DESIGN, PROTOTYPE AND EXPERIMENTAL EVALUATION OF A WHEELCHAIR TREADMILL

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Abstract: Generally, wheelchair users cannot move easily within buildings since living areas in architectural structures are not suitable for them to maintain or to improve their physical capabilities. Because living area restrictions affect the physical performance of the users outside during the day, the reduced mobility causes several health problems. These problems become more intense by the time. Especially heart and lung related illnesses are common among the wheelchair users since the immobility decreases respiration capacity. The aim of this research is to design and prototype a wheelchair treadmill to help wheelchair users improve their upper extremity system. In this study, CAD was employed for the design of wheelchair treadmill. Then finite element analysis (FEA) was carried out for the parts of the wheelchair treadmill and the prototype was manufactured based on the results. The prototype was tested under the conditions the product was originally intended to function. In the experiments, the speeds of wheelchair and wheelchair treadmill were measured. The distances taken by users were also recorded, and the results were evaluated with respect to road surface conditions.

1. INTRODUCTION

Sports are just as important to persons with disabilities as to "able-bodied" people, if not more so (Yim at al., 1993). Sports help maintaining an individual's fitness while improving feelings of self-worth. Lack of physical fitness can cause obesity and cardio respiratory ailments to which manual wheelchair users (MWCU) are particularly prone (Robinson et. al., 1988).

The functional consequences of lower-limb disability result diminished independence, fitness, work capacity and recreational/employment opportunities. Particularly, the upper-limb pain resulting from overuse injury affects the physical performance and the quality of life for MWCU. Chronic conditions such as carpal tunnel syndrome, rotator cuff injuries, elbow/shoulder tendonitis, and osteoarthritis have also been associated with long-term manual wheelchair use. Shoulder or wrist joint pain has been reported in 64-73 % of those who use manual wheelchairs with spinal cord injuries. In the previous studies, 67 % of MWCU had upper-limb mononeuropathies defined by strict electro diagnostic criteria. In addition, ineffective biomechanics can decrease the economy of wheelchair operation and lead to excessive metabolic and cardiopulmonary demand. Investigators have identified several possible contributors to overuse injuries in MWCU, including duration of manual wheelchair use, frequency of arm use, and propulsion style kinematics (Brubaker, 1990). On the other hand, several researchers have proposed that Chronic wheelchair-use creates imbalances in propulsion agonists and antagonists, and training of the antagonists may correct these imbalances, reduces the potential for associated upper-limb pain (Koontz, 2002), and improve the blood circulation in the lower body that is not in motion at all the times (Devillard et. Al., 2001). Therefore, training and related equipment for wheelchair-users offer an area of research that may result increased physical performance, and decreased health care costs for the users (Koontz, 2002).

This device also gives an important adaptation platform for beginners, prevents the possible injuries in user's arms and wrists in daily usages, and introduces a training platform for the people make wheelchair sports. Therefore, the aim of this study is to design and prototype an optimum wheelchair treadmill, which strengthens the upper extremity (shoulder, arm and wrist), and measures performance of the users. According to the extracted design parameters, a prototype was designed using CAD software in detail, and then finite element analyses were performed for the designed parts respectively. Then, the prototype was manufactured according to the results provided by FEA.

2. MECHANICAL SYSTEM DESCRIPTION

A solid model of wheelchair treadmill is shown in Fig. 1. As shown in Fig. 1, Wheelchair treadmill is an entirely user independent system. The system consist of five main components: the roller (1), the frame (2), the ramp (3), the magnetic unit (4), and enter/exit unit (5).

1. Rollers: It is the most critical module of the product. If the rollers are not functional or any problems which affect their functionality are not prevented, the product is essentially useless. Therefore, the core of the roller assembly has to be made of a hardened steel shaft that runs through the length of the roller. This ensures that the ends of the roller assembly be collinear and help with alignment.

The shaft diameter was determined as 17 mm. The DIN 115 Cr V3 shaft material was selected which meets requirements for strength and cost effectiveness. ORS brand high quality roller bearings have been used, rated for an angular velocity of 1700 rpm with a load capacity of 9,55 kN.

2. Frame: Designing the frame is an integral process for several reasons. First, the frame has to be designed to accommodate the motion of the rollers, so the integration between these two parts is crucial. Second, the frame needs to be able to bear the load applied by the user and wheelchair, as well as fit for various different wheelchair sizes. For this reason, the base consists of a flat rectangle made from profile of 60x40 mm. Rectangular comer braces and a center strip are welded to the frame to ensure accurate alignment for the base rollers. Supports are added to hold the shafts for the rollers and the platform.

