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Analysis of a Lever-Driven Wheelchair Prototype and the Correlation between Static Push Force and Wheelchair Performance

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Abstract: In this experimental study a lever-driven wheelchair prototype was compared with a manual wheelchair. The push force of 13 able-bodied human participants was measured over the range of motion required to propel the lever-driven wheelchair prototype and the standard manual wheelchair. The push force that is required to propel each wheelchair was measured statically using strain gauges and dynamically using a purpose built dynamometer to quantify high and low force areas and to determine if correlation exists to wheelchair performance. The force exerted, simulated peak wheelchair velocity, acceleration, torque and power, were examined. The 13 human participants completed five maximal effort tests in the lever-driven wheelchair and three maximal effort tests in a manual wheelchair on the dynamometer. A multiple regression and a Pearson's product-moment correlation coefficient analysis were performed on the acquired data and a p-value of less than 0.05 level of significance was found; suggesting a correlation does exist between the static and dynamic force measurement methods.

1. INTRODUCTION

It has been described that manual wheelchair (WC) propulsion using a push-rim WC is an inefficient form of human locomotion (1). Push-rim WC's have a poor mechanical advantage and cause high strain on the cardiorespiratory and musculoskeletal systems (2). These factors, in combination with general characteristics of the wheelchair-confined population (a physical disability, a sedentary lifestyle, and small muscle mass in upper extremities), can lead to a high physical strain on the user and in effect result in a further debilitated and more inactive lifestyle. This can lead to health risks with respect to the cardiorespiratory system, unhealthy weight-gain and also cause further muscle atrophy (5,6). Crank and lever-propelled WC's appear to be less straining forms of locomotion due to the longer continuous stroking pattern (7-10). The increased use of flexor and extensor muscles in the arms, less complex coupling of the hands and a longer continuous motion appear as major contributing positive factors (7,13). Use of a lever mechanism has been found to be more effective in transmitting human power for WC propulsion by placing the arms in a more natural segmental position (4). Demand on the upper extremities during standard push-rim propulsion has been documented (3,4), however further research of the forces is required to better understand the demands that lever propulsion places on the upper extremities. The objective of this work was to determine the performance capabilities of the lever-drive prototype and to determine whether there is a correlation between static pushing force and high-demand WC performance. It is hoped that this research will help to develop a more effective way to propelling WC for people with spinal cord injuries.

Figure 1 - Lever-Driven Wheelchair Prototype

2. METHODS

2.1 Subjects

Thirteen able-bodied non-WC users (ten male and three female) participated in this study. Ethics approval was obtained and subjects provided written informed consent to participate in this study.

2.2 The Wheelchair

The WC used in this study was a prototype bi-manual independently lever-driven WC designed and fabricated at the University of Canterbury. The levers were coupled to the wheels by a chain and sprocket. The lower sprocket assembly included a sprag clutch to allow the WC to free-wheel in the forward direction. For forward propulsion, the top driver sprocket is attached to the lever. When the lever is pushed forward a torque is transmitted to the wheels to propel the chair. No propulsive torque is generated during the recovery phase of the stroke i.e. when pulling the lever backward. The heights of the handles on each lever arm were adjusted with tests carried out at two effective lever lengths, namely 0.275m and 0.395m. The WC was reconfigured by removing the lever-drive and fitting a standard push-rim. The characteristics of the WC were not adjusted to anthropometry variations between test subjects. The inertia of the wheels was estimated and included in the analysis.

2.3 The Dynamometer

The dynamometer had two independent rollers and the roller inertia was adjustable by adding flywheels. The angular inertia of the system was kept constant across all tests and subjects. The dynamometer rollers are connected to rotary encoders which capture 1000 data points per revolution. The data from the rotary encoders was recorded using a laptop PC and processed using LabVIEW to determine roller angle with respect to time.

2.4 Push Force Rig

Figure 2 - Static Push Force Rig

The push force rig consisted of two calibrated strain gauges located in the sagittal plane on both sides of the user, Figure 2. The position for each strain gauge was independently adjustable and allowed measurements to be taken from any position within the participant's range of motion. The strain gauges were connected to a laptop PC and LabVIEW was used to record the maximum push force exerted on each strain gauge for each position. The output of the analysed results is shown below in Figure 3.

