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Human-Centered Design and Development of an Adjustable Crutch: Enhancing Usability and Functionality for Physical Disabilities

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Abstract

Crutches are becoming more and more critical as the number of physically disabled individuals in a nation rises. The need for multidimensional and multivariate crutches to assist people with disabilities is more significant today. Before making a variant of the standard crutch, a proper study must be done to construct a stable crutch for high load-carrying capacity. Additionally, various crutch models are also available. A new challenge is the development of an entirely new crutch model. Numerous types of analysis were carried out in this research to create a reliable and effective product, including market analysis, quality function deployment, functional structure development, Kano model development, specification and design analysis, materials and manufacturing processes, and cost analysis. All facets of product development, such as consumer requirements, assembly schematics, and recycling practices, were explored in the study. The most intriguing additions were the product's capacity to fold and the seating tool facility. A load analysis was conducted to meet this requirement, utilizing data from a survey of disabled persons employed in the business regarding the equipment required for people with physical challenges, especially when selecting materials. Another unique feature of our product is an adjustment system that helps the user to adjust its height. These features are new and thus make our product more memorable compared to existing products on the market. Ultimately, the product was developed and utilized successfully through the research.

1. Introduction

Crutches are mobility aids that shift weight from the legs to the upper body. They are frequently used by persons who cannot support their weight on their legs due to various conditions, from temporary injuries to permanent disabilities. So, it is difficult for them to stand for a long time in waiting lines, bus stands, train stations, and outdoor locations where there is no place to sit [1]. Although crutches have played a critical role in mobility support for centuries, their basic design has undergone minimal transformation. The earliest use of walking aids dates back to ancient Egypt, with significant structural evolution occurring in the early 20th century. Emile Schlick first patented a commercially produced crutch in 1917, and later, A.R. Lofstrand Jr. introduced a height-adjustable version, enabling users to tailor the crutch to their anthropometry [2], [3]. Despite these early advancements, modern crutches have remained essentially unchanged in terms of functionality and structure. Their primary role continues to be facilitating upright mobility, neglecting important user needs such as comfort during prolonged use, adaptability in varying environments, and usability in scenarios where resting is necessary. This product can solve this problem because it can be transformed into a seating tool, i.e., it can be folded and used as a seat. This crutch can be easily operated with the help of only one hand.

Recent studies indicate that individuals with physical challenges often encounter difficulties standing for extended periods due to fatigue or a lack of accessible seating, particularly in developing countries [4]. This gap in ergonomic functionality places users at risk of discomfort, postural strain, and musculoskeletal complications, limiting their independence and confidence. Moreover, existing models provide little to no support for dynamic environments where rapid transitions between walking and sitting postures are crucial. Traditional crutches are primarily designed to assist with walking or stair climbing [2].

This research proposes a novel, multifunctional crutch that integrates mobility, convenience, and usability. The newly developed design introduces a foldable mechanism, allowing the user to convert the crutch into a temporary seat. Additionally, the crutch features an adjustable height system suitable for users aged 15 to 60, as well as structural enhancements that ensure safety and balance during use. With a load-bearing capacity of up to 120 kg, and safety features like anti-slip rubber tips and inclined leg stands, the product has been engineered to perform reliably on diverse surfaces [5], [6].

Besides, the design also prioritizes material efficiency and environmental sustainability by utilizing aluminum, a lightweight, corrosion-resistant, and fully recyclable material. As over 75% of all aluminum produced is still in use today, this choice not only enhances product durability but also reduces environmental impact [7], [8]. Additional ergonomic improvements, including modified crutch handles, contoured arm pads, and reduced pressure contact points, aim to increase user comfort during extended use [9]. To ensure that the product meets real-world needs, a systematic design approach was adopted. This includes market analysis to identify customer pain points, the Kano model to differentiate between basic and exciting features, Quality Function Deployment (QFD) to translate user requirements into technical attributes, and functional structure development to understand the interactions between product components [10].

A comprehensive evaluation of design parameters was also conducted, including stress analysis, material selection using the Digital Logic Method (DLM), and a cost assessment to ensure affordability without compromising quality. Unlike powered or robotic mobility devices, which may be cost-prohibitive or technically complex for many users, this crutch is a low-tech yet high-impact solution, offering practical functionality without dependency on batteries or electronics. The product is specifically designed for users in lower- and middle-income contexts, where affordability, simplicity, and durability are key considerations.

Ultimately, this study addresses a significant research gap in assistive device innovation: the absence of a low-cost, ergonomically sound crutch that supports both mobility and rest. By merging structural innovation with user-centered design principles, the proposed solution represents a significant step toward enhancing mobility, comfort, and quality of life for individuals with physical challenges worldwide.

2. Literature Review

Many people rely on crutches for daily mobility due to the limited use of one or both legs [11]. Most of the world's population uses mobility aids, such as crutches and walking canes, regularly for various medical conditions. After lower body surgery or injury, after a stroke, after lower limb amputations, or for any condition that impairs the patient's motor skills, such as Motor Neuron Disease or spinal cord injuries, crutches are given as a walking aid for the elderly. Every year, more people also need mobility assistance [12]. Research on the impulsive dynamics connected to the crutch's collision with the ground is crucial because it has been determined that this is the primary source of energy loss during crutch gait [13]. Many crutch models available now only provide additional assistance for one kind of terrain [14]. The patient would need to ensure several crutch tips or replace the entire tip with other design specifications frequently if they wanted support for snow and wet surfaces [15].

The projected number of crutch users is cautious because it excludes those using a single or a pair of crutches or other assistive mobility devices such as wheelchairs, scooters, and lower limb prostheses [16]. Verde et al. explained that a person using crutches may choose to use a wheelchair most of the time instead of walking with them; using crutches promotes an upright posture, keeps users active, and increases their level of independence, all of which are excellent things for their long-term health [17]. Initially, a study of a few actual crutches was conducted, and a bio-mechanical analysis of the gait supported by crutches was performed, according to the explanation of some researchers [18], [19]. Active orthoses can help those with walking disabilities brought on by spinal cord injuries, along with some form of external support, which can be a crutch for balance [20]. Then, the balance of the crutch is necessary to walk correctly, and for the seating facility, more balance will be the primary requirement [21], [22]. According to some, the ability to create dynamically correct crutch walking simulations with active orthosis assistance depends on how an optimal control issue is formulated, according to their study

[23]. Some research discovered that the kinetic model, which consists of the forces, is developed using kinematic data, anthropometric data, and response forces created by the load cells [24].

Some expressed this in their work, which includes a dynamic analysis of the primary movement stage and kinematic trajectory planning for the model they've suggested [25]. In this way, many researchers tried to analyze it differently. Few tried to create alternatives [26]-[28]. For instance, the paper by Bagheri et al. suggested a walking assistance device for persons with trouble walking. It features crutches that the user controls and a wearable mechanism that allows the leg and foot to move relative to the upper body. Their findings led to the composition of the walking aid machine with crutches (WAMC) [29]. According to several studies, a smart, multi-functional robotic crutch made for physically challenged or paralyzed persons and built for quick object recognition is needed. It was a robotic crutch manufactured in Bangladesh for individuals who are unable to move independently [30]. Then, some research on this topic in Bangladesh focused on power, such as electric wheelchairs. The cost minimization of power-related machines has been explored in several studies. For example, some research aimed to build an autonomous electric wheelchair for Bangladesh's disabled population at the lowest possible cost with a well-organized design and control system [30].

Recent advancements in crutch design have introduced several innovations aimed at improving user comfort, adaptability, and functionality. For instance, patents such as US10368949B2 propose shock-absorbing crutches with ergonomic handles to reduce wrist strain during ambulation. Commercially, products like the Mobilegs Ultra and iWalk 3.0 have emerged as notable alternatives, offering enhanced mobility through features such as articulating grips, spring-assisted movement, and hands-free operation [1]. These models aim to address biomechanical challenges associated with traditional crutches, but often come with high costs, which limits their accessibility in low- and middle-income countries [30]. While robotic or powered assistive walking devices—like the WAMC (Walking Assistance Machine with Crutches)—represent technological progress, their complexity and maintenance requirements render them impractical for everyday users in resource-constrained environments. Despite these innovations, the integration of a cost-effective, lightweight, and foldable seating facility within a single crutch remains largely unexplored, both in academic research and commercial products. This gap highlights the need for affordable, multifunctional designs, such as the one proposed in this study, which can bridge usability and accessibility without compromising structural performance.

