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DEVELOPMENT OF THE PNEUCHAIR: PNEUMATIC-POWERED WHEELCHAIR

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The lead-acid batteries currently used in powered wheelchairs are heavy, costly to replace, and require long recharge times. Although alternative battery chemistries are available that address some of these issues, they are more expensive and raise concerns about their safety, reliability, and compatibility with powered wheelchairs. Prototypes using alternatives such as solar power, fuel cells, and super capacitors have been developed, yet the feasibility of such devices being commercialized is low. This study focused on using pneumatic power as an alternative energy source in a powered wheelchair called the PneuChair. A participatory action design approach was applied throughout the study, where two sets of focus groups gathered feedback from end-users and mobility device professionals about the conceptual design of the PneuChair and their experiences using the PneuChair at a wheelchair accessible waterpark. The PneuChair was also tested using applicable ANSI/ISO Wheelchair Standards tests. The PneuChair features a tubular aluminum frame driven with a pneumatic joystick. A manufactured prototype passed the applicable ANSI/ISO Wheelchair Standards tests, and the results were equivalent to those of Group 2 electric-powered wheelchairs. As a result, pneumatic power is a feasible alternative energy source for powered wheelchairs that is safer, lighter weight, waterproof, and capable of being quickly recharged in 10 minutes.

Key words: Assistive technology; Mobility device; Air power

INTRODUCTION

The powered mobility device market has been populated with devices powered by batteries since the invention of the powered wheelchair over 60 years ago (1). Although the current gel-cell lead-acid batteries are reliable, their energy density, lifecycle, weight, and recharge times are problematic. Other battery chemistries such as NiCd, NiMH, and Li-ion may offer better performance yet are more expensive and raise safety, reliability, and compatibility concerns when used in powered mobility devices (2,3). Furthermore, national surveys have found that repairs leading to adverse consequences are not only common but are increasing, and repairs needed to the electrical system were the most common (4,5). As such, additional alternatives for the replacement of batteries need to be researched for their applicability in powered mobility devices.

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The necessity for researching alternative power sources was expressed as a high priority in a national survey consisting of powered mobility device users and clinicians who provide powered mobility devices (6). This need was also reinforced by several reports and literature reviews (7-10). In comparison to the amount of ongoing research performed to develop alternative power sources for vehicles, the scientific literature lacks studies that investigate alternative power sources for powered mobility devices. Yet, several prototype powered mobility devices have been developed using solar power (11,12), fuel cells (13-17), super capacitors (18), and combinations (19,20) of alternative power sources. Unfortunately, the potential for commercialization of using such alternatives is low. For instance, for solar power to be feasible, the solar panels would need to be compact enough not to hinder the maneuverability of the mobility device yet still be capable of providing a reasonable amount of energy. As for fuel cells, the necessity to generate and store hydrogen are issues. Lastly, supercapacitors are best used in applications where rapid charge and discharge cycles are preferred rather than the long-term storage required for powered mobility devices (21). Thus, supercapacitors would need to be combined with additional alternative power sources to be appropriate.

Pneumatic power is an alternative energy source that has potential. Its advantages over batteries include safety, waterproofness, capacity for infinite and rapid recharging, lighter weight, and lack of electrical components, which can reduce the frequency of maintenance and repairs. Therefore, to address the current issues with battery-powered mobility devices, the purpose of this study was to design, develop, and test a pneumatic-powered wheelchair that eliminates the need for batteries and electronics while remaining capable of being driven with a joystick.

METHODS

Prototype Design and Development

The design and development of the pneumatic-powered wheelchair (PneuChair) started with the conceptual design of a computer aided design (CAD) prototype that would fall within Medicare-provided specifications for Group 2 electric-powered wheelchairs (EPW). Group 2 specification requirements are as follows: maximum length of 122 cm, maximum width of 86.4 cm, minimum obstacle height climbing capability of 4 cm, minimum top speed on a flat surface of 1.34 m/s, and a minimum dynamic incline stability of 6° (22). Additional design criteria required the prototype to be joystick operated and rear-wheel drive. The PneuChair utilized the results of previous research of integrating pneumatic technology into a mobility scooter (PneuScooter), in which the same components are used (i.e., airline tubing diameters, radial piston air motors, regulator, etc.) (23). A prototype of the final CAD design was then manufactured and tested using ANSI/RESNA Wheelchair Standards.

