistance	Using one hand	0.34
		Using one hand with grasping aids	1.00
		Using two hands	0.75
		Using two hands with assistance	0.57
	Nesting and tangling	Parts do not severely nest or tangle and are not flexible	0.58
		Parts severely nest or tangle or are flexible	1.00
	Optical magnification	Not necessary	0.80
		Necessary	1.00

Table 3
Manual assembly insertion attributes, C_{if} [20]

Group	Attribute	Description	C_{if}
Insertion attributes	Holding down	Not required	0.54
		Required	1.00
	Alignment	Easy to align or position	0.86
		Not easy to align or position	1.00
	Insertion resistance	No resistance	0.87
		Resistance to insertion	1.00
	Accessibility and vision	No restrictions	0.57
		Obstructed access or restricted vision	0.81
		Obstructed access and restricted vision	1.00
	Mechanical fastening processes	Bending	0.34
		Riveting	0.58
		Screw tightening	0.42
		Bulk plastic deformation	1.00
	Non-mechanical fastening processes	No additional material required	0.58
		Soldering processes	0.67
		Chemical processes	1.00
	Non-fastening processes	Manipulation of parts or sub-assemblies (fitting or adjusting of parts, …)	0.75
		Other processes (liquid insertion, …)	1.00

3. Results and Discussion

The following section presents the results obtained from the calculations performed. The design efficiency of the initial swerve drive module and the improved swerve drive module has been evaluated based on weighted values using the Boothroyd-Dewhurst classification system. It is assumed that the assembly process involves the use of clamping tools, reorientation processes, and penalty time is added for each tool retrieval process for tightening by 2.9 seconds. The assembly process for both swerve drive modules is performed in the same sequence to facilitate the estimation of assembly time, and the classification system is performed by assembling several parts that can be used as sub-assemblies. The estimated assembly time for the initial swerve drive module is 1051.54 seconds (as shown in Table 4), and the estimated manual assembly time for the improved swerve drive module is 647.47 seconds (as shown in Table 5). The complete calculations for the estimated manual assembly time for both modules can be found in Table 7 and 8. Based on the Boothroyd-Dewhurst classification system, the estimated assembly times for each module were obtained. Using equation 1, the assembly efficiency for the initial swerve drive module was determined to be 5%, while for the improved swerve drive module, it was 9%, as shown in Table 4 and Table 5.

Table 4
Estimation of assembly time and assembly efficiency for an initial swerve drive module

Part name (initial swerve drive module)	Total estimation assembly time of each process	Total theoretical minimum part	Information
Sub-assy 1	505.06	17	Assemble the individual parts to create sub-assy 1
Sub-assy 2	80.6		Assemble the individual parts to create sub-assy 2
Sub-assy 3	14.48		Assemble the individual parts to create sub-assy 3
Sub-assy 4	90.07		Assemble the individual parts to create sub-assy 4
Sub-assy 5	153.7		Assemble the individual parts to create sub-assy 5
Sub-assy 1-2	58.28		Assemble sub-assy 1, sub-assy 2, and other parts that are used
Sub-assy 3-4-5	18.35		Assemble sub-assy 3, sub-assy 4, and sub-assy 5
Sub-assy 1-2-3-4-5	131		Assemble all sub-assy and the corresponding parts
Total	1051.54		
Assembly efficiency	0.05 5%		

Table 5
Estimation of assembly time and assembly efficiency for an improved swerve drive module

Part Name (improved swerve drive module)	Total estimation assembly time of each process	Total theoretical minimum part	Information
Sub-assy 1	197.17	20	Assemble the individual parts to create sub-assy 1
Sub-assy 2	9.95		Assemble the individual parts to create sub-assy 2
Sub-assy 3	14.48		Assemble the individual parts to create sub-assy 3
Sub-assy 4	35.6		Assemble the individual parts to create sub-assy 4
Sub-assy 5	105.02		Assemble the individual parts to create sub-assy 5
Sub-assy 1-2	102.56		Assemble sub-assy 1, sub-assy 2, and other parts that are used
Sub-assy 3-4-5	18.35		Assemble sub-assy 3, sub-assy 4, and sub-assy 5
Sub-assy 1-2-3-4-5	164.34		Assemble all sub-assy and the corresponding parts
Total	647.47		
Assembly efficiency	0.09 9%		