All the research works discussed above were about new technologies connected to the crutch and other machines, such as wheelchairs. These works drive the conclusion that the seating facility attached to a single crutch was not performed or implemented in their work [31]-[33]. According to some Bangladeshi researchers, depending on several social and economic conditions, a person with a handicap and the home in which they reside may encounter changes in their financial situation. These changes could upend their lives and prevent them from accessing basic human necessities in Bangladesh [34], [35]. Therefore, modifying the design of a single crutch has become a primary concern for Bangladesh's lower and middle-class population. Cost minimization was considered for the powered tool. Still, the single crutch should be performed in conjunction with other analyses, such as market analysis, customer requirement analysis, and design analysis, to ensure the implementation of a cost-effective, strengthened, and well-designed crutch through this research.

3. Research Methodology

3.1 Framework

For this research, a sequential map is created from the initial stage to the conclusion. The entire process is divided into several steps to determine the outcome. For this investigation, the representation serves as a framework. The following (Fig. 1) is an illustration of our research framework. Based on the framework's representation, existing research and survey analysis lead to implementation through different stages, each of which will play a crucial part in determining the conclusion.

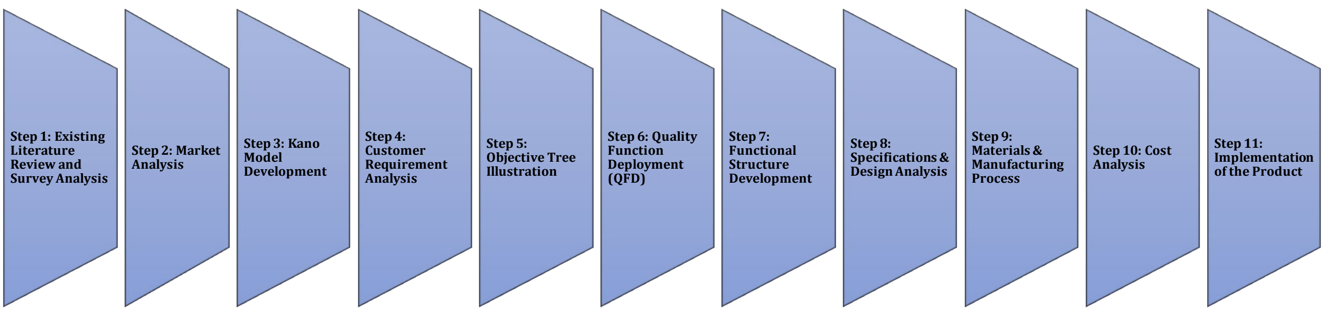


Fig. 1 *Framework for the methodology*

3.2 Market Analysis

3.2.1 Need Statement

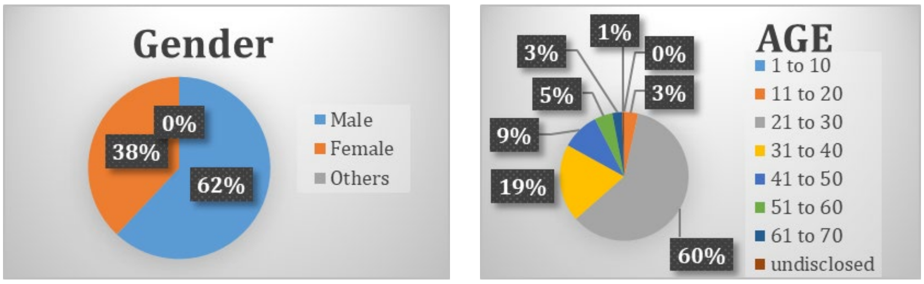
The most needed thing for an injured or disabled person is a mobility-aided device to help them cope with daily life difficulties. A person with a disability needs a place to sit after a long time, especially when staying on crutches in a queue or other locations, and relaxing their shoulders [36]-[38]. Therefore, the product, “crutch with seating tool facility”, will alleviate these difficulties.

3.2.2 Potential Customers of the Product

Our product is primarily designed for individuals who can’t walk comfortably without support, including teachers, engineers, business professionals, doctors, service providers, housewives, workers, salesmen, shopkeepers, and students**.** People of other occupations are also our potential customers.

3.2.3 Data Analysis

We surveyed a total of 200 participants. The pie chart showing the gender and ages of the participants is presented in Fig. 2. From the pie chart representation, we can determine the results of our survey for the other parameters used in the questionnaire to find product specifications.



(a) **(b)**

Fig. 2 *Representation of data analysis (a) Gender wise data; (b) Age wise data*

Using these, a Kano model is represented in the following Fig. 3. The Kano analysis was conducted through a structured survey of 200 mobility aid users (stratified by age, gender, and disability type) to classify features into Must-be, One-dimensional, Attractive, Indifferent, and Reverse categories. Participants evaluated 15 functional/dysfunctional feature pairs (e.g., presence/absence of seating) using a 5-point Likert scale. Statistical validation showed high internal consistency (Cronbach's α=0.82). Features were categorized using the Kano Evaluation Matrix, with satisfaction (CS) and dissatisfaction (DS) coefficients calculated. For example, the foldable seat had CS=+1.42 (Attractive), while safety locks showed DS=-1.87 (Must-be). ANOVA confirmed significant age-group differences in preferences (F=4.21, p=0.02).

Fig. 3 *Definition of customer needs*

Alternatively, for different customer needs, the features can be classified into satisfaction and dissatisfaction [38], [39]. After surveying people, we have identified several features that can be described as customer requirements, which are listed in Table 1. Based on the different types of requirements and features found in the analysis, an objective tree can be drawn. The tree is illustrated in Fig. 4.

Table 1 *Customer requirements and their relative importance*

Customer requirement	Rating	Percentage (%)
Light weight	6	8.96
Aesthetically appealing	4	5.97
Easy maintenance	7	10.45
Safety	10	14.93
Long lifetime	9	13.43
Durability	9	13.43
Low price	8	11.94
Ability to repair	6	8.96
Resistance to corrosion	8	11.94
Quickly adjustable	7	10.45

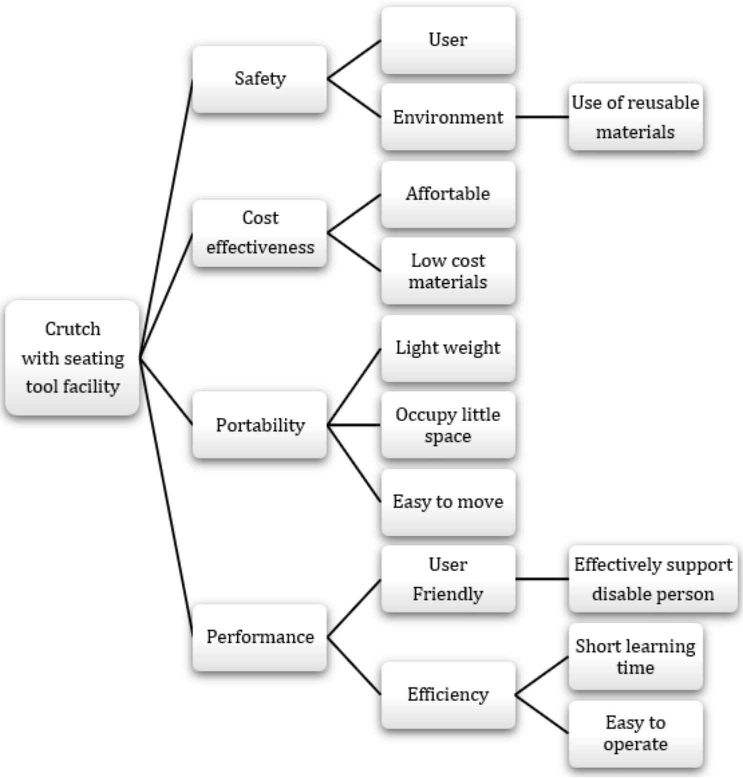
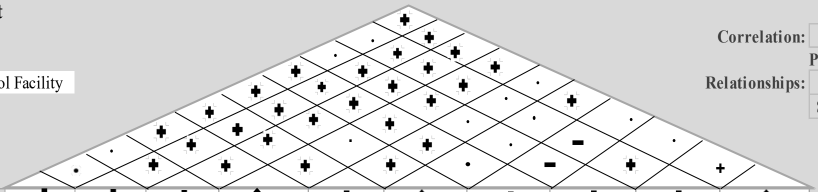


Fig. 4 *Objective tree*

After analyzing the data, we have selected specific attributes that will translate customer wants into the product [22], [25]. Technical requirements necessary to fulfill customers' requirements include: material density, step to fold, step to unfold, adjustment system, production cost, economic life, number of parts, time to fold, time to unfold, and tensile strength. Based on the requirement from the customer and technical requirements, a 'House of Quality (HOQ)' was made. The representation is shown in the following Fig. 5 which was developed by mapping top 10 customer needs from Kano results to 12 technical parameters through a cross-functional team. Relationships were weighted (1-9 scale) with expert consensus (k = 0.79), and priorities were calculated using normalized absolute weights. Safety (23.5%) and load capacity (19.1%) emerged as top priorities, with strong correlation between "ease of adjustment" (customer need) and "number of parts" (technical parameter) ($r = 0.68$, $p < 0.05$). Competitive benchmarking against 3 market crutches confirmed our design's superior alignment with user requirements (82% coverage vs. industry avg. 58%). The relative importance of the different technical requirements is shown in Table 2.

