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Design and fabrication of an engineered multi-mode worker toolkit for construction and agriculture industries

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K E Y W O R D S

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Construction and Agriculture Industries

FEA Analysis

Ergonomics

Low-Cost Toolkit

A B S T R A C T

The workers at construction and agricultural sites face many problems regarding load carrying (body pains), which results in less work efficiency. Therefore, the idea of designing a toolkit is put forward, with the help of which the workers could do their work easily and efficiently. This study aims to design and fabricate a low-cost toolkit that is lighter and easily accessible to all workers. The toolkit is designed to be used in different positions or modes. The most important step in this project is material selection, as it will define the toolkit's final weight, cost, and strength. Various materials, such as wood, bamboo, aluminum, steel, etc., were compared based on their physical properties, such as their strength, weight, and behavior in changing weather. The material selected is steel due to its high strength, weldability, and low cost. A design was finalized by incorporating safety and worker comfort. An ANSYS analysis was then performed on the proposed design to check it for loading capacity and deformation in various modes of operation. After performing the ANSYS analysis, the toolkit was fabricated and tested at various modes of operation. It was found that the tool performed exceptionally well at loads less than 20 Kg, whereas there were some minute deflection errors (max. error of 1.7 mm) at loads greater than 35 Kg.

1. Introduction

Ergonomics is the study of people who work in their working environment. An ergonomist is a person who tries to design or modify the way the work is performed by the workers [1]. The main objective is to eliminate the discomfort and possible injury from the workers' work. While analyzing this job, three attributes were considered, i.e., the effort required to complete that task, the position adopted during performing that task, which may be awkward or static, and how often the task is accomplished. Any one of them or integration of these factors led to significant discomfort. The workplace impacts worker safety, health, and productivity. Smart tools help identify and manage occupational hazards to promote total worker health. Patel et al. [2] reviewed some of the tools workers use and the recent trends in workplace technologies for monitoring and managing occupational risks, injuries, and diseases.

In South Asian countries like India, Pakistan, Bangladesh, etc., millions of people are below the poverty line [3], due to which they are the biggest challenge for their respective governments. These people are compelled to work as workers/laborers in coal mines, construction sites, agricultural sites, brickyards, etc., due to a lack of education and technological advancement. A large proportion of these laborers are women. Physically, these women are weaker than men when working as workers. When these women workers carry heavy loads, they face many problems, such as pains (head and back pains) and respiratory problems. In India, women's participation in the workforce is 24 % [4]. Even men face lots of physical stress and muscular pains when working in these industries. As essential members of society, facilitation in the form of a worker toolkit is the need of the hour.

Moreover, in developing countries such as Pakistan, a large ratio of women are forced to do work in brickyards, construction sites, and agricultural sites. These workers face serious issues regarding their safety due to the high load carried on their shoulders, heads, and backs, which has serious effects on their bodies in the form of pains and strains [5]. As these people cannot afford to maintain their health due to their financial conditions, it leads to some serious physical conditions, because of which they will not be able to work as their age passes on. As safety is the main concern these workers face, researchers performed some work on designing or fabricating a toolkit [6]. The survey conducted by authors [6] concluded that most of the pains associated with overhead loading could be eliminated or reduced significantly using the overhead load manager (toolkit).

By utilizing the overhead toolkit developed by researchers [7], the workers could perform their work easily and efficiently, which helped them carry the load over their heads. Similarly, other researchers [8] also worked on fabricating overhead load managers or carriers, which could help workers perform their tasks safely and easily and reduce musculoskeletal stress. Another study by J. Choudhary et al. [9] discussed the possibility of fabricating an interchangeable-mode toolkit that could carry the load in three different modes, one at a time. These modes were 1) overhead loading, 2) load as a backpack, and 3) trolley mode of loading. The toolkit reduced physiological load and improved posture while carrying a load on the backside. In all the above-mentioned worker toolkits, Aluminium, steel, wood, or combinations of these have been used for fabrication. Aluminium has a high strength-to-weight ratio, wood is inexpensive, and steel has high durability, better weldability, and low cost. Aluminum can also be welded using friction stir welding [10, 11]. Moreover, a shoulder exoskeleton (SE) is a wearable device that reduces shoulder strain by providing assistive torque. This is also an active research domain for researchers working in the industrial fields. Mostly, overhead exoskeletons are under research in many studies, and some work has also been done on shoulder and back exoskeletons [12-15].