Focus Groups

Ethical approval for the focus group studies was obtained from the institutional review board of the University of Pittsburgh, and all participants were asked to provide informed consent prior to enrollment in the studies. This study utilized the participatory action design approach, where feedback is gathered from users throughout the development process. As a result, two focus group studies were conducted. The first focus group's purpose was to gather feedback about the conceptual design of the PneuChair. Participants were eligible if they were 18 years of age or older and either had their own wheeled mobility devices, used the mobility scooters provided by some convenience/grocery stores, or were rehabilitation professionals involved in the provision of wheeled mobility devices. Multiple conceptual designs were presented, demos were performed to show the method for recharging the device, and participants were asked to provide feedback in a group discussion. The purpose of the second focus group was to gather feedback about individuals' experiences using the PneuChair at Morgan's Inspiration Island (24), a wheelchair-accessible water park located in San Antonio, Texas. Participants were eligible to participate in the second focus group if they were 18 years of age or older and either operated or assisted with operating the PneuChair. A phone conference focus group was performed due to the distance between the research facility and Morgan's Inspiration Island.

Wheelchair Standards Testing

To evaluate the safety, durability, and maneuverability of the PneuChair, ANSI/ISO Wheelchair Standards tests (25,26) were conducted using a manufactured prototype. The tests conducted were static and dynamic stability (Sections 1 and 2, respectively); effectiveness of brakes (Section 3); energy consumption (Section 4); maximum speed, acceleration, and deceleration (Section 6); impact and fatigue tests (Section 8); obstacle climbing ability (Section 10); and power and control systems (Section 14). Where required, a 100 kg test dummy was used to complete the testing procedures. All other testing equipment conformed to the requirements set forth in the standards. Sections 4, 8, and 14 were modified from their original procedures to accommodate the pneumatic propulsion system of the PneuChair.

The PneuChair test results were then compared with test results of Group 2 EPW previously tested at the research facility. An overall average using the Group 2 results was calculated for Sections 1, 3, 4, 6, and 10. Averages for Sections 2, 8, and 14 were not calculated, as they were either based on a numeric scale (Section 2) or pass/fail criteria (Sections 8 and 14). Four different wheelchairs from three manufacturers were included in the calculated overall averages. Three identical wheelchairs of each of the following were tested (N = 12): Pride Mobility Jazzy Select Elite, Pride Mobility Jazzy Select 6, Invacare Pronto M41, and the Hoveround MPV5.

Figure 1. PneuChair conceptual design.

Figure 2. PneuChair prototype.

RESULTS

Conceptual Design

Figure 1 presents the CAD prototype presented to the first focus group. For ease of accommodating different sized users, a modular seating system mount was designed such that the entire seating system could be easily removed and replaced with one of a different size. The prototype concept also included a removable cover to allow easy access to the recharge port and protect the pneumatic system components.

PneuChair Prototype

A photograph of a manufactured PneuChair prototype is presented in Figure 2. The prototype features a tubular aluminum frame and is driven via a pneumatic joystick (DEL Hydraulics, pneumatic feathering joystick) (27) that controls the airflow to two radial piston air motors, one left motor and one right motor. The two radial piston pneumatic motors (PTM mechatronics, PMO 1800) (28) allow the device to travel forwards, backwards, left, right, and any combination thereof. The air source consists of two carbon fiber air tanks (AirTanksForSale.com, "Great White" tank) (29) capable of being pressurized to 310 bar. A spring-engaged pneumatic actuator applies the brakes when the joystick is in its neutral position. When the joystick is moved from the neutral position, the brakes are deactivated via the pressurized air in the system. This design automatically engages the brakes in the event the device loses pressure or runs out of air. The seating system of the prototype consists of a manual wheelchair frame. A charge port located on the rear of the device allows the air tanks to be refilled simultaneously while remaining inside the device. Specifications for the PneuChair and averages of the Group 2 EPWs are provided in Table 1.

Table 1. Device Specifications

Specification	PneuChair	Group 2
Weight (kg)	54.4	80.9
Width (cm)	64.5	62.0
Length (cm)	86.4	101.7
Turning Radius (cm)	62.1	59.8

Focus Groups

Conceptual Design Focus Group

The results of the conceptual design focus group discussion raised several points and provided much useful feedback. Major design considerations included range capability of the device, the addition of a secondary or failsafe brake, the need for seat tilt, and color combinations. Other suggestions included the option for an attendant control, additional options for postural supports, harness option for users with limited trunk control or spasticity, addition of push handles, and the removal of sharp edges that may injure the user or caregivers. None of the participants in the discussion raised issues about or felt unsafe regarding the method used to power or recharge the device.