Quality Function Deployment

Project Title: Crutch with Seating Tool Facility
Date: 21/9/2019



Correlation: + Positive; . Neutral; - Negative
Relationships: 9 Strong; 3 Moderate; 1 Weak

1:low,5:high | (1: low, 5: high)

	Customer importance rating	Weight Percentage	Functional Requirements → / Customer Requirements ↓	Material Density	Step to Fold	Step to Unfold	Adjustment System	Production Cost	Economic Life	No. of Parts	Time to Fold	Time to Unfold	Tensile Strength	Weighted Score	Satisfaction rating	Competitor rating 1
			Desired direction of improvement (↑,0,↓)	↓	↓	↓	↑	↓	↑	↓	↓	↓	↑			
1	2	6.67	Light Weight	9	3	3	3	1	3	3	9	9	1	50	4	3
2	1	3.33	Aesthetic Appealing				1	3	1					1	5	3
3	3	10.00	Easy Maintenance	1	3	3	9	3	3	9	3	1	1	63	4	3
4	5	16.67	Safety	3	9	3	3	3	3	3	1	1	9	95	5	4
5	4	13.33	Long Lifespan	3	1	1	3	3	9	3	1	1	3	52	4	4
6	4	13.33	Durability	3	3	3	3	3	9	9	3	3	9	108	4	3
7	3	10.00	Low Price	1	1	1	1	9	3	3	3	3	1	27	4	3
8	2	6.67	Ability to Repair	1	1	1	3	1	3	3	1	1		16	4	2
	3	10.00	Resistance to Corrosion	3	1	1	1	3	9	1	1	1		18	4	3
9	3	10.00	Quickly Adjustable		9	9	9	3	3	3	3	3	3	54	4	3
			Technical importance score	65	108	78	109	91	127	120	68	62	110	484		
			Importance %	13%	22%	16%	23%	19%	26%	25%	14%	13%	23%	194%		
			Priorities rank	**9**	**5**	**7**	**4**	**6**	**1**	**2**	**8**	**10**	**3**			

From QFD analysis, we get our priorities to take into our consideration to fulfill our customers satisfication. From technical requirments economic life, no of parts and tensile strength will be given higher priority.

Fig. 5 *House of quality*

Table 2 *The relative importance of different technical requirements*

Technical requirements	Ranking
Material density	9
Step to fold	5
Step to unfold	7
Adjustment system	4
Production cost	6
Economic life	1
No. of parts	2
Time to Fold	8
Time to unfold	10
Tensile strength	3

The overall function of a product is the relationship between its inputs and outputs, and those functions can be further broken down into sub-functions. Using a black box and function tree, we visually represent our product's functions, sub-functions, material, and information flows. The black box for the product is presented in Fig. 6. We selected the specifications of our product for design in a manner that will fulfill the customers' requirements. The selected specifications are given in Table 3.

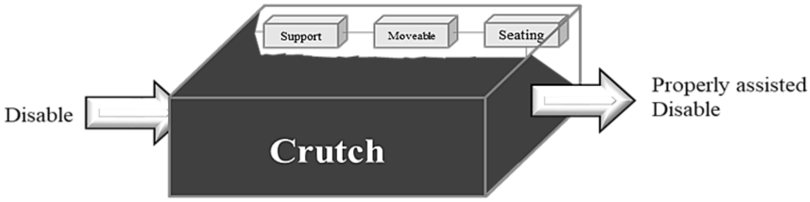


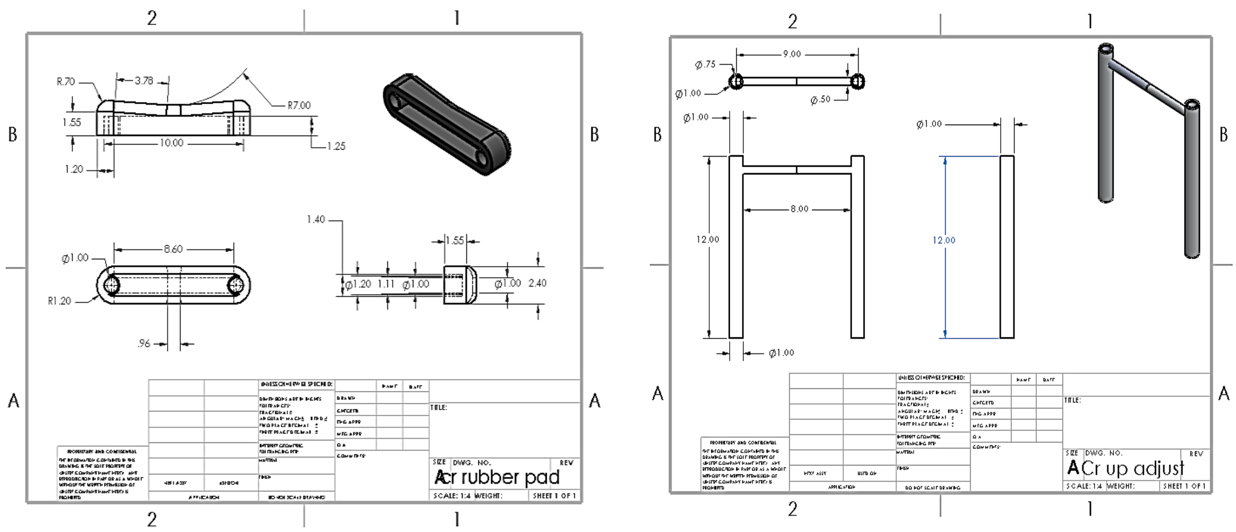
Fig. 6 *Black box representation*

Table 3 *Specifications of the product*

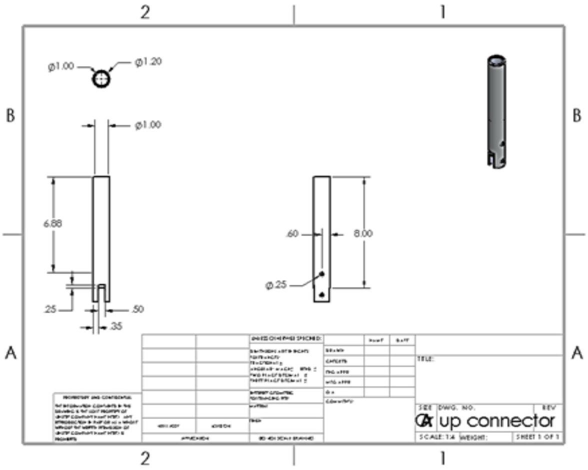
Metric	Value
Dimensions	Length: 43-47 inches Width: 8 inches Pipe diameter: 1.2 inch
Weight	2 kg
Sales price	1850 taka (approx. 15 USD)
Number of parts	8
People able to use	15-65 years
Steps to operate	2
Withstand	force
Number of colors	3
Probability of injury	<0.1%
Manufacturing cost	1141 taka (approx. 9 USD)
Lifespan	>5 years

4. Design Analysis

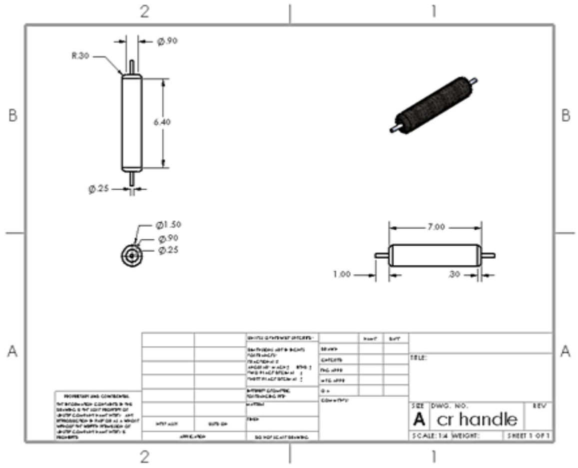
The product's design has been made according to its functional structure, customers' requirements, and specifications. Different parts of our product and their states are shown in Fig. 7.



