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Finite Element Analysis of Force Distribution of Shopping Carts on Human Joints

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Abstract

Shopping carts are essential parts used in shopping. There are differences between shopping carts used today. The most prominent of these differences is that some carts have only the front two free rolling wheels, the rear two wheels are fixed rolling wheels, and some carts have four free rolling wheels. In this study, the effects of this difference in shopping carts on joints of the human body under different conditions were simulated using analysis software and the results were compared. As a result, it has been determined that European style shopping carts with four free rolling wheels need more force when going straight than other type of shopping carts with two free rolling wheels and need less force in case of rotation. In addition, when these forces are applied on the human model and gravity is neglected, it has been determined that the reaction of the joints is close to each other.

Keywords: Analysis, design, ergonomics, force distribution, human model

Alışveriş Sepetlerinin İnsan Eklemleri Üzerindeki Kuvvet Dağılımının Sonlu Elemanlar Analizi

Öz

Alışveriş sepetleri alışveriş kullanımında önemli bir özellik taşımaktadır. Günümüzde kullanılan alışveriş sepetleri arasında farklılıklar vardır. Bu farklılıkların en belirgin olanı; bazı arabaların yalnızca öndeki iki tekeri serbest döner iken, arkadaki iki tekerleğin sabit olması; bazı arabaların dört serbest döner tekerleğe sahip olmasıdır. Bu çalışmada, alışveriş sepetlerindeki bu farklılığın farklı koşullar altında insan vücudunun eklemleri üzerindeki etkileri mekanik analiz yazılımı kullanılarak simülasyonu yapılmış ve elde edilen sonuçlar karşılaştırılmıştır. Sonuç olarak; Avrupa ülkelerinde çoğunlukla kullanılan dört serbest tekerlekli alışveriş arabalarının, düz giderken, diğer iki serbest tekerlekli alışveriş arabalarına göre daha fazla kuvvete ihtiyaç duyduğu ve dönme durumunda daha az kuvvete ihtiyaç duyduğu tespit edilmiştir. Ayrıca bu kuvvetler, yer çekimi ihmal edilerek, insan modeline uygulandığında eklemlerde meydana gelen reaksiyon kuvvetlerinin birbirine yakın olduğu tespit edilmiştir.

Anahtar Kelimeler: Analiz, tasarım, ergonomi, kuvvet dağılımı, insan modeli

INTRODUCTION

The history of shopping carts, which are frequently used in shopping today, dates to 84 years ago. In 1936, a businessman named Sylvan Goldman, who owns a supermarket chain, observed that his customers had problems transporting the products they bought while shopping and invented the folding cart carrier, which was the basis of the shopping cart, to increase sales (Terry and Wilson, 1978).

There are many types of shopping carts currently in use, but we can divide them into two: carts with 4 free-rolling wheels and 2 free-rolling wheels. In accordance with European Union standards 4-wheel free-rolling shopping carts that are used in Turkey. In the United States, shopping carts with two front wheels with free-rolling wheels and two rear wheels with fixed wheels are used. The main reason for this

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can be said to be that the markets in the USA have wide shelf spaces and the markets in Europe have narrow shelf spaces and offer less rotation space to the shopping carts (ASTM F2372 Standardization, 2021; BS EN 1929-1 Standardization, 1998).

This difference causes different force magnitudes on the user during the use of the shopping carts.

However, in some cases, it has been revealed by various studies that there are various injuries due to the use of market carts, and thus the necessity for scientists to carry out studies in this direction has arisen. As an example, in one study, falls from shopping carts and cart tip-overs is considered as 58% and 26% of injuries caused using shopping carts, respectively (Pediatrics, 2006).

To provide ease of use and to develop a more suitable shopping carts, it is necessary to examine the stress distributions that the shopping carts produced in different configurations will create at the joints of the user.

In this study, a reaction force occurs due to the friction force in the contact of the shopping carts with the ground. Resulting from this reaction; To determine the forces applied to the shoulder, elbow, leg and knee joints of the user, a 2-stage analysis plan was created.