From the above discussion, it is clear that there are few studies on the fabrication of worker toolkits, mainly covering overhead loading, and only one study discussed the possibility of a tri-mode worker toolkit [9]. However, proper designing and finite element analysis (FEA) of such design are not reported in the literature. Therefore, this study is conducted to design, analyze FEA, and fabricate a multi-mode worker toolkit (MMWT). This MMWT is engineered with high-quality materials and precisely manufactured. This toolkit is designed to help workers perform jobs in construction, agricultural sites, and other industries. This toolkit can carry loads by using two modes at a time (over the head and back loading modes), while in trolley mode, the load can be carried only in a single mode. This toolkit features a user-friendly design that encourages continuous work without any difficulty. This toolkit can transform from one mode to another according to the toolkit's preference and customization.

2. Material and Methods

2.1 Design

Based on the literature review and the physical body features of human beings, an initial design was proposed, with a total height of 36 inches and the ability to operate in three loading modes. This design is shown in Fig. 1(a). After a few ANSYS tests, the new design (Fig. 1b) was proposed with little modifications. These modifications include two hinges on the top and bottom support structures, each with a support structure, bolts, and nuts, which can be adjusted according to needs. These design modifications make it very easy to transport the toolkit from one place to another because the top and bottom support structures can be converted into a no-use position.

2.2 FEA Analysis Through ANSYS

FEA analysis was performed using ANSYS workbench (student version 2023). After finalizing the CAD design, the next step is to select proper loading and fixed surface conditions. For overhead, backpack, and combined loading conditions, the surfaces of the handles of the structure in an upright position are considered fixed surfaces. In contrast, the wheels, wheels holding the pipe, and the surfaces of the handles of the structure in an upright position are taken as fixed surfaces for trolley mode. A total of 100 pounds of force (lbf) is considered for this study as the test load (equivalent to 45 Kg). This load is uniformly distributed on the top surface as well as on the bottom surface. In the combined loading mode (overhead-backpack combined mode), 50 lbf force on each surface is considered. Fig. 2 shows all toolkit modes, load values, positions, and fixed surfaces.

2.3 Material Comparison

The most important step in this project is material selection, as it will define the toolkit's final weight, cost, and strength. Various materials, such as wood, composites, aluminum, steel, etc., could be employed for fabrication. Composites can be used for applications where single constituent material cannot be utilized [16, 17]. Wood, aluminum, and steel were compared based on their physical properties, such as strength, weight, and behavior in changing weather. ANSYS analysis was performed on these materials, and the results were compared. Table 1 shows the physical and mechanical properties of Steel, Aluminium, and wood. Material selection is one of the main steps in this project, as it plays an important role in its design. There were many materials to choose from, like aluminum, wood, bamboo, iron, steel, etc. The main objective was to select a material with a high strength-to-weight ratio, no or less effects on weather conditions, and a longer lifetime. Wood is one of the first options, but due to its properties changing by changes in weather, it cannot be preferred. Another option is iron, but due to its high weight, it cannot be selected. Aluminum and steel were preferred initially. There were some issues regarding aluminum, like the gauge of aluminum slabs and welding unavailability at the respective sites. Steel was selected as the material for the project's design due to its high strength-to-weight ratio and high tensile yield stress.

2.4 Welding Of Structure

Novel methods are available for welding steel structures, such as friction stir welding [11, 12], electric arc welding [18], etc. Electric arc welding was utilized to join 17 steel pipes to fabricate the worker toolkit. Type 6011 and 6013 electrodes were utilized for welding the columns and beams intersection joints. For trolley mode, plastic wheels (3.5 inches diameter) were installed at the bottom side of the toolkit.