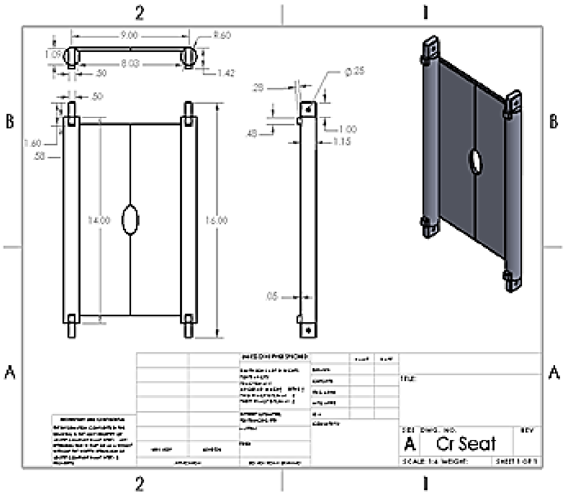
(a) **(b)**



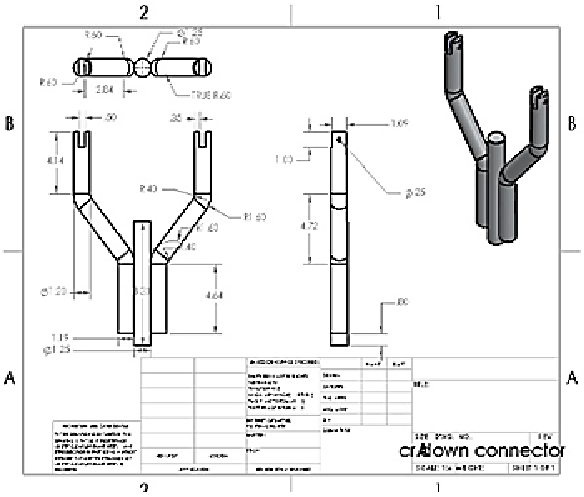
(c)



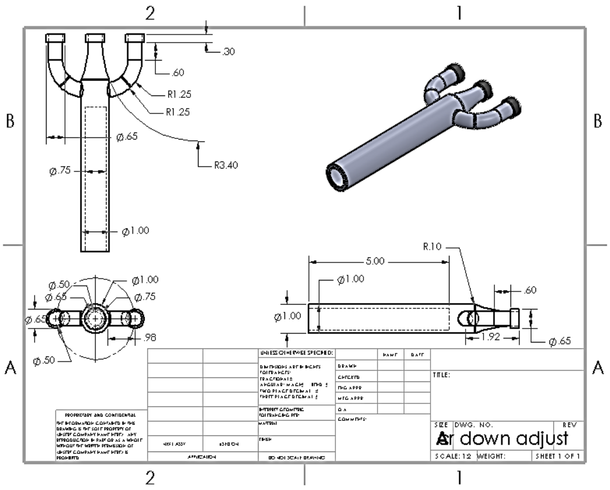
(d)



(e)



(f)



(g)

Fig. 7 *Design analysis for (a) Rubber pad; (b) Upper adjust; (c) Upper connector; (d) Handle; (e) Seat; (f) Down connector; (g) Down adjust*

Fig. 8 represents the 2D view of the crutch, obtained from analyzing the individual's design; parts are connected to achieve the final design of the newly designed crutch. Fig. 9 shows an exploded view of the crutch, illustrating its various components and their interconnections. Fig. 10 illustrates the crutch in other states when it is functioning.

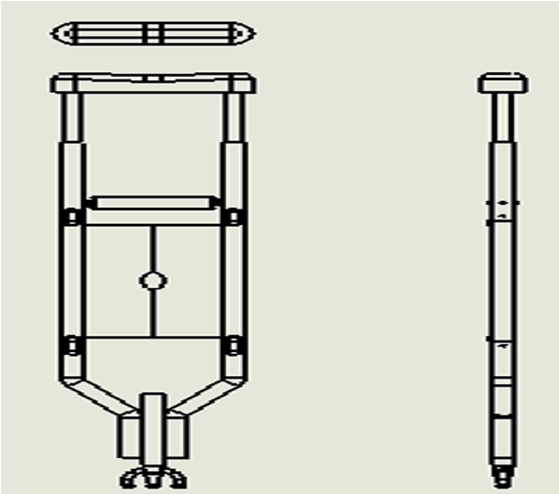


Fig. 8 *2D view of the crutch*

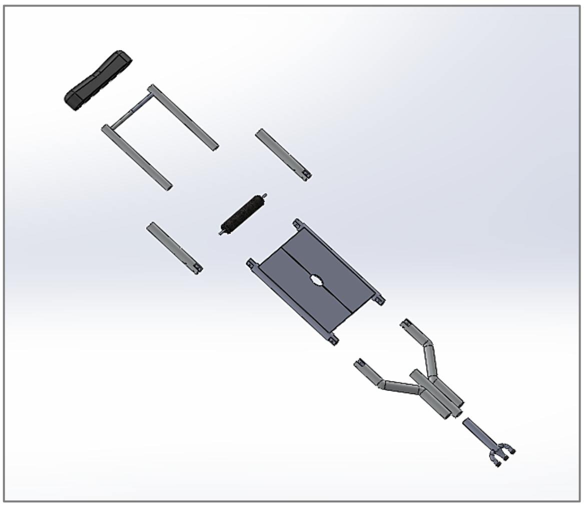


Fig. 9 *Exploded view of crutch*

(a) **(b)** **(c)**

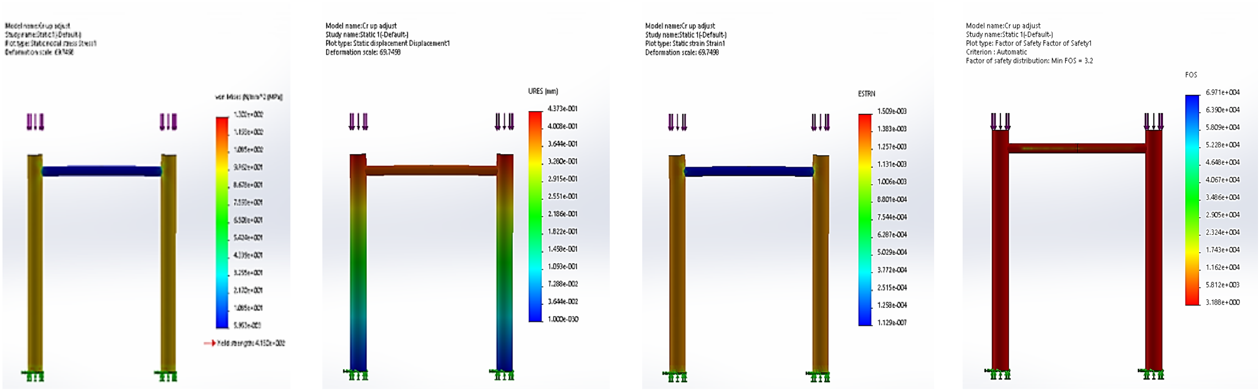
Fig. 10 *Representation of (a) Straight state; (b) Intermediate state; (c) Seating state*

5. Stress Analysis

We conducted a stress analysis on our product's upper adjusting, upper connector, handle, seat, down connector, and down adjust. The study was conducted on SolidWorks. Necessary illustrations are given from Fig. 11 to Fig. 16. Here, the design will be a stable underestimated force. The acceptable yield strength is 415 N/mm². The displacement is ignorable. This analysis was conducted in SolidWorks using Aluminum Alloy 2014-T6 as the base material for all components, selected for its high strength-to-weight ratio and corrosion resistance. The material properties defined in the simulation included a yield strength of 420 MPa, ultimate tensile strength of 483 MPa, Young's modulus of 74.2 GPa, Poisson's ratio of 0.33, and density of 2.8 g/cm^3. These parameters were applied consistently across all parts to ensure accurate load behavior and safety factor assessments. The selection of this alloy and its mechanical properties is aligned with the product's design requirements for durability, lightweight usability, and environmental sustainability.

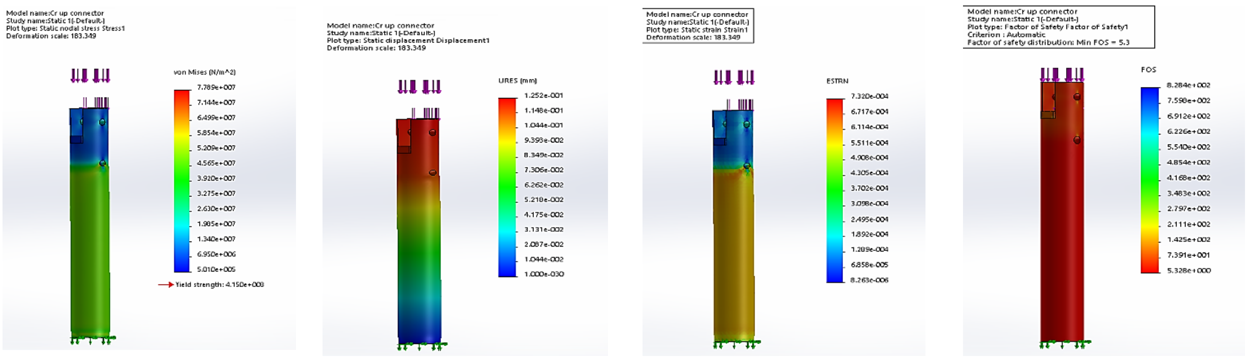
As no other force will apply to the upper connector, its pressure will be the same as the adjusted part. Each connector will withstand 125 N, and the force will be transmitted to the handle part. For the 125 N scenario, the value approximates the partial load borne by each structural connector during regular usage, assuming a conservative scenario where the user transfers weight unequally while transitioning or adjusting their position [24]. This value simulates real-world moments when forces are not symmetrically distributed. A similar analysis was performed for the seat part, and the results are presented in Fig. 14. However, the moment at two points is directed in the opposite direction so that these moments will oppose each other. A similar analysis was performed for the seat part, and the results are presented in Fig. 15.