In the first stage, the forces that must be applied to the cart (considering the technical characteristics of the computers used) to move 1 meter per second to determine the force affecting the handlebar of the cart were obtained, an analysis was simulated by determining the friction coefficients, the boundary conditions such as the weight of the cart and the load inside. The data obtained from the analysis were transferred to the second stage and applied on the human body

Many studies have been carried out on human ergonomics. While some of these studies were about determining risk factors in ergonomics (Da Silva Vieira et al., 2015; Hulshof et al., 2021), some of them were about determining the loads affecting people (Gruben and Boehm, 2012; Jones, 2009; Pinnel et al., 2019; Tsui and Pain, 2018)

Various studies have also been carried out on the design of the human model to determine human ergonomics (Jain et al., 2020; Wolf et al., 2020). Paul and Wischniewski (2012), introduced standard measurements for the digital human model. Wolf et al. (2020) conducted a review study of digital human body measurements.

In this study, the effects of this differential in shopping carts on human joints were modelled using finite element analysis software (Ansys Workbench, 2020 R2), and the results were compared. In order to compare the force distribution of shopping carts on people, various assumptions were made such as car speed, car weight, and human weight.

MATERIAL AND METHODS

Two different programs were used to examine the forces acting on the joints of the shopping cart user. First, a shopping cart was designed by using Solidworks software. Then this shopping cart is imported into ANSYS software, and the mesh quality is tested. Later, simplifications and improvements were made on the designed shopping cart, and a suitable model was created for analysis. A supermarket shopping cartwheel was designed to be mounted on this model, and this wheel was assembled on the designed shopping cart and its suitability for re-analysis was tested. It was determined that the prepared model was complex to obtain the results and the design was simplified.

A simple floor is designed so that the wheels of the cart can move. The final form of the design has been created by assembling the wheels, floor, and shopping cart. The design was transferred to the geometry part in the Rigid Body Dynamics analysis system in ANSYS. Structural Steel with changed density is used as the material of the created geometry.

The weight of the cart is set to approximately 22 kg. Later, a 10 kg “point mass” is defined in the basket section which represents the weight of the goods placed in the cart. To define the movement of the cart, a general joint has been defined on the handlebar. Afterwards, according to the analysis situation to be solved, the wheels, joints of the cart and the contacts between the wheels and the ground are defined. When defining the contact, the required friction values are defined. Friction values are neglected for joint connections.

Rigid Body Dynamics analysis system sets up the finite element mesh with one node per part which is sufficiently enough for a rigid dynamic analysis. As the boundary conditions, gravity and joint displacement with a movement of 1 meter per second to the created general joint are defined.

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Rotation on counterclockwise direction of 90° per second was also defined for this general joint established for rotation analysis. By analyzing four different conditions, the force data required on the handlebar to move the cart 1 meter per second was obtained. The data obtained were recorded to be transferred to the static analysis system to be made on the human model, considering the action-reaction law. A human model was designed for static analysis later. The model created was transferred to ANSYS Static Structural analysis system.

Considering the properties of human bone as a material, a material named "Human Bone" was created and defined to the model. The contact and joint connections of the model are defined, friction to any joint and contact connection is not considered. Then, the mesh was created, and the quality was checked.by comparing with the previously works done in literature (Elise et al., 2018).

As the boundary conditions, the maximum forces obtained in the cart analysis were applied to the hand part of the human model. By assuming that the model remains fixed, fixed support is defined on the foot bases. The data and visuals obtained by running the analysis according to four situations were recorded, and the finite element analysis part of the project was finalized.

Rigid Body Analysis

In the creation of rigid body analysis, it was accepted that an average of 10 kg of material was loaded into the cart during a shopping. This mass is defined as the point mass in the center of the shopping cart. The total mass of the cart is defined as approximately 22 kg.
In the material selection of geometry, modified structural steel was used instead of defining a new material. Since the only property of this material that needs to be changed for this analysis is its density, only the density of the structural steel was changed, and the standard cart mass was obtained. The material properties of shopping cart were given in Table 1.