3. Results and discussions

3.1. Simulation Results

Figures 3, 4, and 5 show the simulation results for aluminum, steel, and wood, respectively, in various loading modes. For simplicity, maximum deformation (MaxD), maximum strain (MaxSn), minimum factor of safety (MinFOS), and maximum stress (MaxSs) are taken as the parameters for comparison. It can be observed that the MaxD for wood is the largest of all materials, followed by aluminum, whereas steel showed the lowest MaxD. MaxSn follows the same trend. Similarly, the MinFOS for wood was the weakest compared to aluminum and steel. Moreover, the MaxSs were highest in the case of Wood, whereas steel showed moderate MaxSs and aluminum showed the lowest MaxSs. Based on the above discussion, steel and aluminum are the best materials to construct the worker toolkit. Wood cannot be used for such a load (45 Kg) because of large deformability, low strength, and low MinFOS.

3.2. Toolkit Material Selection And Fabrication Based On Cost Analysis and Weldability

In Pakistani markets, the cost of aluminum and steel varies, and the average cost per unit length (meter) of rectangular pipes (25.4 mm by 12.7 mm) of aluminum and steel are 680 PKR (approximately 2.3 USD) and 500 PKR (approximately 1.67 USD), respectively. This cost is for a length of up to 100 meters. There was a discount on aluminum and steel of 7 and 6 percent, respectively, for lengths more than 100 meters (may be utilized for mass production of the toolkit). Therefore, the cost of aluminum was approximately 1.2 times that of steel pipes. Another consideration is weldability. Steel is much easier to weld than aluminum. It can be welded with traditional tools and less experience, which makes a huge dent in worker costs. Similarly, other advantages, such as the availability of steel in the market, make it a suitable material for constructing the toolkit. Therefore, steel material is selected for the fabrication of the worker toolkit. The toolkit has been fabricated using electric arc welding. The fabricated toolkit is shown in Fig. 6 (a). A shield of tube foam and a belt are also installed for safety, aesthetics, and comfort, as shown in Fig. 6 (b and c). The total weight of the toolkit is 3.5 Kg.

The cost breakdown analysis of a single toolkit is given in Table 2. It can be observed that the total cost of this project is 5000 PKR (approximately 18 USD). Still, when the toolkit is fabricated in mass production, then it can cost around 4500 PKR (approximately 16 USD) by avoiding miscellaneous charges and availing large quantity discounted rates. If we take, for example, Pakistan as a case study, then the wage of five days a worker can cover the cost of this toolkit, and the worker will be able to earn for the rest of the days for himself. This discussion shows that this toolkit is a low-cost kit that workers in low-income countries can use.

Table 1

Physical and mechanical properties of built-in defined material in ANSYS package

Properties	Units	Steel	Aluminum	Wood
Density	kg/m^3	7750	2270	700
Young Modulus	Pa	1.93 10^{11}	7.1 10^{10}	7.86 10^9
Poisson's ratio	-	0.31	0.33	0.036
Bulk Modulus	Pa	1.693 10^{11}	6.96 10^{10}	2.823 10^9
Shear Modulus	Pa	7.37 10^{10}	2.67 10^{10}	3.79 10^9
Tensile Yield Strength	Pa	2.07 10^8	2.8 10^8	25.5 10^6
Compressive Yield Strength	Pa	2.07 10^8	2.8 10^8	9.10 10^6
Tensile Ultimate strength	Pa	5.86 10^8	3.1 10^8	5.50 10^6

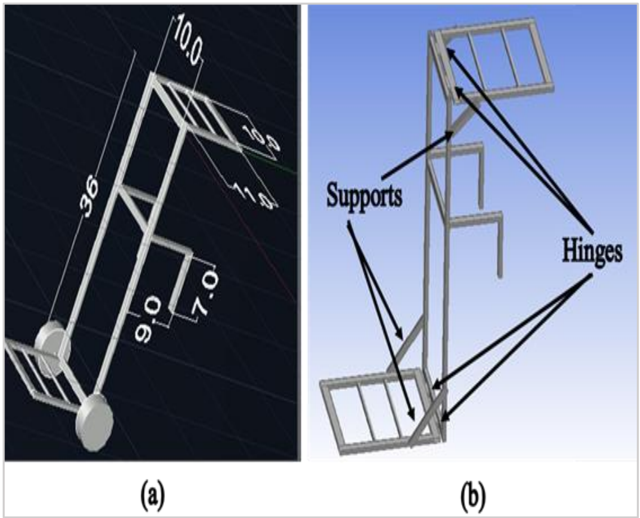

Fig. 1. CAD Design For The Worker Toolkit, (a) Initially Proposed Design (b) Finalized Design