Evaluations on the complexity of manually implementing the swerve drive module onto hospital bed legs have also been conducted. Based on the weighting and calculations as shown in table 6, the initial swerve drive module had a manual assembly complexity index of 16.10, while the improved swerve drive module had a complexity index of 15.74. There was a reduction in complexity in the installation process of the improved swerve drive module onto hospital bed legs. By using equation 8, it was found that the complexity reduction value was 2%. This shows that the implementation of the improved swerve drive module onto hospital bed legs is less complex than the initial swerve drive module, which could potentially increase the convenience of the assembly process.

The evaluation of the design efficiency and assembly complexity of the initial and improved swerve drive modules, based on the Boothroyd-Dewhurst classification system, has provided valuable insights for the development of medical equipment. The results of this study indicate that the improved swerve drive module has a higher assembly efficiency and lower complexity index compared to the initial module.

Table 6
Calculation of assembly process complexity index for the swerve drive module attached to hospital bed legs

		Part name (initial swerve drive module)		Part name (improved swerve drive module)		
		Hospital bed legs	Swerve drive module	Hospital bed legs	Swerve drive module	Socket set screw (M5x8mm)
Handling attributes	Number	4	4	4	4	1
	Symmetry	1.00	1.00	1.00	1.00	0.84
	Size	0.74	0.74	0.74	0.74	0.81
	Thickness	0.27	0.27	0.27	0.27	0.27
	Weight	1.00	0.50	1.00	0.50	0.50
	Grasping and Manipulation	1.00	0.91	1.00	0.91	0.91
	Asisstance	0.57	0.75	0.57	0.75	0.34
	Nesting and tangling	0.58	0.58	0.58	0.58	0.58
	Optical Magnification	0.80	0.80	0.80	0.80	0.80
	$\sum_1^J C_{hf}$	5.96	5.55	5.96	5.55	5.05
	J	8	8	8	8	8
	C_h	0.75	0.69	0.75	0.69	0.63
	$\sum_1^J C_{hf} \times C_h$	4.44	3.85	4.44	3.85	3.19
Insertion attributes	Holding down	1.00	1.00	1.00	0.54	0.54
	Alignment	1.00	1.00	1.00	0.86	0.86
	Insertion Resistance		1.00		0.87	0.87
	Accessibility and vision		1.00		1.00	0.81
	Mechanical fastening processes		0.42			0.45
	Non-mechanical fastening processes					
	Non-fastening processes		0.75		0.75	
	$\sum_1^k C_{if}$	2.00	5.17	2.00	4.02	3.53
	K	2	6	2	5	5
	C_i	1.00	0.86	1.00	0.80	0.71
	$\sum_1^k C_{if} \times C_f$	2.00	4.45	2.00	3.23	2.49
	Total part	8		9		
	Unique part	2		2		
	$\boldsymbol{X_p}$	0.5	0.5	0.44	0.44	0.11
	$\boldsymbol{X_p \times C_{part}}$	3.69	5.34	3.69	4.73	4.25
	$\boldsymbol{C_{part}}$	1.85	2.67	1.64	2.10	0.47
	$\boldsymbol{C_{ap,x}}$	4.52		4.21		
	$\boldsymbol{C_{ma,x}}$	16.10		15.74		
	Complexity reduction	2%				

Table 7
Step of weighting analysis for classification system performed on the initial swerve drive module