Table 1. *Material properties of shopping cart*

Density (kg/mm3)	$2x10^{-6}$
Young's Modulus (MPa)	$2x10^{5}$
Poisson's Ratio	0.3
Bulk Modulus (MPa)	166670
Shear Modulus (MPa)	76923
Isotropic Secant Coefficient of Thermal Expansion (1/°C)	$1.2x10^{-5}$
Compressive Yield Strength (MPa)	250

Wheel to Base joint connection with 0.1 friction coefficient was assumed for a total of four wheels.
For the Handlebar rotation joint connection, the RY rotation was released during the rotation test, and the RZ rotation was released during the straight movement test.
For the caster wheel joints:
Chassis to Upper Shaft joint connection was defined as a fixed connection.
Shaft to Tire joint connection, revolute joint connection type was selected.
Upper Shaft to Bracket joint connection, all wheels were set as revolute joints for the cart model with four wheels with free rolling. In the model with two free rolling wheels, a fixed joint on the rear wheels and a revolute joint on the front wheels were set.
Bracket to Shaft joint connection was defined as a fixed connection. The soles of the feet are fixed to the floor to obtain the tensile forces in the joints. The model of shopping cart was shown in Figure 1.

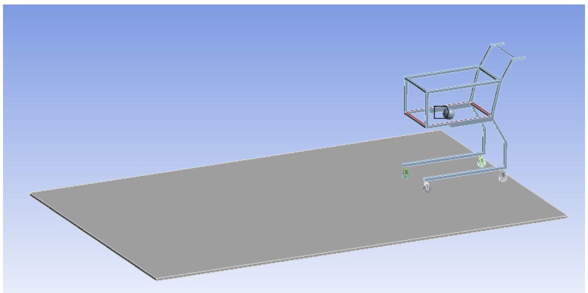

Figure 1. Shopping Cart and Base structure

Static Analysis

In the static analysis, it was aimed to obtain the tensile forces created by the horizontal forces applied to a human hand on the elbow, shoulder, hip and knees. The mass of the human model was defined as approximately 80 kg which was seen in Figure 2.

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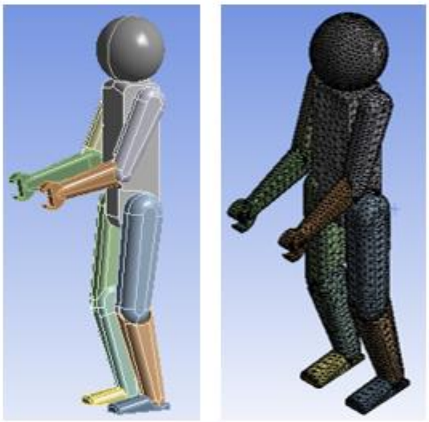

Figure 2. Human model with its meshing view

A new material was defined in the material selection of the human model. A cortical bone was created as a material and its mechanical properties were described as seen in Table 2 (Carter et al., 2009; Kashan and Ali, 2019).

Table 2. *Material properties of human model*

Density (kg/mm3)	$1.6x10^{-6}$
Young's Modulus (MPa)	17000
Poisson's Ratio	0.39
Bulk Modulus (MPa)	25758
Shear Modulus (MPa)	6115.1
Compressive Ultimate Strength (MPa)	160
Compressive Yield Strength (MPa)	150
Tensile Ultimate Strength (MPa)	90
Tensile Yield Strength (MPa)	115

Foot contacts were set as bonded contacts and all other contacts were set as "No Separation". All joints were set as fixed joint.

A joint probe was defined on the handlebar to detect the forces acting on the handlebar. As not the stresses but the forces acting on human body are under consideration no additional attempt was done to improve the mesh quality of the human model.

RESULTS AND DISCUSSION

In the study, four different cases were determined. The cases were given as follows:

Case 1: Four free rolling wheels going straight 1 meter per second,

Case 2: Two free rolling wheels two fixed wheels going straight 1 meter per second,

Case 3: Four free rolling wheels 90^{o} rotation per second,

Case 4: Two free rolling wheels and two fixed wheels 90^{o} rotation per second.