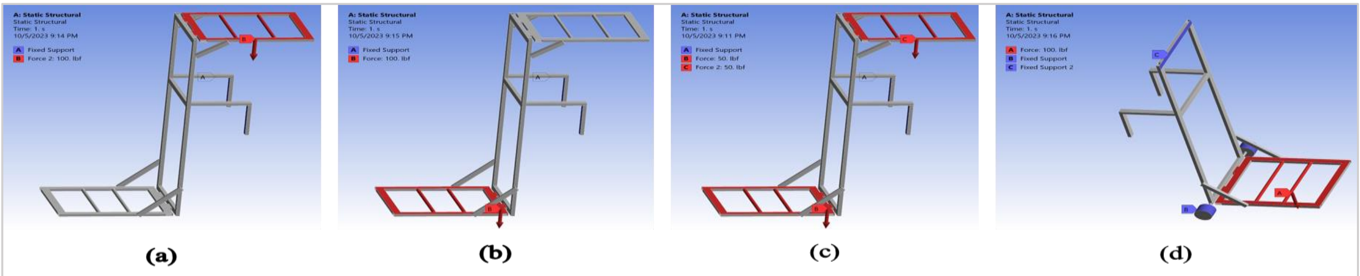

Fig. 2. Shows The Various Load Values, Its Position And Fixed Surfaces For All Toolkit Modes