2.5 Procedure

Each participant was asked to warm-up on the dynamometer and the rolling resistance for both rollers was balanced. The participants completed a maximum acceleration test (Test One), a single push maximum power test (Test Two), and then a 500-meter sprint (Test Three). The participants were allowed as much rest as they required in between each test and were given a minimum recovery period of three days repeating the test on the lever-driven WC. Tests Two and Three were repeated twice for the lever-driven WC, i.e. two different lever arm heights.

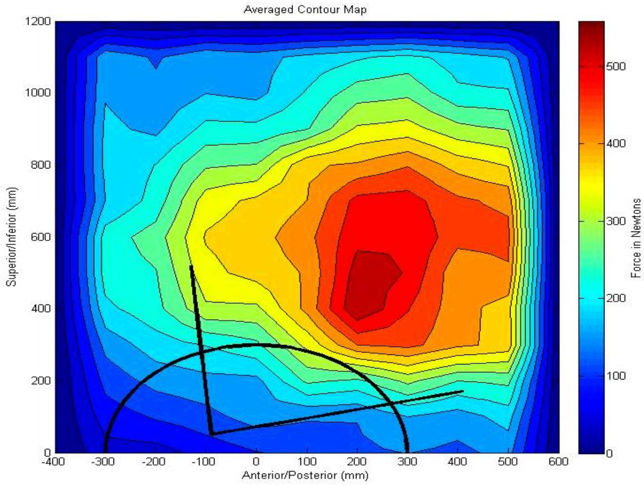


Figure 3 - Force Map of an Able-Bodied Participant

Test One was designed to analyse the participant's acceleration, torque, and power from rest to maximum velocity. Test Two was used to analyse the maximum power, force and torque the subject was capable of exerting. Test Three was used to analyse how fatigue affected torque, power and velocity outputs from each participant.

3. Analysis

3.1 The Dynamometer

The raw data from the dynamometer was analysed using MATLAB and produced the following outputs:

Displacement Curve – The raw angular data was converted from an angular position to an equivalent linear distance for the WC by scaling the roller displacement array.

Velocity Curve – The displacement data was differentiated with respect to time and plotted against the time array. The velocity curve created from the raw data plot was found to be noisy due to the differentiation method and the use of high precision encoders used for measuring roller angle (15). This noise was filtered using a moving average smoothing function.

Acceleration Curve – The displacement data was twice differentiated with respect to time and plotted against the time array. Multiple smoothing functions were required to filter the further propagation of the noise.

Torque Curve – The relationship below was used to find the system's torque (τ).

$$\tau = I \times \alpha_{sys} \quad (1)$$

The rotational inertia (I) of each roller is known and the rotational acceleration of the system (α_{sys}) can be calculated as described above. The torque output from each participant was further defined by including the deceleration of the rollers due to the internal friction (α_{RR}) and rolling resistance.

$$\tau = I \times (\alpha_{SYS} - \alpha_{RR}) \quad (1a)$$

This deceleration was estimated by measuring the slope of the velocity curve for a coast-down test i.e. after the participant had stopped pushing. This method assumed that rolling resistance was independent of WC velocity. Test Three had multiple peak velocities; due to this the rolling resistance was assumed equal to the prior test to maintain autonomy for processing of results. The calculated torque was then plotted against the time array.

Power Curve – The following relationship defining power (P) in relation to torque (τ) and angular velocity (ω) was used.

$$P = \tau \times \omega \quad (2)$$

Force Curve – The following relationship was used to define the force (F) being exerted by each subject for the lever-drive WC.

$$F = \frac{I \times \alpha \times R_{Wheel}}{R_{Dyno} \times R_{Lever} \times GR} \quad (3)$$

Equation 3 was further modified to define the force exerted by the user on the push-rim WC.

$$F = \frac{I \times \alpha \times R_{Wheel}}{R_{Dyno} \times R_{Pushrim}} \quad (3a)$$

The mean and maxima were recorded for each test. The performance curves for each subject were then plotted and the lever-drive and the push-rim tests compared.

To achieve automation for the analysis of all test data, the raw data was selected, starting at the beginning of the first push and ending when the roller came to rest. This was achieved by setting a requirement that the rate of change of the displacement was greater than a threshold for all data points.

3.2 The Push Rig

The results obtained from the force push rig were analysed using MATLAB. Through interpolation, continuous propulsion arcs were generated for both the push-rim and lever-driven WC's. The propulsion arc for each subject was then averaged for comparison with the dynamometer results.