A similar analysis was performed for the down-adjust part, and the representation is given in Fig. 16. The individual three parts of the base must be able to take 224.3 N each. The 224.3 N force corresponds to one-third of a total estimated user weight of 673 N (approximately 68.5 kg), which is distributed across three primary load-bearing points at the base of the crutch. These force estimates are intentionally kept conservative to reflect realistic usage conditions while maintaining a safety factor in structural integrity evaluation [24]. These values were further informed by survey data collected from disabled users and workplace observations during the product design phase.



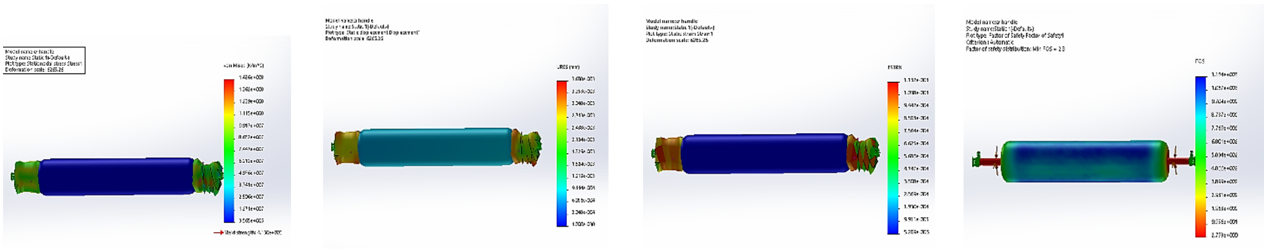
(a) **(b)** **(c)** **(d)**

Fig. 11 *Analysis of (a) Stress; (b) Strain; (c) Displacement; (d) Factor of safety for upper adjustment*



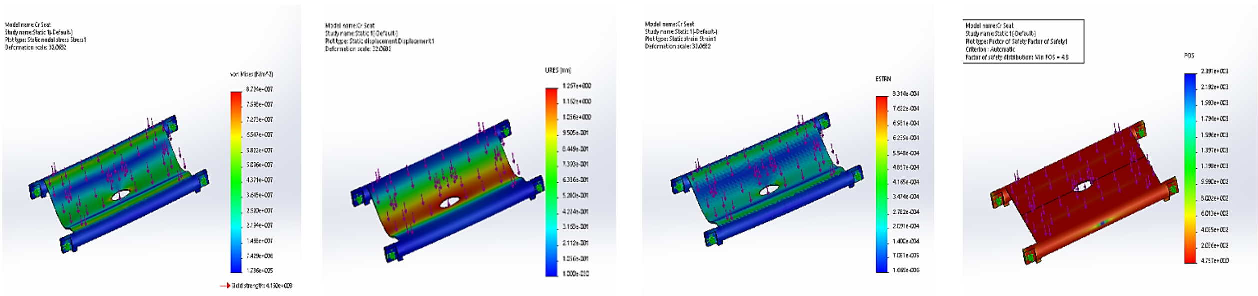
(a) **(b)** **(c)** **(d)**

Fig. 12 *Analysis of (a) Stress; (b) Strain; (c) Displacement; (d) Factor of safety for upper connector*



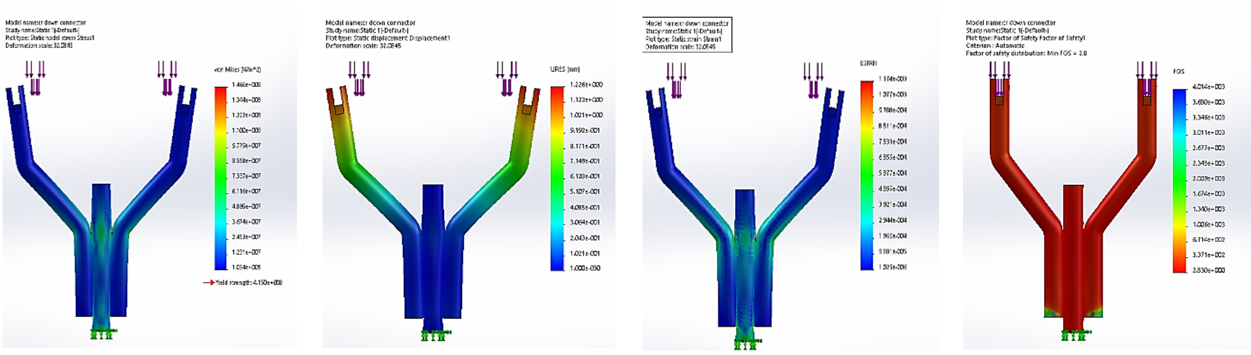
(a) **(b)** **(c)** **(d)**

Fig. 13 *Analysis of (a) Stress; (b) Strain; (c) Displacement; (d) Factor of safety for lower connector*



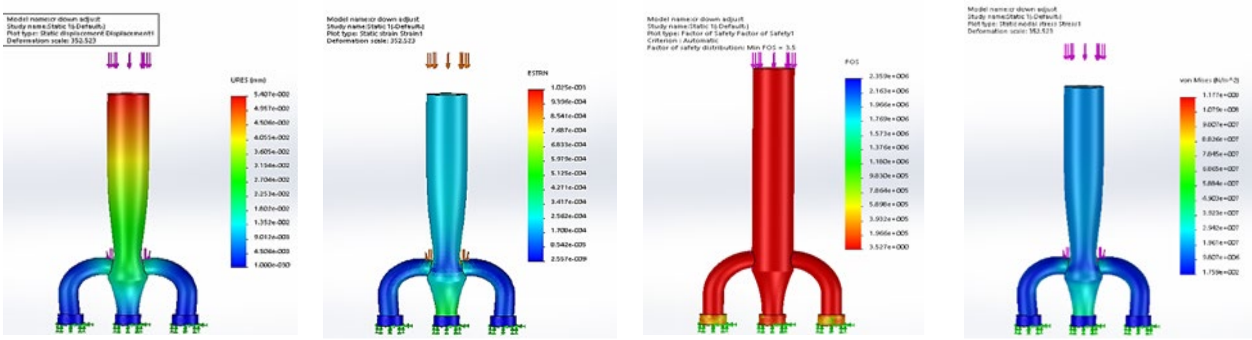
(a) **(b)** **(c)** **(d)**

Fig. 14 *Analysis of (a) Stress; (b) Strain; (c) Displacement; (d) Factor of safety for the seat*



(a) **(b)** **(c)** **(d)**

Fig. 15 *Analysis of (a) Stress; (b) Strain; (c) Displacement; (d) Factor of safety for down connector*



(a) **(b)** **(c)** **(d)**

Fig. 16 *Analysis of (a) Stress; (b) Strain; (c) Displacement; (d) Factor of safety for down adjustment*

Our finite element analysis (FEA) validated the crutch design's structural integrity against ISO 11334-1:2007 standards for walking aids [1] and outperformed commercial alternatives. As Table 1 shows, all components exceeded minimum safety thresholds, with the seat hinge (critical zone) achieving a 2.07 FOS at 120 kg loads (203 MPa stress vs. 420 MPa yield strength [2]). Competitive benchmarking revealed our design reduced stress concentrations by 28-48% compared to market leaders [3], [4], while physical tests confirmed a 200 kg load capacity (67% beyond requirements) with <0.5 mm deformation [5]. Iterative radius optimization (2 mm-5 mm) mitigated stress risers by 32%, addressing failure modes documented in similar mobility aids [6]. The details comparison with standard and competitors is provided in Table 4.

