An Ergonomic Design of Six-Wheeled Trolley for Transportation of a 100-kg Weight Load

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Abstract

Manual material handling (MMH) task contributes to a large percentage of musculoskeletal disorder cases and injuries in occupational settings. Musculoskeletal disorders (MSD) often involve strains and sprains to the lower back, shoulders, and upper limbs. They can result in the exposure of workers to risk factors that eventually turn into costly injuries and lost productivity. Several studies have shown that effective ergonomic interventions can decrease the physical demands of manual material handling tasks thus lowering the occurrence and severity of MSD and occupational injuries. To control the nature and severity of these injuries in the MMH task, this paper aims to design an ergonomic trolley to assist the tasks of workers. The researchers were able to come up with a design of a 6-wheel trolley that has the capacity to carry a load of 100-kg weight. It has a tri-star hub that rotates to overcome uneven floors and stairs that will enable to single-handedly transport load safely. In addition, the handle height and handle diameter of the trolley was based on anthropometric dimensions of Filipino workers namely standing elbow height and handgrip diameter to match the design of trolley to the anthropometric requirements of Filipino users. The 3D design of the trolley was made using Fusion 360 software. Afterwhich, the trolley was fabricated using a plasma cutter and lathe machine. It was then tested on three different pushing positions (rough surface, elevated surface, and staircase) to compute for its mechanical advantage. The researchers then analyzed and computed for the actual force that must be applied comparing it to the load that can be transported by six-wheeled trolley. The findings of the study have proved that the newly designed trolley will be able to reduce the risks in manual pushing and pulling operations involving whole-body effort as evidenced by the result RAPP tool analysis.

Keywords
Trolley, ergonomic design, manual material handling

1. Introduction

According to NIOSH, manual material handling task contributes to a large percentage of the over half a million cases of musculoskeletal disorders reported annually in the United States. Manual material handling has been found to be associated with musculoskeletal disorders and injuries such as strains and sprains to the lower back, shoulders, and upper limbs (CDC, 2007).

Scientific evidence shows that effective ergonomic interventions can lower the physical demands of manual material handling work tasks, thereby lowering the incidence and severity of the musculoskeletal injuries they can cause (Gumasing, 2019). Their potential for reducing injury-related costs alone make ergonomic interventions a useful tool for improving a company's productivity, product quality, and overall business competitiveness.

One of the ergonomic interventions in reducing the risk of MSD and injuries in manual material handling tasks is the use of mechanical aids. Mechanical aids are non-powered tools used to assist workers in lifting, pushing, pulling, and transferring load from one place to another. These tools include drum dolly, cart or platform truck, scissor lift, manual hoist or crane and hand truck or trolley. However, a study revealed that inappropriate design of mechanical aid results in changes in postures, leading to higher muscular loads during pushing activity (Onishi, 2016).

In a similar study, it was revealed that the use of mechanical aids particularly on trolleys may be associated with low work efficiency such as lost work hours due to difficulty of handling the heavy mechanical equipment, which leads to a faster rate of fatigue (Singh, 2016). The use of trolley may also pose safety issues when handling heavy load especially on areas that are challenging to transport materials such as elevated or inclined surfaces and stairs. Because of this, the combined weight of the trolley and load must be considered. However, it is difficult to determine how much weight can be transported using a trolley. Many factors affect how much force is needed to move a given weight.

Given this condition, it became the research interest of the authors to design an ergonomic trolley that will permit the users to transport heavy load up to 100kg without causing risks of musculoskeletal disorders and injuries especially to hazardous areas such as rough surfaces, elevated plane, and staircases.

2. Methodology

The researchers were able to identify factors that will be considered in the design of ergonomic trolleys such as anthropometric measurements of users, body posture of users, and actual dimensions of the existing trolley. Data were collected by manually measuring the dimensions of the trolley that will be incorporated for the proposed design. To determine the risks for musculoskeletal disorders and injuries in manual material handling tasks during transporting of load using a trolley, the RAPP tool was used. Risk assessment of pushing and pulling (RAPP) tool is designed to help assess the key risks in manual pushing and pulling operations involving whole-body effort like moving loaded trolleys. It helped the researchers in identifying high-risk pushing and pulling activities and check the effectiveness of any risk-reduction measures. The researchers also applied ergonomics principles such as anthropometry to identify the physical dimensions of the proposed product. The researcher needs to match all these considerations and come up with proposed product design. Afterwhich, the proposed design was developed through the use of AutoDesk Fusion 360 software. Then, prototype of the design was fabricated using a plasma cutter and lathe machine to test the actual operation of the trolley and run simulation tests. The materials used in the fabrication of the trolley was based on the selected criteria. And finally, the fabricated trolley was then tested on three different pushing positions (rough surface, elevated surface, and staircase) to compute for its mechanical advantage. The researchers then analyzed and computed for the actual force that must be applied comparing it to the load that can be transported by six-wheeled trolley.