3.3 Statistical Analysis

A Pearson's correlation and a t-test were performed for the peak forces generated by the dynamometer and static push force analyses. Multiple factorial ANOVA's were performed on the acquired dynamometer data. These ANOVA's calculated the statistical variances for velocity, acceleration, torque, power and force exerted between the lever-driven and push-rim WC's to test for a statistical correlation.

4. Results

Dynamometer Results

Table 1 below summarises key results obtained through the dynamometer testing. These results show the participants' average values generated from one arm. The results for Test Two have been omitted from Table 1 as this data is displayed in Figures 4 & 5.

The maximum power was found near the beginning of each test where the combination of acceleration and velocity was at a maximum. Once maximum velocity had been reached the power output from each subject was only equivalent to the power generated to overcome the internal friction of the system. The power delivered after the initial acceleration had gone to zero remained reasonably constant throughout the length of Test Three, although it did show a slight negative relation with time due to subject fatigue.

Table 1 – Summary of Dynamometer Results

	Averages of the Mean		
		Test 1	**Test 3**
Force (N)	Lever-Drive	368	405
	Pushrim	259	235
Power (W)	Lever-Drive	50.2	55.2
	Pushrim	32.3	33.4
Torque (N-m)	Lever-Drive	3.8	3.74
	Pushrim	2.6	2.46
Velocity (m/s)	Lever-Drive	1.87	2.68
	Pushrim	1.52	2.09
	Means of the Maxima		
		Test 1	**Test 3**
Acceleration ($m \cdot s^{-2}$)	Lever-Drive	2.54	2.78
	Pushrim	2.42	2.2
Power (W)	Lever-Drive	192	216.9
	Pushrim	159	152.2
Torque (N-m)	Lever-Drive	34.6	37.6
	Pushrim	31.6	29.5
Velocity (m/s)	Lever-Drive	2.92	2.75
	Pushrim	2.42	2.24

Maximum torques were found at the beginning of each test and reduced due to diminishing acceleration at higher velocities. The average maximum torque from the test subjects was found to be slightly higher for the lever-driven WC than the push-rim WC with recorded values of 34.6 N-m and 31.6 N-m.

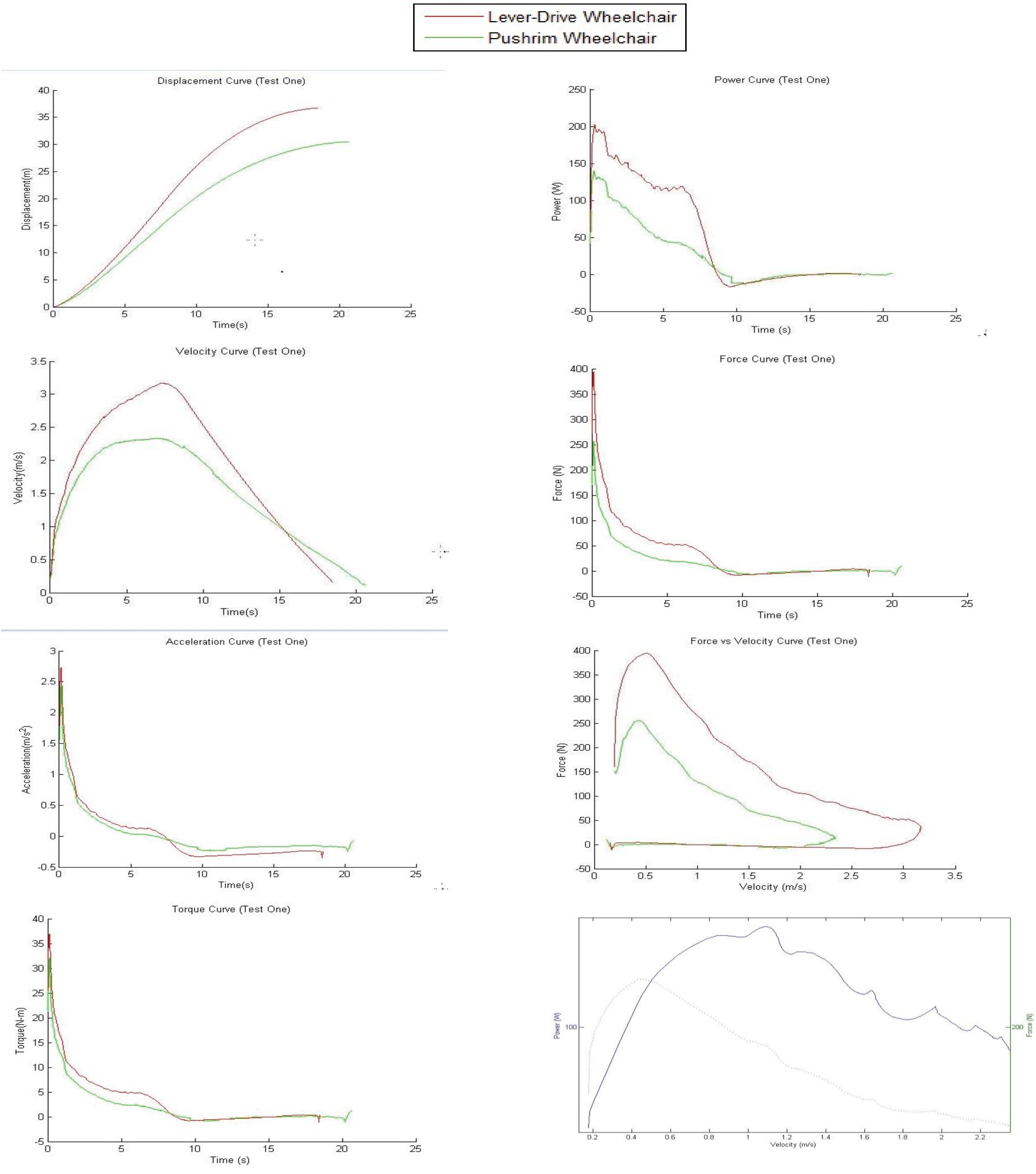
The acceleration was maximum at the start of each test and reduced to zero near maximum or coasting velocities. The lever-driven WC showed a higher peak and mean acceleration average across all tests.