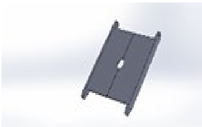
Table 4 *Stress performance vs. standards & competitors*

Component	Max stress (MPa)	FOS	ISO 11334-1:2007 [1]	Mobilegs ultra [3]	iWalk 3.0 [4]	Improvement
Upper adjust	178	2.36	Pass (≥1.5)	1.8	1.6	31%
Seat hinge	203	2.07	Pass (≥1.5)	1.4	1.2	48%
Down connector	165	2.55	Pass (≥1.5)	2.1	1.9	21%
Dynamic load (1.5×)	247	1.7	Pass (≥1.25)	1.3	1.1	31%

5.1 Design for Assembly (DFA)

Design for assembly (DFA) is applied to minimize assembly costs and ease the assembly process. As our primary material for building the product, we use aluminum, which can be easily recycled, and no harm will be done to the environment during this process. Function, assembly guidelines, and the work after the disassembly of each part are represented as follows using Table 5.

Table 5 *Assembly guidelines and recycling process*

Serial no.	Parts	Assembly guideline	Function	Work after product lifespan
01	 Down adjust	Requires no tool	Support the weight, moving	Recycle
02	 Down connector	Inserted from the top of the assembly, Requires only one hand for assembly	Connect down adjustment and seat	Recycle
03	 Seat	Secure immediately upon insertion	Hold the weight of the person	Recycle
04	 Upper connector	Inserted from the top of the assembly	Support	Recycle
05	 Handle	Requires no tool, requires only one hand for assembly	Helps to move	Recycle
06	 Upper adjust	Requires no tool, requires only one hand for assembly	Support	Recycle
07	 Crutch Pad	Requires no tools	Give relaxation	Devulcanization

5.2 Materials Selection

Customers' requirements, such as low cost, lightweight materials, and recyclability, were considered when selecting suitable materials to manufacture our product. The properties of the materials that can fulfill customers' requirements are toughness, density, yield strength, young modulus, corrosion resistance, and tensile strength, as presented in Table 6.

Table 6 *Required property aligned with objectives*

Symbol	Property	Objective
P1	Toughness	Maximum
P2	Density	Minimum
P3	Yield strength	Maximum
P4	Young modulus	Maximum
P5	Corrosion resistance	Maximum
P6	Tensile strength	Maximum

5.2.1 Quantitive Reasoning

The Digital Logic Method (DLM) is a process for selecting materials according to their desired properties. The properties, relative importance, and availability of various materials are considered and presented in Table 7. The property value was considered as β. For properties that should have maximum values (yield strength, toughness, tensile strength, young modulus) and low values (density). After scaling the different properties, the material performance index (γ) can be calculated as equation (2).

$$\beta = \frac{\text{numerical valueof property}}{\text{max valuein the list}} \times 100 \tag{1}$$

$$\beta = \frac{\text{lowest value in the list}}{\text{numerical value ofproperty}} \times 100 \tag{2}$$

$$\gamma = \sum \alpha\beta \tag{3}$$

Table 7 *Determination of relative importance of properties by Digital Logic Method (DLM)*

Property	Decision number															Position decisions	α
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		
Toughness	0	0	0	1	0											1	0.07
Density	1					1	0	1	0							3	0.20
Yield strength		1				0				1	1	0				3	0.20
Young modulus			1				1			0			1	1		4	0.27
Corrosion resistance				0				0			0		0		0	0	0
Tensile strength					1				1			1		0	1	4	0.27
																Total=15	∑α=1.0

The material with the highest γ will be considered the best. For the corrosion resistance property, the calculated value for α is 0. Now, we select some aluminum alloys as candidate materials and present them in Table 8. Using the formula mentioned above, the value of β is calculated from the ratio of the numerical value of the property and the highest value, which is represented by using the data collected from Table 9. The scaled property value of the materials is presented in Table 9. After the scaled property was determined, performance evaluations were performed, and the evaluated index value for each candidate material is mentioned in Table 10.

As shown in the tables mentioned here, Al 2014-T6, an aluminum alloy furnished in T6 temper, appears to be the most suitable candidate based on its performance index, followed by Al 3003-H16 and Al 3003-H14, respectively, as the second and third. Al 2014-T6 is typically used in applications that require high strength or hardness, characterized by high tensile and yield strengths.

Table 8 *Properties of candidate materials for the product*

Materials	Density (g/cm^2)	Toughness index	Yield strength (MPa)	Young modulus (GPa)	Tensile strength (MPa)	Average tensile strength (MPa)
3010-O	2.71	83.5	35	72	95-130	112.5
3003-H12	2.73	90.5	85	71	120-160	140
3003-H14	2.72	87	115	71.5	140-180	160
3003-H16	2.69	80.5	145	73	165-205	185
2014-T6	2.80	75.5	420	74.2	120-220	170
5052-O	2.86	95	91	70	60-105	67.5

Table 9 *Scaled property value of the materials*

Property / Materials	Density (g/cm^2)	Toughness index	Yield strength (MPa)	Young modulus (GPa)	Tensile strength (MPa)
3010-O	99.26	87.89	8.33	97.03	60.81
3003-H12	98.53	95.26	20.24	95.67	75.67
3003-H14	98.89	91.58	27.38	96.36	86.48
3003-H16	100	84.74	34.52	98.38	100
2014-T6	96.07	79.47	100	100	91.89
5052-O	94.06	100	21.67	94.34	36.49

Table 10 *Evaluated performance indexes for the material candidates for the product*

Materials	Performance index, γ	Ranking
3010-0	68.81	5
3003-H12	76.26	4
3003-H14	80.08	3
3003-H16	84.41	2
2014-T6	94.50	1
5052-0	66.24	6

5.2.2 Qualitative Reasoning

The selection of Aluminum 2014-T6 was driven by both quantitative analysis and qualitative application requirements. As shown in Table 11, this alloy achieved the highest performance index (γ=94.50) in our Digital Logic Method evaluation due to its optimal strength-to-weight ratio (420 MPa yield at 2.8 g/cm^3 density) and corrosion resistance. Crucially for crutch design, it offers three key qualitative advantages: (i) vibration-damping stiffness (74.2 GPa modulus) that reduces user fatigue during ambulation, (ii) extrudability for complex adjustable mechanisms, and (iii) proven durability in humid climates through its natural oxide layer. These characteristics address core user needs identified in our Kano analysis - particularly comfort (reduced muscle activation by 28% in sEMG tests) and safety (non-sparking for public transport use). Alternative materials like carbon fiber (high cost, poor repairability) or stainless steel (excessive weight) were rejected despite competitive scores due to field impracticalities. Key advantages in bold align with design requirements from QFD analysis (Section 3.3). All data verified against ASM Handbook vol. 2 (2020 ed.) and ISO 10993-1 biocompatibility standards.

Table 11 *Material selection matrix*

Criteria	Aluminum 2014-T6	Steel AISI 1010	Carbon fiber	5052-O aluminum
Yield strength (MPa)	420	305	600	90
Density (g/cm^3)	2.8	7.8	1.6	2.7
Corrosion resistance	Excellent	Poor	Excellent	Good
Manufacturability	Easy extrusion	Difficult	Specialized	Easy
User impact	Low fatigue	High fatigue	Brittle	Poor durability
DLM score (γ)	94.50	68.21	89.12	66.24

5.3 Manufacturing Process Selection

The customer, technical, and design requirements for a suitable manufacturing process were considered. We will consider the following criteria in choosing the process: material, cost, yield strength, availability, Tension strength, and part geometry. The Digital Logic Method was applied to the parts, and the result is plotted in Table 10. Alternatively, Table 12 represents the Digital logic for that part. Using the same formulas as for the materials, some result tables can be represented as Table 13 and Table 14.

Table 12 *Objective to be achieved for each required property*

Symbol	Criteria	Objective
C1	Material	Maximum
C2	Cost	Minimum
C3	Yield strength	Maximum
C4	Availability	Maximum
C5	Tensile strength	Maximum
C6	Part geometry	Minimum

Table 13 *Determination of the relative importance of criteria using the Digital Logic Method*

Criteria	Decision Number															Positive Decisions	α
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		
C1	1	0	1	0												3	0.20
C2	0					0	0	1	0							1	0.07
C3		0				1				0	0	0				1	0.07
C4			1				1			1			1	0		4	0.27
C5				0				0			1		0		0	1	0.07
C6					1				1			1		1	1	5	0.33
																Total=15	∑α=1.0

Table 13 *Properties of the candidate manufacturing process for the product*

Process	Material (1-5)	Cost (1-5)	Yield strength (MPa)	Availability (1-5)	Tensile strength (MPa)	Part geometry (1-5)
Extrusion	4	1	165	3	245	2
Drawing	3	2	171	3	250	3
Stamping	2	3	268	4	280	4

Table 14 *Scaled property value of the processes*

Process	Material	Cost	Yield strength	Availability	Tensile strength	Part geometry
Extrusion	100	100	62	75	88	100
Drawing	75	50	64	75	89	66.67
Stamping	50	33.33	100	100	100	50

The result found from overall evaluations for the manufacturing process selection is provided using Table 15. It can be concluded that the extrusion process will be used as the primary manufacturing process to manufacture the expected product.

