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ON THE DESIGN OF MANUAL WHEELCHAIRS FOR PEOPLE WITH SPINAL CORD INJURIES

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1. Introduction

For people with Spinal Cord Injuries (SCI's), manual wheelchair propulsion is an important part of daily living. Manual wheelchairs are generally preferred over their electric counterparts due to their light weight, high manoeuvrability, low cost and 'minimal aesthetic' properties. Whether or not a person can effectively use a manual wheelchair is dependent on their upper body strength and function. For people with SCI's, strength and function are closely related to the level at which the spinal cord has been injured.
Orthopaedic surgeons have been performing surgical procedures to better enable people to live independently. One of authors has performed or supervised around 100 posterior deltoid to triceps transfer procedures. One of the benefits of this surgery is that it improves a person's ability to propel a manual wheelchair [Gooch et al., 2007].
Health practitioners, eg physiotherapists, prescribe assistive devices such as manual wheelchairs. The main considerations include mechanical specifications such as: frame materials (cromolly steel, aluminium alloy, titanium alloy and carbon fibre); wheel type and proprietary fittings. A big emphasis is placed on minimising the weight of the device verses cost. Little consideration is given to matching a particular configuration for a particular user's ability. The most common level of SCI [O'Connor, 2001] is in the cervical spine. In the majority of cases this results is limited or no elbow extension ability.

Table 1. SCI level and function (adapted from [Floris et al. 2002])

No. Subjects	SCI Level	Function
7*	Cervical injuries (C5-C6)	• Preservation of shoulder abduction + external rotation • Preservation of elbow flexion + variable wrist extension • Little/no voluntary control of elbow extension • No hand function
6	Cervical injuries (C7)	• Elbow extension /Wrist extension • Finger extension, no grasp
4	Thoracic injuries (T1-T8)	• Near normal upper limb function • Limited abdominal function and trunk control
4	Thoracic injuries (T9-T12)	• Full upper limb function • Good abdominal function and trunk control
2	Lumbar and Sacral injuries	• Full upper limb function • Good abdominal function and trunk control

* 5 of the subjects with cervical injuries have received a posterior deltoids to triceps transfer

The purpose of this study is to investigate the appropriateness of prescribing a standard manual wheelchair for a person with a SCI. Twenty three people voluntarily participated in this study, the criteria was that they had complete tetraplegia or paraplegia and that they used a manual wheelchair as their primary means of mobility. A summary of the number of subjects, SCI level and function is given in Table 1.

2. Measuring wheelchair propulsion ability

There are many different ways of measuring wheelchair propulsion ability. Ideally measurements should be made while negotiating real obstacles in everyday environments or simulating these environments using a pre-prepared test track. Erogometers and dynamometers are often used. They include a means for applying a propulsion resistance load and a means for measuring power output. Instrumented push rims are used extensively in the literature [Koontz et al., 2005] to measure wheelchair propulsion ability. They use strain gauges to measure forces directly and can measure push rim forces with very high accuracy. The purpose of this section is to establish an appropriate method for measuring wheelchair propulsion ability. Firstly we must consider the techniques adopted by our subjects.

2.1 Wheelchair propulsion techniques

As all humans are different; there are many different techniques adopted by people propelling wheelchairs. An important parameter to consider in measuring wheelchair propulsion ability is the grip technique. We observed participants during wheelchair propulsion and noticed a wide range of grip techniques were used. Figure 1a shows the grip technique adopted by an able bodied non wheelchair user. The subject in Figure 1a is grasping the push rim in the way it is designed to be used.

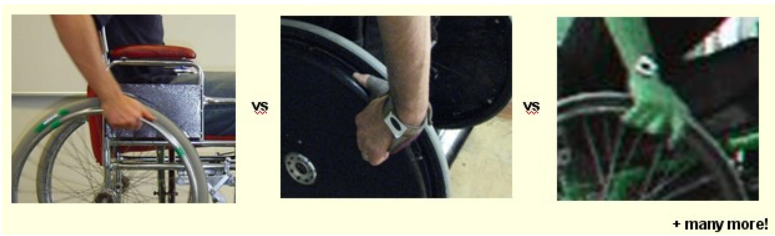


Figure 1. Grip technique

The subject in Figure 1b has tetraplegia and very weak grip. To compensate for his weak grip he lodges his thumb against one of the rim attachment bolts. Others with limited hand strength and function, wedge their hands between the rim and the tyre. This reduces the magnitude of the medial rim force required to achieve a friction grip. Grip technique was also found to be dependent on load. For example, the subject in Figure 1b, who lodges his thumb against one of the rim attachment bolts, only does this during start-up or when climbing ramps and getting over curbs. Figure 1c shows the grip adopted by a paraplegic subject who has a fully functioning hand, when asked to accelerate the wheelchair as fast he could from rest, he grasped the tyre and push rim together to achieve maximum acceleration. The implication for measuring propulsion forces is that push rim forces cannot be measured in isolation. Using a device such as the instrumented push rim would require users to change their technique otherwise an underestimate of propulsion forces will be obtained.