Comparing power against velocity showed the average maximum power across the participants to be at 1.07 m/s for the lever-driven WC and 0.89 m/s for the push-rim WC.

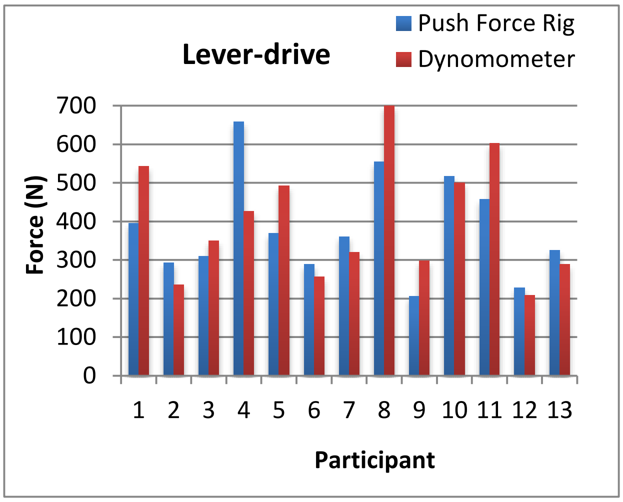
The mean maximum velocity for all participants was found to be 23 percent greater using the lever-driven WC for Test One. Test Three showed the mean velocity to be 28 percent greater for the lever-driven WC compared to the push-rim WC.

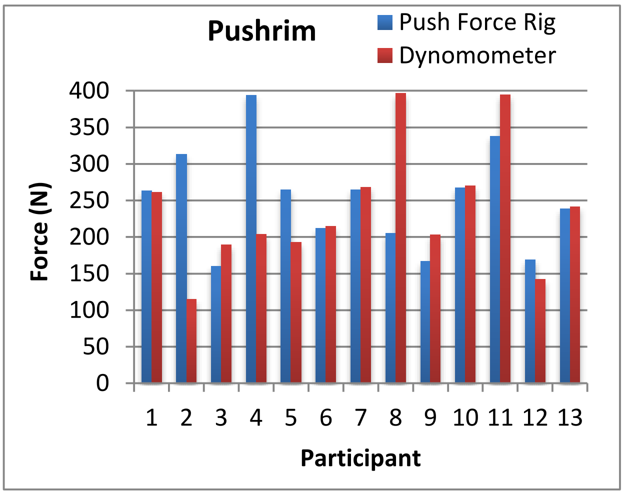
The Pearson product-moment correlation coefficient was evaluated to be 0.66 and 0.81 for the push-rim and lever-drive results, respectively. This shows there is a statistical correlation between the force measured from the dynamometer and the push force rig for both the push-rim and lever-drive WCs (0 means there is no correlation and 1 means both data sets are equal).

The t-test results confirm that the data attained for each kind of WC is statistically similar.