The analysis results of each analysis within 0.21 seconds were given in Table 3 and the results of the maximum solution time intervals of each analysis were given in Table 4, respectively.

Table 3. *Analysis results of each analysis within 0.21 seconds*

	Maximum Force Required (N)	Average Force Required (N)
Case 1	33.5	5.2
Case 2	31.4	3.7
Case 3	45.6	15
Case 4	45.5	16.8

Table 4. *Analysis results of the maximum solution time intervals of each analysis*

	Maximum Force Required (N)	Average Force Required (N)
Case 1	33.5	5.2
Case 2	31.4	4.4
Case 3	45.6	14.8
Case 4	45.5	18.7

The analysis results of human model with maximum reaction forces obtained from cart analysis when gravity included and excluded were given in Table 5 and Table 6, respectively.

Table 5. *Analysis of human model with maximum reaction forces obtained from cart analysis when gravity included*

	Case 1 Force: *33.5 (N)*	Case 2 Force: *31.4 (N)*	Case 3 Force: *45.6 (N)*	Case 4 Force: *45.5 (N)*
Elbow	51.8	51.5	54	54
Shoulder	135	135	136	136
Leg	535	535	541	541
Knee	724	724	730	730

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Table 6. *Analysis of human model with maximum reaction forces obtained from cart analysis without gravity effect*

	Case 1 Force: *33.5 (N)*	Case 2 Force: *31.4 (N)*	Case 3 Force: *45.6 (N)*	Case 4 Force: *45.5 (N)*
Elbow	16.8	15.7	22.8	22.8
Shoulder	16.7	15.7	22.8	22.8
Leg	16	15	21.9	22
Knee	16	14.9	21.8	21.8

When the results of the shopping cart analysis, which is the first stage of the analysis, are examined:

It has been observed that the maximum force required to rotate the cart 90^{o} per second is greater than the maximum force required to move it straight 1 m/s.

Among the maximum forces required to move the cart 1 m/s, it has been observed that the model with four free rolling wheels requires more force than the model with two free rolling wheels. When the maximum forces required to rotate the cart 90^{o} per second were examined, no significant difference was observed between the four free rolling wheel model and the two free rolling wheel model.

When the results of the analyzes with different solution time intervals and the results of the first 21 milliseconds to have the same duration as the analysis with the least solution time, it was observed that there was no change in the required maximum forces.

Among the average forces required to move the cart 1 m/s, it has been observed that the model with four free rolling wheels requires more force than the model with two free rolling wheels. When the average forces required to rotate the cart 90^{o} per second were examined, it was observed that the model with two free rolling wheels requires more force than the model with four free rolling wheels. It was understood that turning a stationary model with two wheels requires more force than a stationary model with four wheels.

When the human model analysis, which is the second stage of the analysis, is examined:

In case of the analysis results of the human model in the absence of gravity were examined, it was observed that the maximum reaction forces from the cart do not make a significant difference between the forces acting on different joints.

In the analyzes of the human model made under the effect of gravity, it has been observed that the forces acting on the joints change depending on the weight of the limbs when each maximum force was applied to the human model. Force magnitudes increased from head to toe. This situation was in direct proportion to the distance to the applied force and the weight of the limbs.

When the maximum reaction forces obtained from the 1 m straight travel analysis of the cart and the 90^{o} rotation analysis per second were applied to the human model, it has been observed that the reaction forces for each joint are very close.

CONCLUSION

In this study, it was aimed to examine the force distribution of two and four wheel free rotating shopping carts on humans. According to the results and evaluations, it has been determined that European standard shopping carts with four free-rolling wheels need more force in case of going straight compared to the American standard shopping carts with two free rolling wheels, and less force in case of rotation. In addition, when these forces are applied on the human model and gravity is neglected, it has been determined that the reaction of the joints is close to each other.

CONFLICT OF INTEREST

There is no conflict of interest relevant to this article.

RESEARCH AND PUBLICATION ETHICS STATEMENT

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author(s) also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

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