2.2 Selecting a method of Propulsion Measurement

Methods of measuring wheelchair propulsion ability were evaluated using the selection chart shown in Figure 2. There were principally two sets of parameters to measure, namely: ‘work and power output’ and bio-kinematics. From Figure 2, the selected method for measuring work and power output was the dynamometer. Ideally some means for accurately predicting rim contact times would be included with the dynamometer. Manual video data analysis was selected for acquiring the kinematic data. Since this study has been completed we have evolved a cheap, simple and effective means for measuring kinematic data using computational video data analysis.

Selection chart

Propulsion Measurement Methodolgy

	Methods considered	Ease of Measuring Force/Work/Power	Acquisition of Kinematic Data	Repeatable / Comparable Tests	Measure users under realistic conditions	Economical and efficient test (cost/time)	Comments	Develop further	Eliminate	Select
Work/Power	Field test / Obstacle Course	D	A	T	U	M	**Pros** - realistic simulation of all conditions **Cons** - repeatability difficult - time consuming testing		✓	
Work/Power	Dynamometer	✓ ✓	✓	✓	x	✓ ✓	**Pros** - Repeatable and efficient data capture - Not affected by grip technique **Cons** - Difficult to simulate some conditions (curb)			✓
Work/Power	Instrumented Push-rim	✓	✓		x x	✓	**Pros** - ability to accurately determine contact timing **Cons** - not all participants use push rim exclusively - wheelchair is modified		✓	
Kinematics	Manual Video Data Analysis	D	A	T	U	M	**Pros** - cheap/simple and accurate method **Cons** - time consuming			✓
Kinematics	Computational Video Data Analysis	✓	✓	✓ ✓	✓ ✓	✓	**Pros** - efficient (once working) **Cons** - expensive for a system which will produce satisfactory results	✓		

Key: (✓) yes +1, (x) no -1, ( ) neutral 0, (?) not enough information

Figure 2. Propulsion measurement methodology selection chart

2.3 The wheelchair dynamometer

An inertia dynamometer, shown in Figure 3, was built at the Department of Mechanical Engineering, University of Canterbury. The wheelchair was rigidly fixed onto the dynamometer with the rear wheels sitting on two independent rollers. Additional flywheels (solid steel discs) are fitted to the

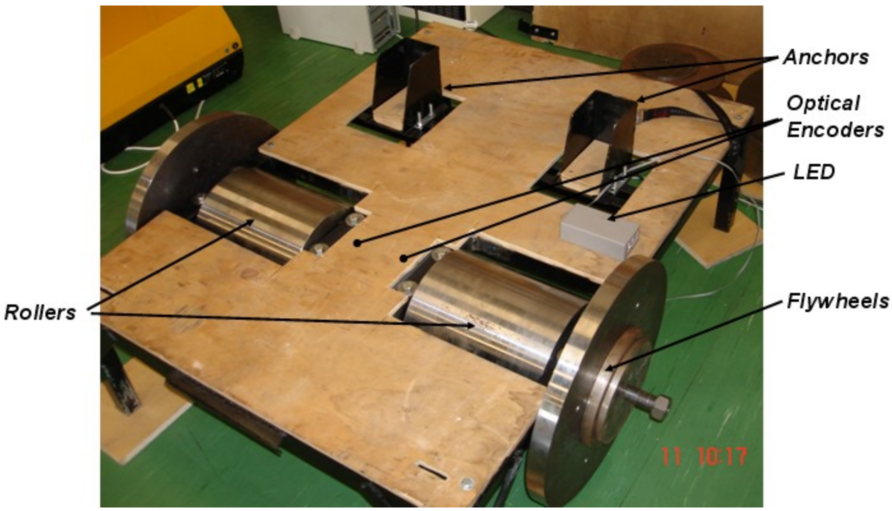


Figure 3. Wheelchair dynamometer

outboard end of the rollers to achieve a required mass moment of inertia to simulate the mass of the subject in their wheelchair. Two rotary encoders are coupled to the inboard end of the dynamometer. These encoders are connected to a personal computer to record the roller position with respect to time. Video cameras were positioned on each side of the dynamometer at elbow height to capture the participants arm motion during wheelchair propulsion. An LED counter, visible in the video frames, shows the time so that the video can be synchronised with the wheel position data. Figure 4 shows some sample frames from the video recording. Markers were attached to the participants to determine

Figure 4. Wheelchair dynamometer

the location of their wrist, elbow, shoulder neck and head. The centre of the wheel was used as a stationary reference point. The events in the propulsion cycle, such as contact and release angles were measured from the video frames.