Initial swerve drive modul parts name (sub-assy 1)	No of Items "RP"	Tool acquire time "TA"	α	β	α+β	Handling code	Handling time per part "TH"	Insertion code	Insertion time per part "TI"	Total time "TA+RP*(TH+TI)"	Theoretical minimum part	Information
Top plate	1		360	360	720	30	1.95	98	9	10.95	1	Place in fixture
Hospital bed adaptor	1		360	180	540	20	1.8	31	5	6.8	1	Add
Washer (M6)	4		180	0	180	03	1.69	28	10.5	48.76	0	Add
Nut (M6)	4		180	0	180	01	1.43	28	10.5	47.72	0	Add
Slot head bolt (M6x20mm)	4	2.9	360	0	360	10	1.5	48	8.5	42.9	0	Add and tightening
Upper spacer	4		180	0	180	00	1.13	28	10.5	46.52	0	Add
Washer (M5)	4		180	0	180	03	1.69	18	9	42.76	0	Add
Hex bolt (M5x50mm)	4	2.9	360	0	360	10	1.5	48	8.5	42.9	0	Add and tightening
Washer (M3)	2		180	0	180	08	2.45	08	6.5	17.9	0	Add
Phillip bolt (M3x12mm)	2		360	0	360	13	2.06	28	10.5	25.12	0	Add
Angle hall sensor	1		360	360	720	30	1.95	00	1.5	3.45	1	Add
Washer (M3)	2		180	0	180	08	2.45	12	5	14.9	0	Add
Nut (M3)	2	2.9	180	0	180	06	2.17	49	10.5	28.24	0	Add and tightening
Reorient	1							98	9	9		Reorient and adjust
DC motor PG36	1		360	360	720	30	1.95	18	9	10.95	1	Add
Washer (M3)	4		180	0	180	08	2.45	06	5.5	31.8	0	Add
Phillip bolt (M3x12mm)	4	2.9	360	0	360	13	2.06	48	8.5	45.14	0	Add and tightening
Reorient	1							98	9	9		Reorient and adjust
Gear 30T	1		180	360	540	20	1.8	31	5	6.8	1	Add
Gear 36T and 18 T	1		360	360	720	30	1.95	31	5	6.95	1	Add
Rectangular key	1		180	180	360	10	1.5	31	5	6.5	0	Add
										505.06	6	Total

Initial swerve drive modul parts name (sub-assy 2)	No of Items "RP"	Tool acquire time "TA"	α	β	α+β	Handling code	Handling time per part "TH"	Insertion code	Insertion time per part "TI"	Total time "TA+RP*(TH+TI)"	Theoretical minimum part	Information
Gear 60T	1		180	90	270	00	1.13	00	1.5	2.63	1	Place in fixture
Hex bolt (M5x65mm)	4	2.9	180	0	180	00	1.13	38	6	31.42	0	Add and tightening
Reorient	1							98	9	9		Reorient and adjust
Turntable bearing	1		180	90	270	00	1.13	12	5	6.13	1	Add
Bottom spacer	4	2.9	180	90	270	00	1.13	38	6	31.42	0	Add and tightening
										80.6	2	Total

Initial swerve drive modul parts name (sub-assy 3)	No of Items "RP"	Tool acquire time "TA"	α	β	α+β	Handling code	Handling time per part "TH"	Insertion code	Insertion time per part "TI"	Total time "TA+RP*(TH+TI)"	Theoretical minimum part	Information
Right bearing housing	1		360	360	720	30	1.95	00	1.5	3.45	0	Place in fixture
Ball Bearing	1	2.9	180	0	180	00	1.13	91	7	11.03	1	Add
										14.48	1	Total

Initial swerve drive modul parts name (sub-assy 4)	No of Items "RP"	Tool acquire time "TA"	α	β	α+β	Handling code	Handling time per part "TH"	Insertion code	Insertion time per part "TI"	Total time "TA+RP*(TH+TI)"	Theoretical minimum part	Information
Wheel cylinder	1		360	60	420	10	1.5	00	1.5	3	0	Place in fixture
Wheel axle	1		360	60	420	10	1.5	09	7.5	9	1	Add
Socket set screw (M5x10mm)	1	2.9	180	0	180	06	2.17	48	8.5	13.57	0	Add and tightening
Rim	1		360	60	420	10	1.5	31	5	6.5	1	Add
Slot head bolt (M6x30mm)	6	2.9	360	0	360	10	1.5	38	6	47.9	0	Add and tightening
Tire	1		180	0	180	80	4.1	34	6	10.1	1	Add
										90.07	3	Total