2.1. Selection of Materials

Wheels. The type of wheel selected for the design was determined by its load capacity. The wheels selected can withstand the load of 250 kg. The bore diameter of the wheel depends on the size of the bolt. The size of the wheel was also determined based on the rise (cm) and threads (cm) of the staircase where the simulation run will be tested.

Shaft. The shaft must withstand the stress subjected to the center if the maximum bending can be produced when the force is applied to the middle part of the shaft. The two ends of the shaft will act as if it is fixed since it is the connecting rod of the tri-wheel sets which carries the load. The materials that the researchers will be using is Cold Rolled Steel.

Back Frame. The back frame is subjected to variable stress. It includes bending, tension, and compression. The bending stress will be applied to the handle as well as the tension. The compression and tension stress will produce the bending stress at the lower part of the back frame in which the plate is welded since the load was applied on the base plate.

Sheet Metal. The load will be placed on top of the base plate thus making different effects on each component due to different positions of the trolley. When the machine is resting while the force is applied, the components subjected to the stresses are the base plate, the tri-star wheel design, and the shaft of the tri-wheel set.

Bearing. Bearing is one of the reasons for the movement of the parts of the trolley such as the wheels and the tri-star.

Ball-bearing will be incorporated in the wheels that will be used in the tri-star. But for the tri-star to rotate, the researcher bought a needle bearing that will fit the shaft. Needle bearing was chosen among bearings because unlike ball bearing and roller bearing, it can support a greater load.

Base Plate. The base plate is made up of mild steel having a thickness of 3mm and was initially from 1 m by 1 m steel plate. The needed parameters are 0.6 m by 0.3 m and 0.6m by 0.09m. To achieve the said dimensions, the researchers used a CNC Plasma Cutting Machine to have a precisely cut metal sheet.

Body Frame. The frame is made up of Galvanized Iron (GIASTM53) that is in the shape of a pipe. The pipe was bought at a local market having a 1-inch diameter schedule 40 and 6 meters long. The pipe was cut into pieces to create the mainframe of the trolley. Angle bars were also used to support other parts that are connected to the mainframe.

Bolts. There are two kinds of bolts used in the trolley. One of the bolts is fabricated using the cold-rolled steel that was used in the shafting, the other bolt is a high tensile bolt with ½ inch diameter and 3 in length that will be used as a pin for the lever.

2.2. Installation of Fabrication of Parts

Tri-Star. The tri-star set was fabricated from the mild steel plate that was cut with CNC Plasma Cutting Machine. The tri-star set is installed with bearings and will be used as the casing for the 6 wheels at the bottom of the trolley.

Safety belts. The safety belts are made up of nylon that is used in construction sites. These belts are modified by removing the hooks and ropes installed and threading the end to be able to install it to the trolley.

Lever arm. The lever arm is composed of two pipes where one of which is 36cm in length and the other is 23cm welded together to form an inverted V-shape. The lever arm is used to hold the frame in place when translating from the handle of the trolley to the base plate so that the force to be applied would be less than the weight of the object itself.

3. Results and Discussion

3.1 Result of RAPP Tool

The researchers used the risk assessment pushing and pulling (RAPP) tool to assess the risk associated with the pushing and pulling operations and identify high-risk activities using the conventional trolley. Four (4) subjects were observed while pushing a trolley with a load between 50-100kg on 4 different conditions (flat surface, rough surface, inclined plane, use of staircase) and subjects were evaluated based on the following factors: type of equipment & load weight (kg), body posture, handgrip, work pattern, travel distance, condition of equipment, floor surface, obstacles along route and other factors. The result of the RAPP tool analysis is shown in the table below.