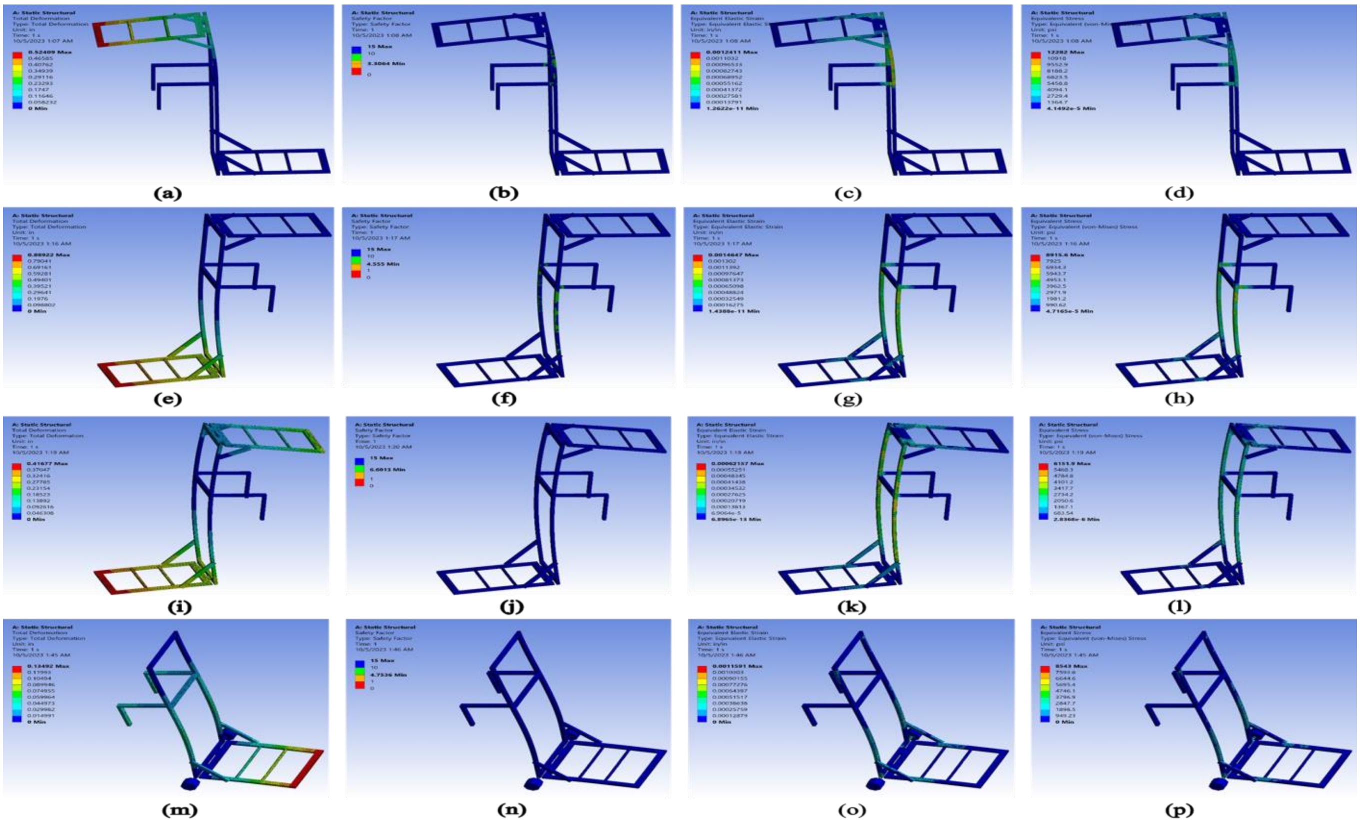

Fig. 3. Simulation Results For Aluminum, (A - D) Overhead Loading Condition Showing MaxD, MinFOS, MaxSn, MaxSs, (e - h) Backpack Loading Condition Showing MaxD, MinFOS, MaxSn, MaxSs, (i - l) Combined Loading Condition Showing MaxD, MinFOS, MaxSn, MaxSs, (m - p) Trolley Loading Condition Showing MaxD, MinFOS, MaxSn, MaxSs