3. Calculating human output using the dynamometer

The purpose of the dynamometer is to provide a resistance to propulsion which can be measured and compared with normal wheelchair propulsion ability. Figure 5 shows the free body diagram of the wheelchair wheel (5a) and the dynamometer drum (5b).

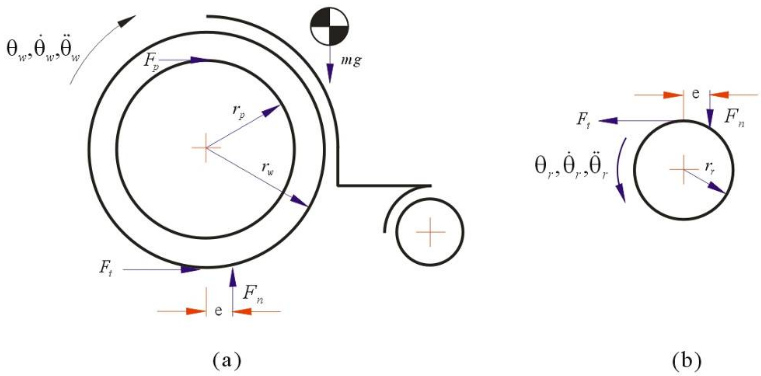


Figure 5. Free body diagram for the wheelchair and dynamometer roller

Applying Newton's second law, assuming mechanical friction and windage losses are small, the equation of motion for one of the rear wheelchair wheels take the form

$$F_p r_p - F_t r_w - F_n e = I_w \ddot{\theta}_w \tag{1}$$

Rearranging in terms of the tractive force, F_t, gives

$$F_t = \left[F_p r_p - I_w \ddot{\theta}_w - F_n e\right] \frac{1}{r_w} \tag{2}$$

Similarly, considering the free body of the roller, Figure 5b, F_t may be written in terms of the roller inertia as

$$F_t = \left[I_r\ddot{\theta}_r - F_n e\right]\frac{1}{r_r} \tag{3}$$

The effective push rim force, $F_{p,}$ may be calculated by equating Equations 2 and 3 to give

$$F_p = \frac{1}{r_p}\left[F_n e\left[\frac{r_w}{r_r}+1\right]+\frac{r_w I_r\ddot{\theta}_r}{r_r}+I_w\ddot{\theta}_w\right] \tag{4}$$

The purpose of a wheelchair is to enable a person to move from one place to another. To move from position x_0 to position x_1 requires a ground force F_t to be applied over distance x. This ground force is created by a force F_p applied at a radius r_p over angle θ. If a force or torque have been applied to move from position x_0 to position x_1 then work has been done. Work is a useful quantity to measure because it determines whether or not a person has the ability to move prescribed distance. For the subject in the wheelchair, work can be defined as

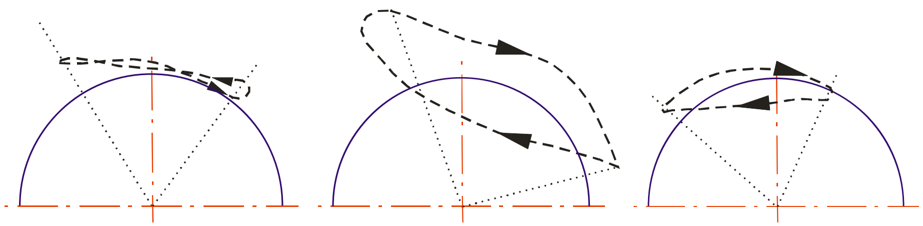
$$W = \int_{\theta_{w1}}^{\theta_{w2}} F_p r_p \theta_w . d\theta_w \tag{5}$$

While a certain amount of work is required to move from position x_0 to x_1, the task of moving must be completed within a reasonable time otherwise the method will be impractical. Hence it is also useful to measure of the rate at which work can be done, i.e. the power. Power can be calculated using

$$P = \frac{dW}{dt} \tag{6}$$

4. Results

The video recordings were analysed and the path of each subjects hand mapped during wheelchair propulsion for the first few propulsion cycles. Figure 6 shows typical results obtained from this analysis.