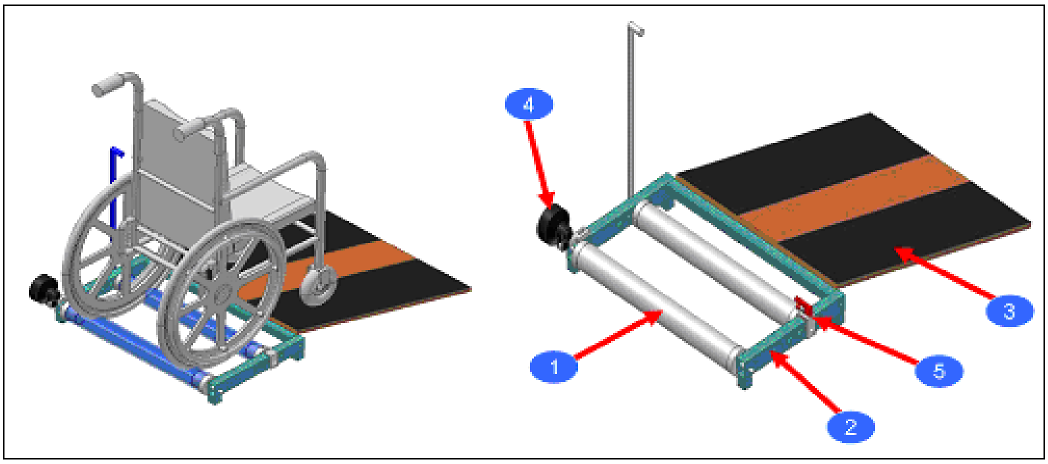

Fig. 1. A Solid Model of Wheelchair Treadmill

3. Ramp: The ramp, though seemingly a small part of the entire design, is important because it supplies what is desired for the overall comfort levels of the users. If the user cannot easily set him or her up on the machine, surely customers won't be happy to use it. Therefore, the ramp and the platform are constructed from 18 mm plywood. The platform is designed for a height of 100 mm. This low profile allows for a short (381 mm) ramp with a practical l/10 ratio. The large platform (1000 x 900 mm) allows the user to train using standard wheelchairs, as well as long racing wheelchairs.

4. Magnetic Device: A commercial magnetic device was attached to the Wheelchair Treadmill mechanism. The device supplies resistance to the rear roller through a belt and pulley system. A mounting block is welded to the frame to support the magnetic resistance device. Two rollers are used with deflection devices that eliminate the need for a clamping mechanism. Essentially, the magnetic unit is coupled to the back roller to allow seven levels of workouts corresponding to various levels of user abilities, and it can be disconnected to perform hand stroke analyses.

5. Enter/Exit Brake: A brake system was designed in order to lock the front roller into the frame. By locking the front roller, the mechanism between rollers and wheelchair is transformed to a static structure. So wheelchair users can safely enter and exit the equipment.

In the model the followings are assumed:

- Wheelchair users do not change posture,
- The weight of wheelchair users is 100 kg,
- The weight of wheelchair is 20 kg,
- Wheelchair has a 40 cm wheelbase,

The way to estimate center of mass (COM) described by Tomlinson (2000)

Fig. 2 shows weight distribution for a typical wheelchair.

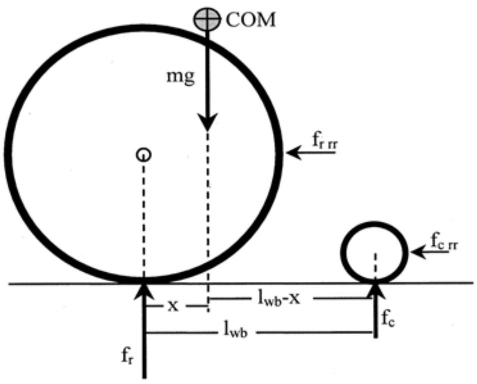

Fig. 2. Wheelchair weight distribution

Equations used:
Weight distribution

$$r_{wd} = \frac{f_r}{mg} = \frac{l_{wb} - x}{l_{wb}} \quad , \quad c_{wd} = \frac{f_c}{mg} = \frac{x}{l_{wb}} \qquad (1)$$

Using this Equation (1), weight on caster (f_c) and weight on rear wheels (f_γ) can be calculated.

$$f_c = m.g.c_{wd} \qquad (2)$$

$$f_r = m.g.r_{wd} \qquad (3)$$

Results: $f_c = 294$ N , $f_r = 883$ N

Two major geometrical factors can affect the radial load applied at each bearing. These are "Roller Distance", the horizontal distance between each roller, and "Roller Size", the diameter of the roller. Fig. 3 shows cross-sectional view of a wheelchair wheel in contact with a set of rollers. The Figure simply includes the wheelchair and two rollers represented by a large circle and two small circles respectively, and a number of different forces exerted on the bodies.