Figures 4 – 11: MATLAB outputs for one test subject, comparing their lever-drive WC results with the Pushrim WC





Figures 12 & 13 above compare the maximum forces measured for each participant from both the push force rig analysis and the dynamometer analysis for the lever-driven WC and push-rim WC.

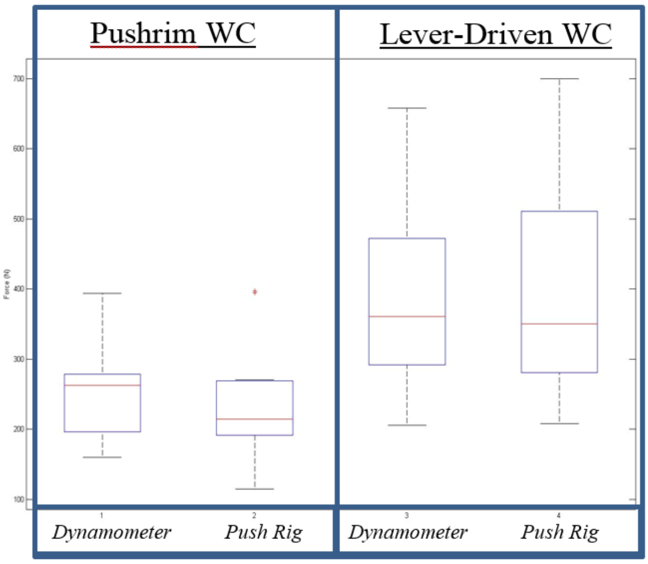


Figure 14 above is a box and whisker plot for the force data displayed in figures 12 & 13. The first two columns are the results of the statistical analysis for the push-rim WC; while the third and fourth columns are the lever-driven WC results.

Table 2 - Maximum Force Measured for each participant on both the Push Force Rig and Dynamometer for the Lever-Driven WCs

	Pushrim		*Lever-Drive*	
	Push Rig (N)	Dynamometer (N)	Push Rig (N)	Dynamometer (N)
Mean	250.5	238	381.8	401.7
Std Dev.	67.1	80.3	127.1	131.4
Maximum	394	396.8	658	699.5
Minimum	160.2	115.3	206	208.3
t-test	0.0053		0.0034	
Pearsons	0.660		0.812	

5. Discussion

Participants 2, 4 and 8 showed a large difference between their static and dynamic force measurements. This could be due to these participants positioning themselves in a different way on the static force test rig to help achieve a higher force. Using a different seating position could allow the participant to exert different muscle groups than they would normally use in propelling the WC; this could be the underlying cause of these discrepancies. To help prevent this, the test bench could be redesigned to prevent participants from acquiring any reaction force using their legs or the wheelchair.

The push force rig measures the static tangential force for each propulsion arc test. While this tangential force is the dominant force used for propulsion, a WC user also applies a moment generated from their wrists and a radial force onto the push-rim. The wrist force contributes minimally to the propulsion of the WC (14). The effective force applied to the WC can be described by the square of the tangential force applied divided by the square of the total force applied (14). As the effective force was found for both the push-rim WC and the lever-driven WC using the same measure, results were considered consistent. One study showed the effective tangential force for push-rim WCs made up 79 percent of the total force exerted by each arm (14)

The dynamometer results show that the maximum force exerted by the subject is from the rest position and progressively declines with increasing velocity. This phenomenon is well described in the literature and is due to the maximum concentric muscle contraction force being less than the maximum isometric muscle contraction force (4). The correlation between the static force measurements and dynamic force measurements only remained statistically similar at the initial instant after each participant began pushing the WC.

The difference in mechanical advantage between the push-rim and lever-driven WC's suggest an advantage for the push-rim WC for the initial push. This is because for a given muscular force, the turning moment is higher at a larger radius. However, this is not consistent with the results of this study which suggest a higher force for the lever-driven WC due to the use of alternate muscle groups. This has a larger effect on performance than the mechanical advantage of the push-rim WC. Similarly, the geometry of the lever-driven WC provides an additional benefit such that it is easier to propel the WC at a higher velocity. This phenomenon can be observed in the 500-meter sprint test results, where the cadence is lower for the lever-driven WC yet the velocity remains higher than the push-rim WC.

The length of the propulsion arc, where force was effectively transmitted, was found to be greater on the lever-driven WC than for the push-rim WC. This results in more work done and more energy transferred into propulsion for the same cadence.