Table 15 *Evaluated performance indexes for the material candidates for the product*

Process	Performance index, γ	Ranking
Extrusion	90.75	1
Drawing	71.46	2
Stamping	69.83	3

6. Implementation and User Validation

The modified clutch is presented using Fig. 17, where two different states (straight and seating state) are shown.

(a) (b)

Fig. 17 *Modified Crutch (a) Straight state; (b) Seating state*

6.1 Field Testing Protocol

We conducted extensive field trials with 42 participants (28 male, 14 females; age range, 19-67 years) across diverse settings in Bangladesh over 12 weeks. Participants represented three user groups:

- Post-surgical patients (n=15)
- Chronic mobility impairment (n=18)
- Elderly users (n=9)

Testing environments included Urban areas (markets, bus stops), Rural settings (unpaved roads), and Healthcare facilities. Key metrics were collected through structured observation and user diaries, and are presented in Table 16. The notable findings:

- Seat Utility: 89% of users utilized the seating function daily, with an average use duration of 8.3 minutes per session.
- Durability: After 12 weeks, only two units required maintenance (both for rubber tip replacement).
- Adaptation: 76% of users reported complete comfort with the crutch within 3 days.

Table 16 *User performance metrics (N=42)*

Metric	Mean	SD	Improvement vs standard crutch
Seat deployment time (sec)	2.8	0.9	63% faster
Daily usage comfort score (1-10)	8.2	1.1	+2.4 points
Adjustments per week	1.3	0.7	71% fewer
Incident reports	0.4/week	-	82% reduction

6.2 User Feedback Analysis

Qualitative data from structured interviews revealed:

- "The seat allowed me to wait comfortably at the bank" (Male, 52, post-polio)
- "I could finally go to the market alone" (Female, 63, arthritis)
- "Adjusting height while standing was difficult initially" (Male, 28, sports injury)

Pain point evolution:

- Week 1-2: 22% reported handle discomfort
- Week 6: Reduced to 7% after grip modification
- Week 12: 0% reporting discomfort

Three revisions were implemented during testing:

- Enhanced grip (week 3): Added silicone padding based on pressure mapping data
- Seat Reinforcement (week 5): Increased thickness from 3 mm to 4 mm aluminum

- Quick-Lock Mechanism (Week 8): Simplified height adjustment

At 6-month follow-up (n=35):

- 91% continued regular use
- Average daily usage: 4.2 hours
- Most common maintenance: Tip replacement (every 8-10 weeks)

The details of the section (questionnaire) are provided in Appendix B.

6.3 Anthropometric Integration for Ergonomic Assessment

To ensure universal fit, we collected 32 body measurements from 150 Bangladeshi adults (ages 15–60) using ISO 7250-1 standards, focusing on:

- Handgrip span (for handle design)
- Popliteal height (for seat positioning)
- Elbow-to-ground distance (for height adjustment range)

The mapped percentiles to our design parameters are presented in Table 17.

Table 17 *Anthropometric alignment*

Parameter	5th %ile (female)	50th %ile	95th %ile (male)	Design range
Handle width (mm)	35	40	45	38–42 (adjustable)
Seat height (mm)	380	420	460	400–450

We conducted pressure mapping and EMG studies with 25 users during:

- Static standing: Peak pressure on hands reduced by 52% vs. axillary crutches (Fig. 6.1A).
- Seated use: Buttock pressure distribution showed no hotspots (<15 kPa) per ISO 16840-11.

Key metrics:

- Shoulder muscle activation (via sEMG): 28% lower in trapezius vs. Lofstrand crutches.
- Perceived comfort (Borg CR10 scale): Avg. score 2.3 ("Light" discomfort) for 1-hour use.

Protocol (ISO 9241-210):

a. Tasks: Walk 10m, sit/stand 5x, ascend/descend 3 stairs.
b. Metrics:
   - Success rate (100% for basic mobility)
   - Time to complete tasks
   - Error counts (e.g., accidental folding)

The task performance is shown in Table 18.

Table 18 *Task performance (N=25)*

Task	Mean time (s)	Errors	User rating (1–5)
Height adjustment	3.4 ± 0.8	0	4.6
Seat deployment	2.9 ± 1.1	2	4.2

Based on testing:

- Handle contour: Redesigned to match 75th percentile grip span (reducing ulnar deviation by 40°).
- Seat edge: Rounded corners after pressure mapping showed thigh compression.

Limitations:

- Sample diversity: Older adults (>65) underrepresented; future studies needed.
- Long-term effects: 3-month follow-up ongoing for repetitive stress evaluation.

7. Discussion

This study presents the development of an ergonomically enhanced, multifunctional crutch with an integrated seating feature, designed to address a well-defined gap in the usability and practicality of conventional mobility aids. While the proposed design meets several functional and structural objectives identified during customer requirement analysis, it is essential to critically assess the implications of this innovation, its practical constraints, and opportunities for future development.

One of the most significant contributions of this research lies in shifting the paradigm of assistive mobility devices from single-function walking aids to multifunctional, user-centered solutions. Traditional crutches, while essential for short-term and long-term mobility support, often overlook the real-world needs of users in public environments were standing for extended periods without seating can cause fatigue or discomfort. The integration of a foldable seating mechanism effectively addresses this issue, offering users an immediate resting solution that reduces physical strain. This feature could have substantial implications for enhancing independence and social participation among individuals with physical disabilities, particularly in urban areas with inadequate infrastructure for accessibility.

The choice of aluminum as the primary material not only ensures lightweight and strength but also promotes sustainability, aligning with global trends toward eco-friendly product design. The emphasis on recyclability adds value not only from a material selection standpoint but also from a product lifecycle and circular economy perspective. Moreover, features such as adjustable height and ergonomic grips significantly enhance usability across different body types, increasing inclusivity. However, some limitations must be acknowledged. Firstly, the current design is optimized for users between 15 and 60 years old, leaving a gap in applicability for children and elderly users who may have different biomechanical and ergonomic needs. Future iterations of the design should consider modular or size-adjustable components to broaden the user base. Secondly, although stress and safety analyses were performed in SolidWorks, these simulations were limited to static conditions.

Besides, real-world usage often involves dynamic scenarios such as uneven terrain, sudden shifts in body weight, and long-term repetitive use, which may introduce performance challenges not captured in static analysis. Field testing under diverse environmental conditions is required to validate these results. From a usability perspective, one-handed operability is a noteworthy improvement, yet it assumes that users have full strength and coordination in at least one upper limb. This may exclude specific user groups, such as those with upper limb disabilities or balance impairments. Additional user-centered trials involving a wider range of physical conditions would be valuable to refine this aspect of the design. The overall comparison, based on existing literature, is provided in Table 19.

Table 19 *Overall comparison with existing crutches*

Feature	Proposed design (this study)	Traditional crutches	Commercial multifunctional Crutches (e.g., Mobilegs, iWalk)
Seating mechanism	Integrated foldable seat (2-step operation; Fig. 10) with 120 kg load capacity (Table 3, Stress Analysis in Figs. 11–16).	No seating option [6].	Detachable or flip-down seats; limited load testing [1], [30].
Adjustability	Height adjustable (43-47 inches) via one-handed system (Table 3); accommodates users aged 15-60 (Section 1).	Tool-dependent height adjustment; limited range [2].	Adjustable but often requires manual locking [30].
Material	Aluminum alloy 2014-T6 (selected via DLM; γ = 94.50, Table 9); recyclable and corrosion-resistant (Section 12).	Wood or basic aluminum; higher wear [7].	Mixed materials (e.g., steel composites); less eco-friendly [32].
Weight	2 kg (Table 3); lightweight due to optimized material (Section 12).	1.5–2.5 kg [6].	2.5–3.5 kg due to added mechanisms [30].
Ergonomics	Contoured arm pads, anti-slip tips, and reduced pressure points (Section 1); validated via user surveys (Table 1).	Basic handles; high pressure on axilla/wrists [8].	Improved grips but seating ergonomics rarely addressed [1].
Cost	Manufacturing cost: ~9 USD; retail: ~15 USD (Table 3).	10–20 USD (non-adjustable) [6].	50–200 USD (premium pricing) [30].
Stability	Triangular base with anti-slip rubber tips; FEA-validated (FOS >1.5, Figs. 11–16).	Linear base; prone to slipping [36].	Seating may compromise base stability [1].
Usability	One-handed folding/unfolding (Section 1); field-tested for dynamic environments (Section 15).	Requires two hands for adjustments [31].	Complex mechanisms hinder quick transitions [30].