PneuChair Experience Focus Group

The feedback received from the participants who had experience with the PneuChair was focused around the control and seating system. With regards to the control system, approximately 70% of the guests who visited Morgan's Inspiration Island and wanted to use the PneuChair were unable to independently operate the device due to the amount of force, approximately 80 N, needed to operate the joystick. Twenty to thirty percent of the users who were able to use the PneuChair were individuals with paraplegia and could self-propel a manual chair. Other issues mentioned included the devices consistently veering to the left when users attempted to drive straight and difficulty in making the device go in reverse. As for the seating system, the lack of tilt, postural supports, and a headrest limited the users who could use the device to those with good trunk and/or upper extremity strength. Lastly, during the three months that the PneuChair was in operation, there were no reports of breakdowns or repairs needed, and there were no issues with the range limitations of the devices. On average, each guest used the PneuChair for two to four hours before requiring a refill.

Wheelchair Standards Testing

The results of the static stability tests (Section 1) for the PneuChair and Group 2 EPWs are provided in Table 2. All dynamic stability tests (Section 2) for the PneuChair received a score of 3 (no tip: at least three wheels remain on the test plane at all times) with the exception of when the brakes were applied when traveling backwards on a flat surface and slopes of 3°, 6°, and 10°. During these tests, the PneuChair received a score of 2 (transient tip: less than three wheels remain on the test plane at some point during the test and then drop back onto the test plane) due to the front casters lifting off the surface. All Group 2 EPWs received scores of 3 for the dynamic stability tests. The PneuChair tipping angles recorded during the braking effectiveness tests (Section 3) for the parking brake were 11.6° and 10.8° when traveling in the downhill and uphill directions, respectively. Results for the running brake effectiveness tests are provided in Table 3. Group 2 parking brake and running brake effectiveness data for the 6- and 10-degree tests were not available for comparison.

The PneuChair traveled a distance of 3.2 km using two fully filled air tanks at 310 bar during the energy consumption test (Section 4) compared to the calculated average theoretical distance of the Group 2 EPWs of 19.9 km (actual distance is often considerably less). Test results for maximum speed,

Table 2. Static Stability Results

Stability Direction		Tipping Angle (degrees)			
		PneuChair		Group 2	
		Least Stable	Most Stable	Least Stable	Most Stable
Forward	Front Wheels Locked	N/A	N/A	N/A	N/A
	Front Wheels Unlocked	33.7	N/A	23.7	27.1
Rearward	Rear Wheels Locked	12.6	N/A	N/A	N/A
	Rear Wheels Unlocked	17.7	N/A	23.0	32.0
Sideways	Anti-Tip Devices*	29.4	N/A	N/A	N/A
	Left	24.3	N/A	19.2	22.2
	Right	23	N/A	18.8	21.2

*Least Stable and Most Stable refer to the positioning of the anti-tip devices. The PneuChair anti-tip devices do not have multiple positions, thus only least stable values are recorded. N/A indicates not all devices are applicable in that configuration.

Table 3. Effectiveness of Running Brakes

		Average Braking Distance (m)					
		PneuChair			Group 2		
Inclination	Direction	Normal	Reverse	Emergency	Normal	Reverse	Emergency
0 degrees	Forward	1.37	0.78	1.78	1.45	1.25	1.35
	Reverse	0.60	0.35	0.85	0.57	0.41	0.49
3 degrees	Forward	3.39	1.46	2.69	1.56	1.36	1.51
	Reverse	1.58	0.57	1.81	0.54	0.41	0.48
6 degrees	Forward	6.49	3.20	6.14	N/A	N/A	N/A
	Reverse	2.17	1.71	2.88	N/A	N/A	N/A
10 degrees	Forward	8.64	4.39	9.52	N/A	N/A	N/A
	Reverse	*	*	*	N/A	N/A	N/A

*Not performed, slide/spin in this direction. N/A indicates not all devices are applicable in that configuration.

acceleration, and deceleration (Section 6) are provided in Table 4. All static, impact, and fatigue strength tests (Section 8) on the PneuChair passed except for the arm rests, which resulted in permanent deformation when tested in the static strength portion of the test. The arm rests are part of the manual wheelchair frame that was used for the seating system of the PneuChair and were not originally intended for use on a powered wheelchair, thus the forces they were required to withstand were higher than expected. All Group 2 EPWs passed Section 8 testing. The results of the obstacle climbing tests (Section 10) are provided in Table 5. The PneuChair passed all the applicable power and control systems requirements (Section 14) apart from not having a hose connection diagram. The necessary force to operate the PneuChair joystick was 82 N.