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Initial swerve drive modul parts name (sub-assy 5)	No of Items "RP"	Tool acquire time "TA"	α	β	α+β	Handling code	Handling time per part "TH"	Insertion code	Insertion time per part "TI"	Total time "TA+RP*(TH+TI)"	Theoretical minimum part	Information
Left bearing housing	1		360	360	720	30	1.95	00	1.5	3.45	0	Place in fixture
Ball Bearing	1	2.9	180	0	180	00	1.13	91	7	11.03	1	Add
Reorient	1							98	9	9		Reorient and adjust
Side plate	1		360	360	720	30	1.95	08	6.5	8.45	0	Add
Allen bolt (M4x10mm)	6	2.9	360	0	360	13	2.06	38	6	51.26	0	Add and tightening
DC motor PG46	1		360	360	720	30	1.95	18	9	10.95	1	Add
Allen bolt (M4x10mm)	4	2.9	360	0	360	13	2.06	38	6	35.14	0	Add and tightening
Pulley (driver)	1		360	360	720	30	1.95	08	6.5	8.45	1	Add
Socket set screw (M5x8mm)	1	2.9	360	0	360	16	2.57	49	10.5	15.97	0	Add and tightening
										153.7	3	Total

Initial swerve drive modul parts name (sub-assy 1-2)	No of Items "RP"	Tool acquire time "TA"	α	β	α+β	Handling code	Handling time per part "TH"	Insertion code	Insertion time per part "TI"	Total time "TA+RP*(TH+TI)"	Theoretical minimum part	Information
Sub-assy 1	1		360	360	720	35	2.73	98	9	11.73	0	Place in clamping tool
Sub-assy 2	1		360	360	720	30	1.95	28	10.5	12.45	0	Add
Flange nut (M5)	4	2.9	360	0	360	11	1.8	38	6	34.1	0	Add and tightening
										58.28	0	Total
Initial swerve drive modul parts name (sub-assy 3-4-5)	No of Items "RP"	Tool acquire time "TA"	α	β	α+β	Handling code	Handling time per part "TH"	Insertion code	Insertion time per part "TI"	Total time "TA+RP*(TH+TI)"	Theoretical minimum part	Information
Sub-assy 3	1		360	360	720	30	1.95	00	1.5	3.45	0	Place in fixture
Sub-assy 4	1		360	360	720	30	1.95	16	5.5	7.45	0	Add
Sub-assy 5	1		360	360	720	30	1.95	16	5.5	7.45	0	Add
										18.35	0	Total

Initial swerve drive modul parts name	No of Items "RP"	Tool acquire time "TA"	α	β	α+β	Handling code	Handling time per part "TH"	Insertion code	Insertion time per part "TI"	Total time "TA+RP*(TH+TI)"	Theoretical minimum part	Information
Sub-assy 1-2	1		360	360	720	35	2.73	98	9	11.73	0	Place in clamping tool
Sub-assy 3-4-5	1		360	360	720	35	2.73	28	10.5	13.23	0	Add
Nut (M5)	4	2.9	180	0	180	01	1.43	59	12	56.62	0	Add and tightening
Reorient	1							98	9	9		Reorient and adjust
Pulley (driven)	1		360	360	720	30	1.95	18	9	10.95	1	Add
Socket set screw (M5x8mm)	1	2.9	360	0	360	16	2.57	49	10.5	15.97	0	Add and tightening
Timing belt	1		180	0	180	85	5	44	8.5	13.5	1	Add
										131	2	Total

Table 1
Step of weighting analysis for classification system performed on the improved swerve drive module