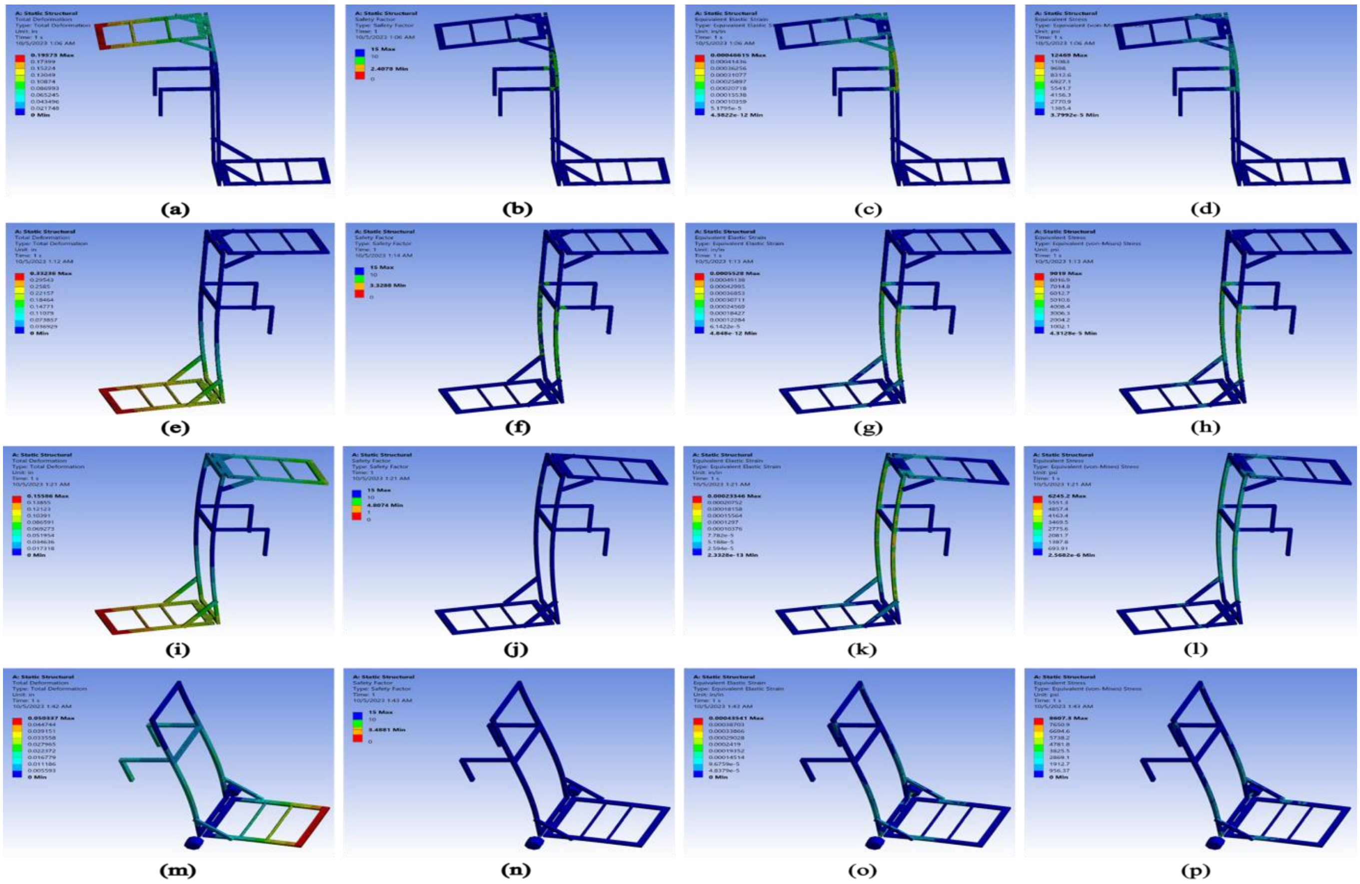

Fig. 4. Simulation Results For Steel, (a - d) Overhead Loading Condition Showing MaxD, MinFOS, MaxSn, MaxSs, (e - h) Backpack Loading Condition Showing MaxD, MinFOS, MaxSn, MaxSs, (i - l) Combined Loading Condition Showing MaxD, MinFOS, MaxSn, MaxSs, (m - p) Trolley Loading Condition Showing MaxD, MinFOS, MaxSn, MaxSs