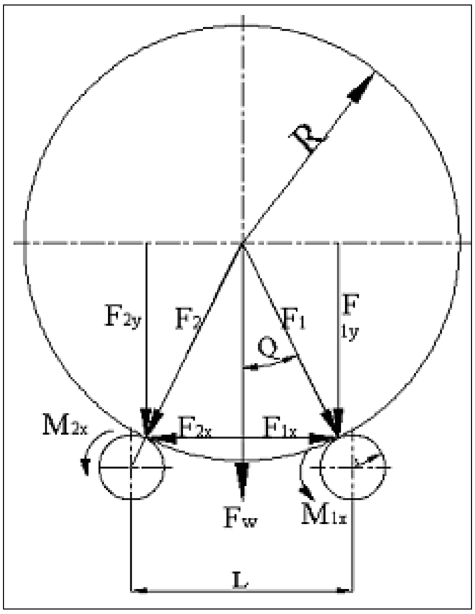

Fig. 2. Forces and force components exerted on rollers due to wheelchair load

As shown in Fig. 3, L, R, and r represent the distance between roller axes, the radius of the wheelchair wheel, and the radius of the roller respectively. The force due to weight of the wheelchair and person is defined as F_w, and F_1 is used to define the radial force on the rollers. "½ F_w" simply corresponds to a component of the radial force, and Q stands for the angle between the radial force and force due to the weight of the wheelchair.

$$\theta = \sin^{-1} \frac{L}{2(R+r)} \qquad (4)$$

$$F_N = \frac{1}{Cos\theta} * (\frac{1}{2} F_w) \qquad (5)$$

Using the equations (4) and (5), the relationship between roller distance and radial load can be calculated, as shown in Tab. 1.

Tab. 1. Radial load on rollers

L [mm]	200	250	300	350
F_x [N]	64,9	81,7	97,5	113,7
F_y [N]	211,0	205,1	198,1	189,2
M [N.m]	19,2	24,1	28,8	33,6

3. DESIGN ANALYSIS

The roller, which is the major component of the wheelchair treadmill, is the most critical part of the device. It supports all of the weight of a person and a wheelchair. In this study, a computer model of the wheelchair treadmill was produced using a CAD software, and then, each part in the model was transferred to ANSYS Workbench 10.0 FEA software. The frame and the rollers were assembled for the analysis. Then, aluminum 6063-T6-pipe roller material has been chosen because of its strength and affordability. Next, interactions have been defined by introducing the contact pairs between the related surfaces of the parts in the assembled model. In addition, loads and boundary conditions have been assigned (Fig. 4) and a suitable mesh was generated for each part. At the end, a general static geometrically nonlinear analysis was submitted to FEA software.

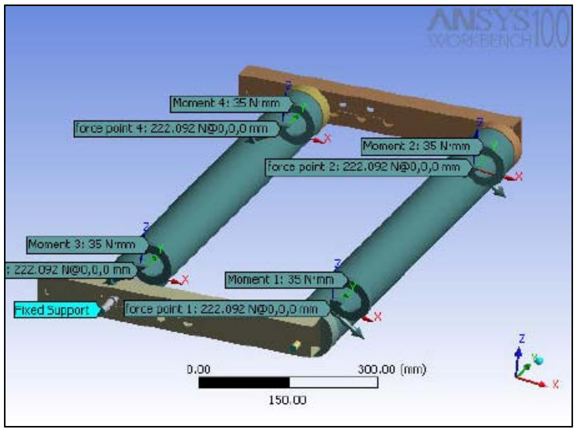

Fig. 3. Load Distribution of the Rollers

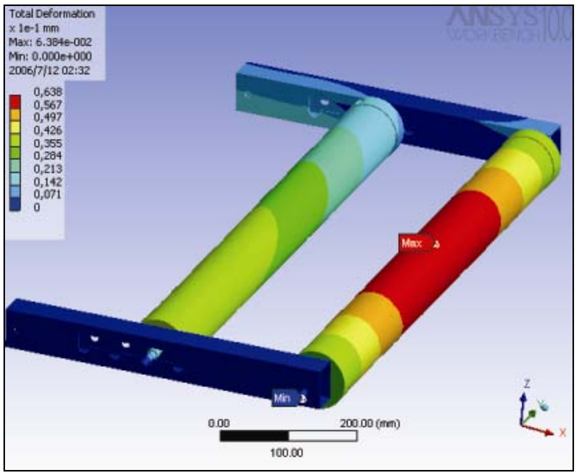

Fig. 4. Deformation on the roller

Having completed the analysis, the results have been obtained as shown in Fig. 5 and Fig. 6. Fig. 5 reveals that the critical point on the roller is located at the middle of the first roller where the deflection and the moment are the highest. Similarly, by looking the results, the stresses have been controlled to make sure that no place in the model has exceeded the mechanical limits.