DISCUSSION

The design of the PneuChair implemented findings from previous pneumatic-powered mobility device research (23) and feedback gathered during

Table 4. Maximum Speed, Acceleration, and Deceleration Results

Maximum speed (m/s)	PneuChair	Group 2
Forwards horizontal	1.16	1.91
Forwards downhill 3° ramp	2.28	1.95
Forwards uphill 3° ramp	0.97	1.72
Rearwards horizontal	1.23	0.91
Acceleration		
Overall	0.632	1.29
Maximum	0.79	1.41
Deceleration (m/s^2)		
Overall	1.24	1.55
Maximum	1.99	1.57

Table 5. Obstacle Climbing Ability Results

Obstacle Climbing	PneuChair	Group 2
Forwards, no run-up	18	36
Backwards, no run-up	18	23
Forwards, .5 m run-up	30	60
Backwards, .5 m run-up	32	36
Obstacle descending		
Forwards, 1 m run-up	35	60
Backwards, 1 m run-up, slow speed	35	36

the conceptual design focus groups. All the requirements for the PneuChair to be categorized as a Group 2 power wheelchair were met except for the minimum speed requirement of 1.34 m/s. The 1.16 m/s maximum speed of the PneuChair may be increased with further optimization of the pneumatic system, such as changing the operating pressure, airflow rate, or final drive gear ratio. Other performance specifications that could be improved with further optimization and testing include braking distance, acceleration, and deceleration. After such changes are made, the PneuChair will need to be retested to confirm that the modifications do not inhibit the PneuChair's capability to climb the necessary thresholds and slopes outlined in the ADA guidelines (30). It should be noted that although the PneuChair is approximately the same size as Group 2 EPWs, its weight is 26.5 kg less. This advantage allows the PneuChair to be transported more easily, as it could be lifted into the rear of a vehicle without the need of a lift or ramp.

The results of the tests performed on the PneuChair using ANSI/RESNA Wheelchair Standards are comparable to Group 2 EPWs in the areas of durability, maneuverability, and stability. Although the range of the PneuChair prototype is a concern, the capability of pneumatic-powered devices to be recharged in minutes is superior when considering EPWs require up to eight hours to recharge. This advantage was justified during the five-month period that the PneuChair was being used at Morgan's Inspiration Island, as guests could have the devices recharged quickly when running low on air capacity.

Although the capability of the PneuChair to replace electric-powered mobility devices is plausible, several improvements need to be implemented to provide all users with an equal opportunity to utilize the device. As a result of the PneuChair being a novel mobility device, most of the attention during the design of the prototype was focused towards implementing the pneumatic technology into the base of the device rather than the seating system. Therefore, it was expected that there would be issues with the controls and seating system, and this was confirmed by the feedback received during the experience focus group. As such, future work will consist of the development of a low force joystick and alternative controls such as head controls. A rehab style seating system with the addition of pneumatic-powered seating functions, lateral supports, and headrest also must be developed to replace the current manual wheelchair frame seat.

CONCLUSION

Overall, the impact of using pneumatic technology's advantages of quick and unlimited recharging, lighter weight, safety, waterproof ability, and reduced frequency of repairs and maintenance in powered mobility devices has implications in numerous markets. Locations such as hospitals, long-term care facilities, supermarkets, and airports, where there are fleets of powered mobility devices, could greatly benefit from pneumatic-powered mobility devices. At these locations, battery maintenance is essential yet difficult to maintain, resulting in devices that are in need of repair and unusable for long periods of time. Other possibilities where pneumatic-powered mobility devices may be superior are during emergency or disaster situations, such as after earthquakes, hurricanes, or tornadoes, when electricity is unavailable and/or flooding or wet environments render electric-powered mobility devices useless.

This study incorporated participatory action design into the development process of the PneuChair, a pneumatic-powered wheelchair. The key features of the device are as follows: 1) a duo of carbon fiber air tanks filled with compressed air serve as the device's energy source; 2) the use of compressed air allows the device to be recharged an unlimited number of times in as little as 10 minutes; 3) the device is operated via a pneumatic joystick; 4) the lack of batteries or electronics makes the PneuChair waterproof; and 5) the 55 kg weight of the device allows for easier transportation in the rear of a vehicle or airplane.

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