Improved swerve drive modul parts name (sub-assy 1)	No of Items "RP"	Tool acquire time "TA"	α	β	α+β	Handling code	Handling time per part "TH"	Insertion code	Insertion time per part "TI"	Total time "TA+RP*(TH+TI)"	Theoretical minimum part	Information
Top plate	1		360	360	720	30	1.95	98	9	10.95	1	Place in fixture
Hospital bed adaptor	1		360	360	720	30	1.95	08	9	10.95	1	Add
Flange button head hex socket bolt M5x10mm	4	2.9	360	0	360	10	1.5	48	8.5	42.9	0	Add and tightening
Angle hall sensor	1		360	360	720	30	1.95	08	6.5	8.45	1	Add
Flange button head hex socket bolt M3x6mm	2	2.9	360	0	360	11	1.43	48	8.5	22.76	0	Add and tightening
Reorient	1							98	9	9		Reorient and adjust
DC motor PG36	1		360	360	720	30	1.95	18	9	10.95	1	Add
Flange button head hex socket bolt M3x10mm	4	2.9	360	0	360	11	1.95	48	8.5	44.7	0	Add and tightening

Gear 30T	1		360	360	720	30	1.95	06	5.5	7.45	1	Add
Socket set screw M3x5mm	1	2.9	360	0	360	19	3.38	58	10	16.28	0	Add and tightening
Gear 36T and 18 T	1		360	360	720	30	1.95	06	5.5	7.45	1	Add
Socket set screw M3x5mm	1	2.9	360	0	360	19	3.38	58	10	16.28	0	Add and tightening
										197.17	6	Total

Improved swerve drive modul parts name (sub-assy 2)	No of Items "RP"	Tool acquire time "TA"	α	β	α+β	Handling code	Handling time per part "TH"	Insertion code	Insertion time per part "TI"	Total time "TA+RP*(TH+TI)"	Theoretical minimum part	Information
Turntable bearing	1		180	0	180	00	1.5	00	1.5	3	1	Place in fixture
Gear 60 T	1		360	360	720	30	1.95	12	5	6.95	1	Add
										9.95	2	Total

Improved swerve drive modul parts name (sub-assy 3)	No of Items "RP"	Tool acquire time "TA"	α	β	α+β	Handling code	Handling time per part "TH"	Insertion code	Insertion time per part "TI"	Total time "TA+RP*(TH+TI)"	Theoretical minimum part	Information
Bearing housing (right side)	1		360	360	720	30	1.95	00	1.5	3.45	0	Place in fixture
Ball bearing	1	2.9	180	0	180	00	1.13	91	7	11.03	1	Add
										14.48	1	Total sub-assy 3

Improved swerve drive modul parts name (sub-assy 4)	No of Items "RP"	Tool acquire time "TA"	α	β	α+β	Handling code	Handling time per part "TH"	Insertion code	Insertion time per part "TI"	Total time "TA+RP*(TH+TI)"	Theoretical minimum part	Information
Wheel axle	1		360	180	540	20	1.8	00	1.5	3.3	1	Place in fixture
Rim	1		360	180	540	20	1.8	02	2.5	4.3	1	Add
Countersunk bolt M6x30mm	2	2.9	360	0	360	10	1.5	38	6	17.9	0	Add and tightening
Tire	1		180	0	180	80	4.1	34	6	10.1	1	Add
										35.6	3	Total

Improved swerve drive modul parts name (sub-assy 5)	No of Items "RP"	Tool acquire time "TA"	α	β	α+β	Handling code	Handling time per part "TH"	Insertion code	Insertion time per part "TI"	Total time "TA+RP*(TH+TI)"	Theoretical minimum part	Information
Bearing housing (left side)	1		360	360	720	30	1.95	00	1.5	3.45	0	Place in fixture
Stopper	1	2.9	180	0	180	00	1.13	91	7	11.03	0	Add
Ball bearing	1	2.9	180	0	180	00	1.13	91	7	11.03	1	Add
Dc motor PG45	1		360	360	720	30	1.95	18	9	10.95	1	Add
Reorient	1							98	9	9		Reorient and adjust
Allen bolt M4x10mm	4	2.9	360	0	360	13	2.06	38	6	35.14	0	Add and tightening
Driver sprocket	1		360	360	720	30	1.95	08	6.5	8.45	1	Add
Socket set screw M5x8mm	1	2.9	360	0	360	16	2.57	49	10.5	15.97	0	Add and tightening
										105.02	3	Total