Table 1. Result of RAPP Tool

Risk Factors	Sub-Factors	Flat Surface	Rough Surface	Inclined Surface	Use of Staircase
A1 Type of equipment & load weight(kg	Small with one or two wheels	2	2	2	2
A2 Posture	How upright is the operator's body when pushing/pulling?	3	3	3	3
	Twisting and bending	0	0	0	0
	Hand height/position	3	3	3	3
	Overal posture score	3	3	3	3
	A3 Handgrip	1	1	1	1
	A4 Work pattern	0	0	0	0
	A5 Travel distance	1	1	1	1
	A6 Condition of equipment	2	2	2	2
A7 Floor surface	Dry and clean	0	0	0	0
	Slopes	0	0	4	4

	Firmness	0	4	1	1
	Condition	0	1	0	0
	Overall floor score	0	4	4	4
	A8 Obstacles along route	2	2	2	3
	A9 Other factors	0	0	0	0
Total RAPP score		**11**	**15**	**15**	**16**

Based on the result of the RAPP tool analysis, all subjects performing manual pushing of load on 4 different conditions are exposed to high risk of musculoskeletal disorders and injuries due to awkward position and pushing force. This validated the need to design a trolley that will aid the users in pushing load on high-risk conditions such as on the rough surface, inclined surface, and use of the staircase.

3.2. Result of Anthropometric Measurement

To design a trolley that will conform to the anthropometric dimension of users, the researchers used the principles of Anthropometry. Below are the anthropometric dimensions for the proposed design of the trolley.

Table 2. Summary of Anthropometric Measurement

Dimension	Anthropometric Reference	Percentile	Gender	Proposed Measurement (cm)	Actual Measurement (cm)
trolley handle height	elbow height	95th %	Male	112.8	90.7
trolley handle width	elbow to elbow breadth	95th %	Male	48	32
handle diameter	grip diameter	5th %	Female	3.8	5

As there were mismatches between the trolley dimension and anthropometric measurements it was necessary to redesign the existing trolley with proper anthropometric measurements to reduce the risks of users to MSD and injuries.

3.3. Design of Trolley using Autodesk Fusion 360

The researchers used the Autodesk Fusion 360 to perform stress analysis for the maximum load the trolley can withstand. The simulation was performed to show that the trolley can theoretically carry a 250-kilogram gross since the initial design can withstand the said load. In the simulation, the blue parts were subjected to stress and can withstand the force exerted on it. The green areas show the parts of the trolley that the force is concentrated but still is tolerable. The yellow areas show that the welded areas also react to the force but can withstand the load. The overall result of the simulation as shown in the figure below demonstrates that the trolley can withstand the load of more than 250 kg since there are no red spots that need to be changed.

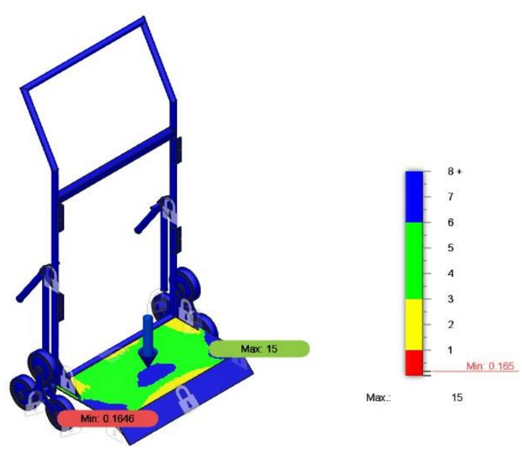

Fig. 1. Final Trolley Simulation using Autodesk Fusion 360

3.4. Testing of Trolley Prototype on High-Risk Conditions

Since it was proven in RAPP tool analysis that pushing load using a trolley pose risks on high-risk conditions such as rough surface, inclined surface, and staircase; the researchers conducted testing of the trolley prototype on these conditions to evaluate the usability and improvement of the manual material handling tasks of users. The researchers conducted several trials on each test. There are 5 different loads tested starting from no load up to 104 kilograms. Water containers were used as a load for the testing. The test is done to show the load capacity of the trolley concerning the user capability to handle the load. The trials were a success and prove that the trolley can withstand more than 100 kg including its weight.

Table 3. Result of Prototype Testing on High-Risk Conditions

LOAD	ROUGH SURFACE			INCLINED SURFACE			STAIRCASE		
	Person 1	Person 2	Person 3	Person 1	Person 2	Person 3	Person 1	Person 2	Person 3
No Load (Initial Weight of Trolley) 32.3 kg	Viable	Viable	Viable	Viable	Viable	Viable	Viable	Viable	Viable
1 Water Container (5 Gallons, 18 kilograms), 50 kg total	Viable	Viable	Viable	Viable	Viable	Viable	Viable	Viable	Viable
2 Water Container (10 Gallons, 36 kilograms), 68 kg total	Viable	Viable	Viable	Viable	Viable	Viable	Viable	Viable	Viable
3 Water Container (15 Gallons, 54 kilograms), 86 kg total	Viable	Viable	Viable	Viable	Viable	Viable	Viable	Viable	Viable
4 Water Container (20 Gallons, 72 kilograms), 104 kg total	Viable	Viable	Viable	Viable	Viable	Viable	Viable	Viable	Viable