The peak power was measured at the beginning of each test. After this peak, acceleration of the WC decreases with increasing velocity and increasing system losses such as internal friction.

The internal friction of the system varies between participants due to variations of mass, alignment, and required anchor forces. The rolling resistance was calculated for each test and applied throughout the calculations to normalise the test data. However, it is possible that the variance in internal friction between participants could have caused a discrepancy in the effort required to maintain the same power output.

The maximum and average power achieved over Test Three was far greater for the lever-driven WC for every test subject. This confirms that the high force area anterior to the user's chest and abdomen provides greater power to the user through each stroke.

6. Conclusion

The lever-drive WC prototype showed greater performance on average across all tests. The force maps have shown a statistical significance for correlation between the maximum static force that can be exerted by each participant and the performance of both WC's. Further development and testing of this system is recommended to further increase performance of the lever-driven system. Research is also required to quantify the performance capabilities that can be delivered from lever-driven WC systems for each classification of the disabled population. A similar geared lever driven system needs to be developed and tested to define further possible benefits to WC users across a range of paralysis. The continuation of this research could bring a better standard of living to many people in the WC confined population.

7. References

1. van der Woude, L. H., et al. (2001). , **80(10)**, 765-777.

2. Gellman, H., D.R. Chandler, D.R. Petrasek, and J.I. Sie (1988). Carpal tunnel syndrome in paraplegic patients. *J Bone Joint Surg*, **70A(4)**, 517-9.

3. Apple, D.F., R. Cody, and A. Allen (1996). Overuse syndrome of the upper limb in people with spinal cord injury. In: Apple DF, editor. Physical fitness: a guide for individuals with spinal cord injury. *J Rehabil Res Dev 1996;(Clin Suppl)* ((Apple, D.F. (Ed)), **26(4),** 97-108.

4. van der Woude, L. H., et al (1997). effect of intensity in able-bodied subjects, *J Rehabil Res Dev*, **34(3)**, 286-294.

5. H.E.J. Veeger, L.A. Rozendaal, and F.C.T. van der Helm (2002). Load on the shoulder in low intensity wheelchair propulsion, *Clin Biomech*, **17(3),** 211–218.

6. Groot, S, M. de Bruin, S.P. Noomen, and L.H. van der Woude (2008). Mechanical efficiency and propulsion technique after 7 weeks of low-intensity wheelchair training. *Clin Biomech*, **23(4)**, 434–441.

7. Gangelhoff, J., L. Cordain, A. Tucker, and J. Sockler (1988). Metabolic and heart rate responses to submaximal arm lever and arm crank ergometry. *Arch Phys Med Rehabil*, **69(2)**, 101-5.

8. van der Woude, L.H.V., H.E.J. Veeger, Y.A. de Boer, and R.H. Rozendal (1993). Physiological evaluation of a newly designed lever mechanism for wheelchairs. *J Med Eng Technol*, **17**, 232-40.

9. Boer, Y.A. de, W. Cambach, H.E.J. Veeger, and L.H.V. van der Woude (1992). Wheelchair prototype testing : a new lever-drive system in comparison with existing propulsion mechanisms. *J Rehabil Sci*, **5**, 39-44.

10. Engel P. and K. Seeliger (1986). Technological and physiological characteristics of a newly developed hand-lever drive system for wheel-chairs. *J Rehabil Res Dev*, **23(4)**, 37-40.

11. van der Woude, L.H.V. G. de Groot G., A.P. Hollander, G.J. van Ingen-Schenau and R.H. Rozendal (1986). Wheelchair ergonomics and physiological testing of prototypes. *Ergonomics*, **29**, 1561-73.

12. Maki, K.C., W.E. Langbein, and C. Reid-Lokos (1995). Energy cost and locomotive economy of handbike and row-cycle propulsion by persons with spinal cord injury. *J Rehabil Res Dev,* **32**, 170-8.

13. van der Woude, L.H.V, E. van Kranen, G. Ariens, R.H. Rozendal and H.E.J. Veeger (1995). Physical strain and mechanical efficiency in hubcrank and handrim wheelchair propulsion. *J Med Eng Technol*, **19**, 123-31.

14. Vanlandewijck, Y., D. Theisen[2] and D. Daly (2001), Wheelchair Propulsion Biomechanics Implications for Wheelchair Sports, **7**, 21-32

15. Marin, L. and Xiao D. (2011). Numerical Differentiation of Noisy, Nonsmooth Data. ISRN Applied Mathematics, **3,** 1-11.