Improved swerve drive modul parts name (sub assy 1-2)	No of Items "RP"	Tool acquire time "TA"	α	β	α+β	Handling code	Handling time per part "TH"	Insertion code	Insertion time per part "TI"	Total time "TA+RP*(TH+TI)"	Theoretical minimum part	Information
Sub-assy 1	1		360	360	720	35	2.73	00	1.5	4.23	0	Place in fixture
Flange button head hex socket bolt M5x40mm	4		360	0	360	10	1.5	06	5.5	28	0	Add
Reorient	1							98	9	9		Reorient and adjust
Sub-assy 2	1		360	360	720	35	2.73	22	6.5	9.23	0	Add
Flange nut M5	4	2.9	360	0	360	11	1.8	49	10.5	52.1	0	Add and tightening
										102.56	0	Total

Improved swerve drive modul parts name (sub assy 3-4-5)	No of Items "RP"	Tool acquire time "TA"	α	β	α+β	Handling code	Handling time per part "TH"	Insertion code	Insertion time per part "TI"	Total time "TA+RP*(TH+TI)"	Theoretical minimum part	Information
Sub-assy 3	1		360	360	720	30	1.95	00	1.5	3.45	0	Place in fixture
Sub-assy 4	1		360	360	720	30	1.95	16	5.5	7.45	0	Add
Sub-assy 5	1		360	360	720	30	1.95	16	5.5	7.45	0	Add
										18.35	0	Total

Improved swerve drive modul parts name	No of Items "RP"	Tool acquire time "TA"	α	β	α+β	Handling code	Handling time per part "TH"	Insertion code	Insertion time per part "TI"	Total time "TA+RP*(TH+TI)"	Theoretical minimum part	Information
Sub-assy 1-2	1		360	360	720	35	2.73	98	9	11.73	0	Place in fixture
Sub-assy 3-4-5	1		360	360	720	35	2.73	28	10.5	13.23	0	Add
Flange nut M5	4	2.9	360	0	360	11	1.8	59	12	58.1	0	Add and tightening
Driven sprocket	1		360	360	720	30	1.95	18	9	10.95	1	Add
Socket set screw M5x8mm	1	2.9	360	0	360	16	2.57	49	10.5	15.97	0	Add and tightening
Chain	1		180	0	180	85	5	28	10.5	15.5	1	Add
Chain press fit	1		180	180	360	06	2.17	28	10.5	12.67	1	Add
Adjusment	1							98	9	9		Adjust chain
Chain connecting link plate	1		180	180	360	01	1.43	06	5.5	6.93	1	Add
Chain spring clip	1	2.9	180	360	540	23	2.36	41	5	10.26	1	Add and tightening
										164.34	5	Total

4. Conclusion

Reducing the number of parts used and carefully selecting fasteners in the swerve drive module can significantly reduce the estimated assembly time, indicating that the improved swerve drive design has a significant impact on the assembly process. The improved module also has a lower complexity index compared to the initial module. The number of parts used in the improved swerve drive module does not significantly affect the complexity of the assembly process. The factor that affects the high complexity of the assembly process is the complexity of the swerve drive module itself. These findings have important implications for the design and development of medical equipment. The use of the Boothroyd-Dewhurst classification system can help guide future improvement efforts and optimize the assembly process of similar medical devices.

Acknowledgement
This research is funded by a grant disbursed through my supervisor, Dr.Eng. Radon Dhelika, B.Eng., M.Eng.

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