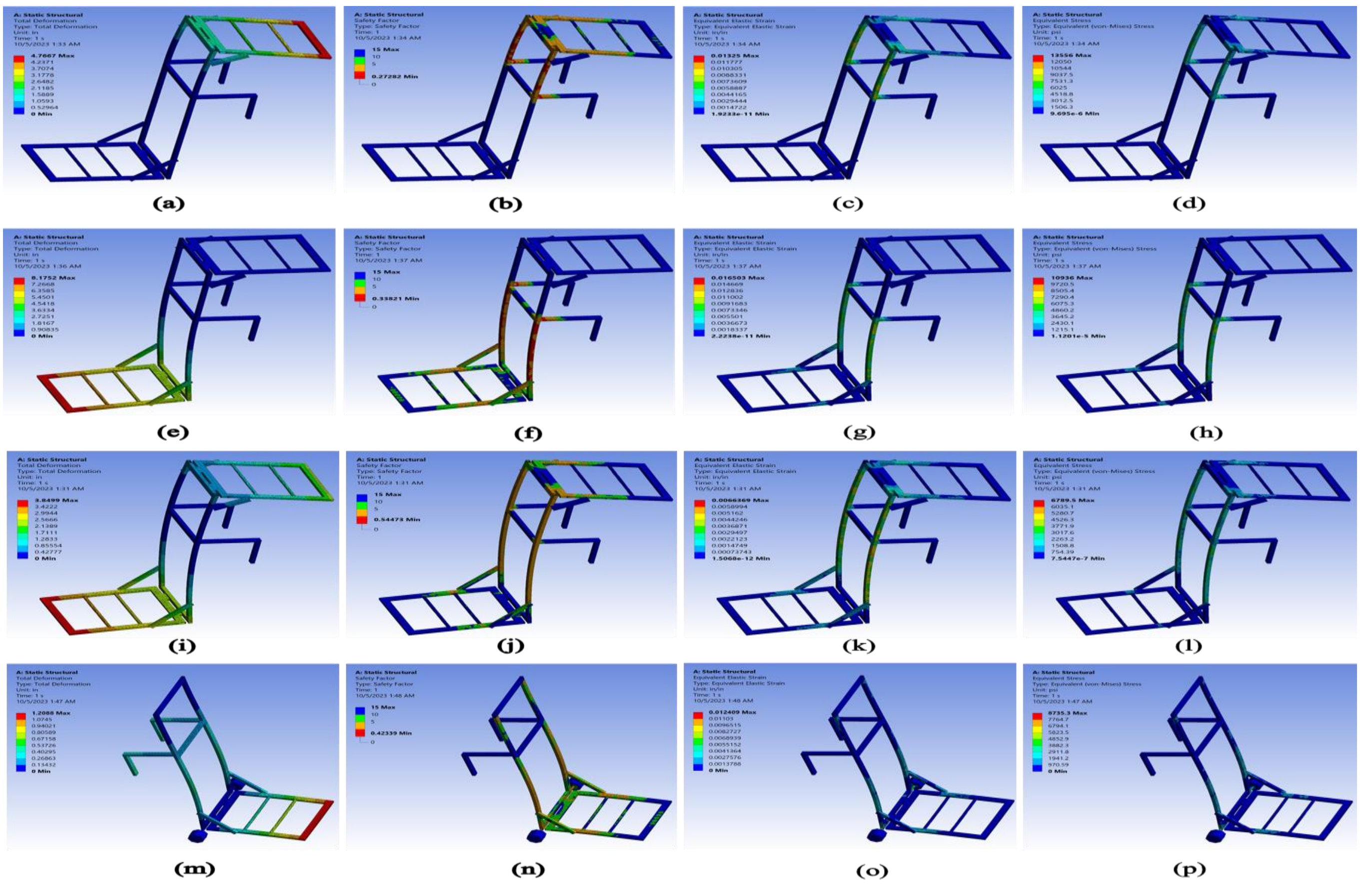

Fig 5. Simulation Results For Wood, (a - d) Overhead Loading Condition Showing MaxD, MinFOS, MaxSn, MaxSs, (e - h) Backpack Loading Condition Showing MaxD, MinFOS, MaxSn, MaxSs, (i - l) Combined Loading Condition Showing MaxD, MinFOS, MaxSn, MaxSs, (m - p) Trolley Loading Condition Showing MaxD, MinFOS, MaxSn, MaxSs

Table 2

Cost breakdown of the worker toolkit in PKR

Serial #	Material/Part/Process	Cost
1	Material Used (6 meter)	3000
2	Wheels, Belt, and cushioning etc	750
3	Welding and cutting charges	750
4	Miscellaneous Charges	500
	Total Cost	5000

3.3 Practical Testing In Various Application

To test the fabricated toolkit, various loads such as flowerpots, buckets, steel pots, and bricks) were applied in multiple modes on the toolkit, such as overhead loading mode (OLM), backpack loading mode (BLM), combined loading mode (CLM), and trolley loading mode (TLM). Fig. 6 shows various loads in various modes of the toolkit. It can be observed from Fig. 6 that the fabricated worker toolkit can be used in a number of loading conditions in various modes, such as transportation of bricks, flowerpots, steel pots, heavy goods bags, and paint boxes in modes such as OLM, BLM, TM, and CLM. This shows the fabricated toolkit's effectiveness and potential applications, such as in the construction and agriculture industries.

Table 3 shows the error in the deflection of support surfaces (mainly the top and bottom surfaces of the toolkit) for various loading conditions relative to the ANSYS deflection values for the same load in lbf. This error is due to the welding processes and difference in the material utilized for fabrication of the toolkit (the physical and mechanical properties of real-world material might be different than the built-in defined material in ANSYS). It can be observed from Table 3 that the maximum deflection error is 1.7 mm in OLM of a 40 Kg brick load. Moreover, it can also be observed that for loads less than 20 Kg, the deflection error was negligible, which confirms its effectiveness and load transportation ability without major deflection and failure.