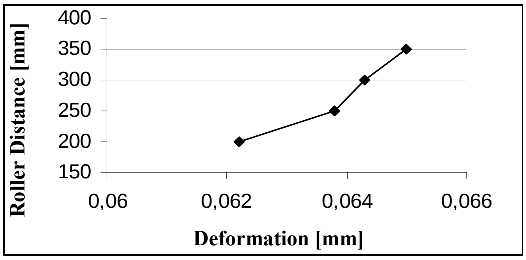

Fig. 5. The relationship between roller distance and deformation

4. TESTING AND EXPERIMENTAL RESULTS

After manufacturing the designed prototype (Fig. 7), several experiments have been planned and conducted. To choose suitable users for the experiment, the weight and age of the wheelchair users and the time of the wheelchair's usage have been considered carefully. In the first experiment, velocities of several wheelchair users on the road conditions such as the flat asphalt and the ceramic tile coated surfaces in buildings have been measured and the average velocity, maximum velocity, and the distance covered by the users have been recorded. In the second experiment, similar parameters have been observed. However, during this experiment, the resistance level of magnetic brake located on the wheelchair treadmill has been increased step by step from 0 to 7, and for each level, the average velocity, the maximum velocity, which the wheelchair user is able to reach, and the equivalent distance have been measured with a digital speedometer mounted on the wheelchair. The duration of experiment at each resistance level has been determined for at least one minute to fulfill the requirements. Finally, the velocity of the subjects in wheelchair treadmill has been shown in Fig. 8.

Fig. 6. Schematics of experimental prototype

Table 2. Velocities of users

	1.Subject		2.Subject		3.Subject		4.Subject	
	Asphalt	Parquet	Asphalt	Parquet	Asphalt	Parquet	Asphalt	Parquet
Average Velocity [km/h]	1,275	1,336	1,333	1,575	1,116	1,183	1,216	1,366
Maximum Velocity [km/h]	1,422	1,475	1,605	1,672	1,422	1,475	1,416	1,733
Trip Distance [m/min]	77	80	80	95	67	71	73	82

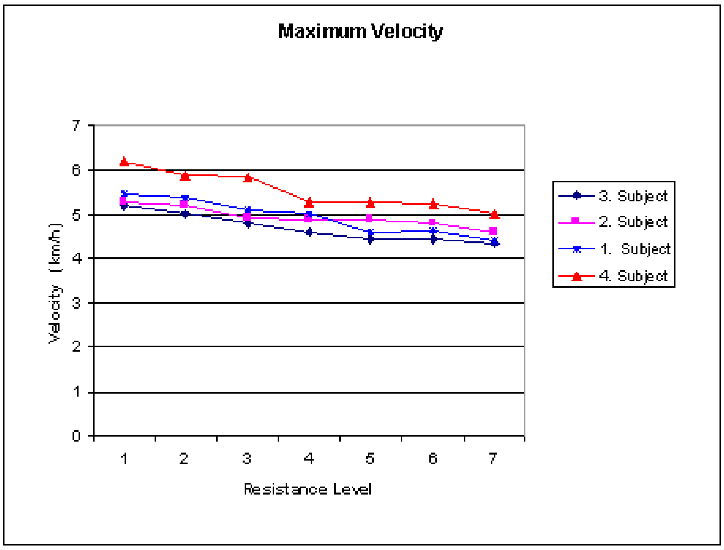

Fig. 8. Subjects velocity in the wheelchair treadmill

5. CONCLUSIONS

In this study, a wheelchair treadmill mechanism has been designed, and a prototype of it has been manufactured. The mechanism has been tested both for disabled and normal people. The average, maximum speed and the distance covered have been measured on asphalt road, parquet surface as well as on the produced wheelchair treadmill. These measurements have been performed taking the values from a digital speedometer for one minute period. The experiments have been conducted in the rehabilitation center of Marmara University

The average speed while increasing the magnetic resistance level of the wheelchair treadmill for different subjects is shown in Fig.7. In order to achieve the speed on the normal ground, wheelchair users should simply adjust the resistance to level 2. Similarly, the users can increase the resistance level to maximum for claiming a ramp. For these proposes, the system has been constructed in such a way that the different resistance levels are achieved by adjusting the distance between rollers. This functionality provides users with a useful tool to make their daily activities even in small living areas.

On the other hand, it has been observed that various factors associated with manual wheelchair driving force have strong effect on the results of experiments performed on the wheelchair treadmill. These factors are (a) wheelchair design and quality of the components, (b) environment in which the wheelchair is used, (c) the extent of person's disability, (d) person's level of physical fitness, and (e) person's skill and experience in using a wheelchair.

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