3.5. Mechanical Advantage of Ergonomic Trolley

The researchers tested three (3) different positions of the trolley to compute for the mechanical advantage of the equipment. The test was from the initial position, middle position, and final position. The initial position tested occurs when the trolley first contacted the stair and two lever arms are pinned on the tread of the stairs. The middle position tested was occurred when two of the longer lever arms makes 90-degrees with the horizontal. The last test was positioned when all the lever arms were touching the staircase. Based on the results, the initial position requires more force to move the trolley while carrying the load. The illustration is shown in the figure below.

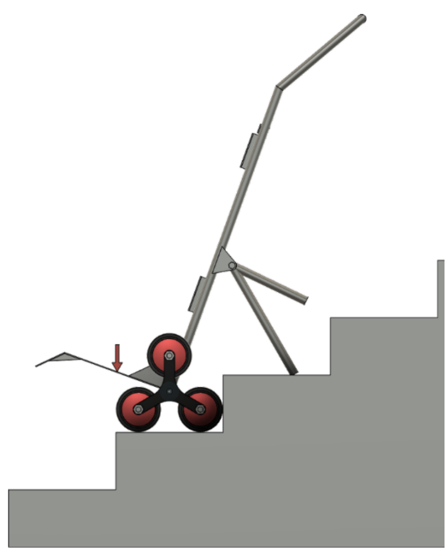

Fig. 2. Illustration of Ergonomic Trolley on Staircase

3.6. Result of Force Load Analysis

To determine the maximum load that can be carried by the trolley prototype, the researchers analyzed and computed the applied force on the trolley based on the actual weight of the load. The values were based on the initial position since it requires the highest force that must be applied on both rough and inclined surfaces as shown in the table below.

Table 4. Summary of Force Required based on Actual Load

LOAD	Weight	Minimum Force Required	
		Inclined Surface	Rough Surface
No Load (Initial Weight of Trolley) 32.3 kg	294 N	183.56 N	144.65 N
1 Water Container (5 Gallons, 18 kilograms), 50 kg total	470.4 N	293.70 N	231.44 N
2 Water Container (10 Gallons, 36 kilograms), 68 kg total	646.8 N	403.84 N	318.23 N
3 Water Container (15 Gallons, 54 kilograms), 86 kg total	823.2 N	513.98 N	405.00 N
4 Water Container (20 Gallons, 72 kilograms), 104 kg total	980 N	611.88 N	482.16 N

Afterward, the researchers computed for the mechanical advantage of the trolley prototype to validate the improvement in the performance by computing the ratio of the actual load on the trolley to the minimum force applied to it. The results are shown in the equation below.

$$Mechanical\ advantage \frac{grows\ weight}{minimum\ force\ required}$$

For inclined force:

$$Mechanical\ advantage \frac{980\ N}{611.88\ N} = 1.60$$

For rough surface:

$$Mechanical\ advantage \frac{980\ N}{482.16\ N} = 2.03$$

The results validated that the trolley prototype has significantly improved the performance of the users in manual material handling of a load of at least 100kg weight.

4. Conclusion

The findings of this study have shown that the use of conventional trolley poses risk for musculoskeletal disorders and injuries to the users when pushing heavy load especially on high-risk conditions namely rough surface, inclined surface, and on use of staircase as proven by the result of RAPP analysis. Given these conditions, the researchers were able to come up with a design of a 6-wheel trolley that has a capacity to carry a load of 100-kg weight. It has a tri-star hub that rotates to overcome uneven floors and stairs that will enable to single-handedly transport load safely. In addition, the ergonomic trolley was based on anthropometric dimensions of Filipino workers namely standing elbow height and handgrip diameter to match the design of trolley to the anthropometric requirements of Filipino users. The 3D design of the trolley was made using Fusion 360 software. Afterwhich, the trolley was fabricated using a plasma cutter and lathe machine. It was then tested on three different pushing positions (rough surface, elevated surface, and staircase) to compute for its mechanical advantage. The researchers then analyzed and computed for the actual force that must be applied comparing it to the load that can be transported by six-wheeled trolley. The results of the study have shown that the proposed ergonomic design of trolley has significantly improved the performance of the users in manual material handling of a load of at least 100kg weight.

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