Table 3

Deflection error for various loads as compared to ANSYS results

Load (type)	Total Mass (Kg)	Mode	Surface(s) deflected	Deflection error as compared to ANSYS results (mm)
Bricks	40	OLM	top	1.36
Bricks	40	BLM	bottom	1.70
Bricks	17	TLM	bottom	0.32
Bricks	20	CLM	Top and bottom both	0.21 (combined error)
Steel pot	15	OLM	top	0.41
Steel pot	30	BLM	bottom	0.69
Steel pot	30	TLM	bottom	0..42
Steel pots	30	CLM	Top and bottom both	0.58 (combined error)
Flowerpot	19	OLM	top	0.59
Flowerpot	17	BLM	bottom	0.31
Flowerpot	19	TLM	bottom	0.64
Flowerpots	36	CLM	Top and bottom both	0.87 (combined error)
Bag and Paintbox	38	TM	Top and bottom both	0.91 (combined error)

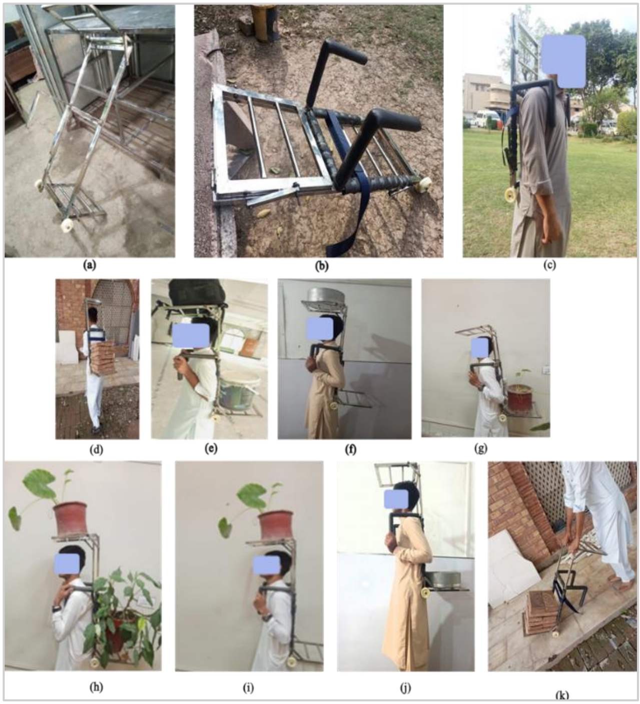

Fig. 6. Fabricated Toolkit And Its Utilization Of Toolkit By Workers For Various Loading In Various Modes, (a) Toolkit After Welding And Wheel Assembly, (b) Toolkit After Cushioning And Belt Installation, (c) Toolkit In Inactive-Mode (Closed Top And Bottom Surfaces), (d) Transportation Of Bricks By Worker In BLM, (e) Paint Box And Filled Bag Carried By A Worker In CLM, (f) Steel Pot Carried By Worker In OLM, (g) Flowerpot Carried By Worker In BLM, (h) Flowerpots Carried By Worker In CLM, (i) Flower Pot Carried In OLM, (J) Steel Pot Carried In BLM, (k) Bricks Transportation In TM.

4. Conclusion

In this study, a novel worker toolkit design was proposed and analyzed using FEA. The design transported food, pot, etc., in 4 modes: OLM, BLM, CLM, and TLM. The analysis was performed for steel, aluminum, and wood as the feasible construction material for the toolkit. A test load of approximately 45 Kg was considered for the loading conditions in the FEA analysis. After comparing the three materials, steel was selected as the final construction material for the toolkit due to its better weldability, availability, durability, low MaxD, low cost, low MaxSn, moderate MinFOS, and moderate MaxSs. After fabrication, the toolkit was tested in real-world applications, and it was found that it performs well in applications related to construction and agriculture industries, such as the transportation of goods, construction materials, pots, etc. Working in different modes enables workers to work in a more diverse environment. The deflection error analysis also confirmed that the toolkit can safely be used in the abovementioned applications. The proposed toolkit is a low-cost worker toolkit and could be used by workers (male and female) in developing and low-income countries such as Pakistan. Further analysis related to ergonomics and redesigning the toolkit can be performed in the future for the betterment of the workers.

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