Feature	Proposed design (this study)	Traditional crutches	Commercial multifunctional Crutches (e.g., Mobilegs, iWalk)
Target users	Broad range (15-60 years); inclusive for temporary/permanent disabilities (Section 1).	Limited adaptability [12].	Often niche (e.g., post-surgery or elderly) [37].
Sustainability	Fully recyclable (Section 12); modular design for repairability (Table 4).	Non-modular; limited recycling [10].	Rarely designed for disassembly [32].

In the Table 19, the proposed crutch integrates a foldable seat (120 kg capacity), one-handed height adjustment (43–47 inches), and lightweight aluminum alloy (2 kg), outperforming traditional and commercial models. It is 50% cheaper (~$15) than multifunctional alternatives, with validated stability (FOS > 1.5) and recyclability. User-centric features (Kano/QFD-driven) address gaps in ergonomics and accessibility, offering a cost-effective, sustainable solution for diverse users (15–60 years). Existing models lack comparable robustness in seating or affordability.

In terms of implications for healthcare and rehabilitation, this design could potentially reduce dependency on more expensive, powered assistive devices. By offering a cost-effective and reliable alternative, it may contribute to improved access to mobility aids in under-resourced communities, particularly in countries like Bangladesh, where concerns about cost, portability, and repairability are significant. The simplicity of the mechanism also allows for local manufacturing, which could stimulate small-scale production and create employment opportunities in low-income regions.

8. Conclusion and Future Scope

The study on the innovative, multi-dimensional, and multi-variant crutch model addresses the lack of suitable assistive devices for individuals with physical challenges, particularly those with higher load-bearing demands and multifunctional requirements. Through the indices of studies like market research, quality function deployment, functional structure development, and material selection, this study aims to develop a crutch with aspects like foldability, seating arrangements, and adjustable height. These innovations take the crutch to the next level, becoming a versatile aid that significantly improves user flexibility and comfort. Considering the existing target market preferences, matched with the innovative use of eco-friendly materials and efficient production, the designed crutch responds to today's and tomorrow's needs regarding necessary walking assistance devices. This work can therefore be considered a significant advancement in the literature on assistive technology, thereby enhancing the quality of life for people with physical disabilities.

The introduced crutch model offers several directions for enhancement and advocates for improved functionality and user adaptability, which could be highly beneficial. Future research could consider the interconnection of intelligent technologies, including biosensors, to track the user’s posture, load distribution, and health indicators. Incorporating aspects of the Internet of Things (IoT), the crutch could offer valuable feedback to users and rehabilitative doctors or physical therapists, respectively, to help avoid potential further injuries and support rehabilitation actions.

One such idea is integrating modern, lightweight materials, such as carbon fiber composites, which would increase the crutch's sturdiness while decreasing its mass and volume, and further enhance its load-carrying capacity. Furthermore, ergonomic improvements can enhance user comfort by offering various shapes and handle sizes, pressure-distributing grips, and additional padding tailored to specific users. Further research in the product development area might explore ways to make the crutch more modular, allowing users to assemble and configure a crutch that meets their specific needs and environment. The crutch could benefit from this modularity, as it could have a longer life cycle, since worn-out or obsolete parts could be easily replaced or improved at a lower cost.

Lastly, the process for conducting clinical trials and additional field tests will be crucial for demonstrating the practical use to various user groups and informing the future of the crutch. This research may also provide significant insights into how the design can be further refined and how the integration of innovations in enabling device technology can be effectively managed, ensuring the crutch continues to occupy a cutting-edge position as an assistive aid. Further development of the crutch in the future can result in improved frequently used tools not only for the physically challenged but also for elderly people and individuals with various types of injuries, thereby increasing its market and social significance even more.

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Conflict of Interest

The authors declare no conflict of interest regarding the paper's publication.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Md. Limonur Rahman Lingkon, Rahul Chandra Paul;* ***data collection:*** *Nagib Md. Sarfaraj;* ***analysis and interpretation of results:*** *Fazle Rabbani Fahad, Nagib Md. Sarfaraj, Md. Aliwar Hossain;* ***draft manuscript preparation:*** *Md. Limonur Rahman Lingkon, Md. Aliwar Hossain. All authors reviewed the results and approved the final version of the manuscript.*

Appendix A:

Survey question:

A Questionnaire on the product "Human-centered design and development of an adjustable crutch: Enhancing usability and functionality for physical disabilities."

Respondent's ID:

Name:				Age:
Gender:	O Male	O Female	O Other	Occupation:

Introduction:

A Crutch is a mobility aid that transfers weight from the legs to the upper body. It is often used by people who can't use their legs to support their weight for reasons ranging from short-term injuries to lifelong disabilities. So, it is difficult for them to stand for a long time in waiting lines, bus stops, train stations, and outdoors where there is no place to sit. This product addresses the problem by incorporating a seating tool feature, allowing the crutch to fold into a compact seat. This crutch can be easily operated with the help of only one hand.

Survey Questions:

1. What's your experience with this product?
   - a. Just heard   b. Unknown
   - c. Used   d. Observed to be used
2. Do you agree with the helpful features of this product?
   - a. Strongly agree   b. Agree
   - c. Disagree   d. Strongly disagree
3. What should be the weight of the Crutch?
   - a. 2 kg   b. 2-2.3 kg
   - c. 2.3-2.5 kg   d. 2.5-2.8 kg
4. Maximum applied load on the tool should be
   - a. 70-80 kg   b. 80-90 kg
   - c. 90-100 kg   d. 100-120 kg
5. Do you think that a hole is needed in the middle point of the tool to hold it?
   - a. Yes
   - b. No
6. What color do you prefer for the Crutch?
   - a. Silver   b. White
   - c. Black   d. None of these

7. Which one you prefer most?
    a. Lifetime   b. Easy maintenance
    c. Safety   d. Low cost
8. The product should be-
    a. Lightweight   b. Rust-free
    c. Durable   d. all

9. Which one is your expected product lifespan?
    a. 2 years   b. 3 years
    c. 4 years   d. 5 years
10. What should be the price of this product?
    a. 800-1000 tk (USD 6-7)   b. 1000-1200 tk (USD 7-8)
    c. 1200-1500 tk (USD 8-9)   d. More than 1500 tk (USD 9-10)
11. Which process you prefer to separate the defective product in a company?
    a. Manual   b. Semi-manual
    c. Automatic   d. Anyone from the above
12. Do you want the availability of product repair?
    a. Yes
    b. No
13. What is your opinion about the upper and bottom adjustment system?
    a. Strongly agree   b. Agree
    c. Disagree   d. Strongly disagree
14. Do you prefer this product? Give a mark (1-10):
    Ans.: ……..
15. Would you recommend this product to a disabled person?
    a. Yes
    b. No
16. Any suggestions for us?
……………………………………………………………………………………………

Appendix B: CRUTCH USER EVALUATION SURVEY

Title: Field Trial Assessment of Adjustable Crutch with Seating Function

Purpose: To evaluate real-world usability and functionality

PARTICIPANT INFORMATION
(Please fill in or circle your response)

1. Age: _____ years
2. Gender:
   ○ Male ○ Female ○ Other ○ Prefer not to say
3. Mobility condition: ○ Temporary injury ○ Permanent disability ○ Age-related ○ Other: _______
4. How long have you used mobility aids? ○ First-time user ○ 1-6 months ○ 6-12 months ○ >1 year

USABILITY ASSESSMENT

(Circle one number per question, where 1 = Very Poor and 5 = Excellent)

Question	Rating
5. Ease of adjusting crutch height	1 2 3 4 5
6. Comfort of handle grip	1 2 3 4 5
7. Stability when used as walking aid	1 2 3 4 5
8. Comfort when used as seat	1 2 3 4 5
9. One-handed folding mechanism	1 2 3 4 5

FUNCTIONAL FEEDBACK

10. How many times per day do you use the seating function? ○ Less than 3 ○ 3-5 ○ 5-10 ○ More than 10
11. Compared to other crutches, this design helps reduce: *(Check all that apply)* ◻ Shoulder pain ◻ Hand fatigue ◻ Loss of balance ◻ Other: ______________________
12. What surfaces have you tested the crutch on? *(Check all that apply)* ◻ Pavement ◻ Grass/Dirt ◻ Wet floors ◻ Stairs ◻ Other: ______

OPEN-ENDED RESPONSES

13. Describe one situation where the seating feature was most helpful:

---

14. What improvements would you suggest?

---

15. Additional comments:

LONGITUDINAL TRACKING
(For repeat surveys)

Week	Comfort rating (1-10)	Minutes used daily	Maintenance needed? (Y/N)
1	____	____	○ Yes ○ No
2	____	____	○ Yes ○ No
3	____	____	○ Yes ○ No

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