(a) (b) (c)

Figure 6. Wrist movement during wheelchair propulsion

Figure 6a shows the path of the wrist of a person with no triceps function. During contact the hand tracks around the rim to the release point. Following release of the push rim, as the upper arm moves back, the forearm acts like a swinging pendulum. The wrist and hand are observed to lift moving in an anticlockwise direction. This path is distinctly different from the path taken by the person with active

triceps, Figure 6b. The person with active triceps applies an arm extension force to control elbow angle as the arm moves back, the wrist and hand move back in a circular clockwise direction. For the post deltoid to triceps transfer subjects, a circular clockwise path was also observed, Figure 6c.
Two tests were conducted to establish human work and power output. For the first test, the inertia of the two rollers was set to simulate the equivalent mass of the subject plus their wheelchair. In this test the resistance is close to what the subject would experience when accelerating on a hard flat surface. The subject was asked to accelerate as fast as they could from rest. Figure 7 shows typical results obtained for the power output vs time curves for the first propulsion cycle in the normal resistance test. The stroke progress during the propulsion cycle is indicated by the ¼, TDC (hand at vertical Top Dead Centre), ¾ and end (release) points.

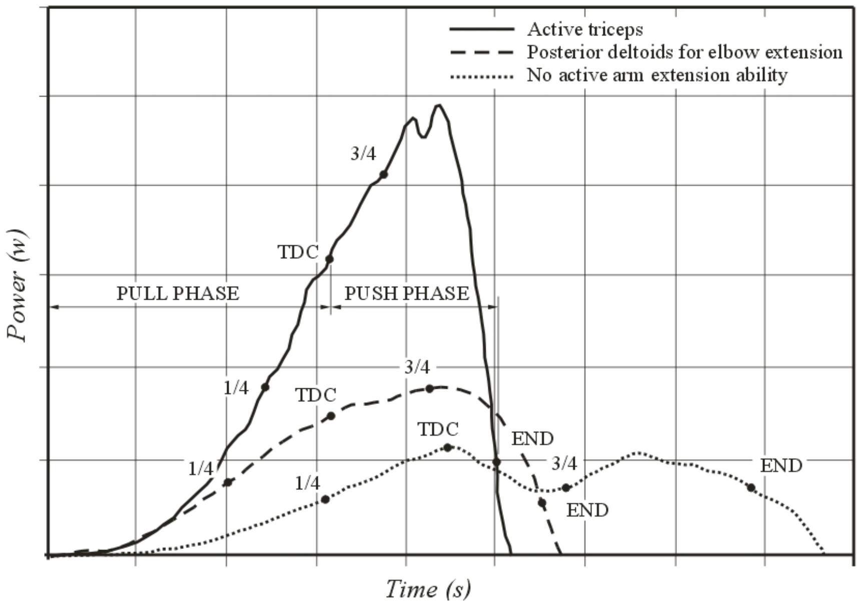


Figure 7. Power output during the normal resistance test

In a second high resistance test we increased the roller inertia to equal the mass of the wheelchair plus double the mass of the subject. The second test gives a measure of the subject's ability to propel themselves in a high resistance situation e.g. ascending a ramp or propelling on a soft surface. Figure 8 shows power output vs time for the first propulsion cycle in the high resistance test.

5. Discussion

One of the motivations for commencing this study was to establish the benefits of procedures such as posterior deltoid to triceps transfer surgery. Patients have made comments like "now we can propel our wheelchairs like paraplegics". This anecdotal evidence along with observed differences in hand movement between the people with and without the posterior deltoid to triceps transfer surgery suggests that a change in wheelchair technique has occurred.
In the normal resistance acceleration test, the maximum power output is produced during the later push phases for the people with active triceps and for the posterior deltoid to triceps transfer subjects whereas the maximum power is produced in the pull phase for the person with no active triceps. While this is not a surprising result it does it does illustrate one of the difficulties for people with no triceps. Namely they are missing out on one of the opportunities to produce maximum power output.

For the normal resistance acceleration test, approximately one third of the work done during the propulsion cycle (equal to the area under the power curve) is done between initial rim contact and TDC. This is the assumed pull phase of the propulsion cycle. Two thirds of the work is done during the push phase in all groups. For the high resistance test this work balance is unchanged for the person with normal active triceps. For the posterior deltoid to triceps transfer subjects the work is balanced to an equal amount in both the push and pull phases. For the subjects with no active triceps, two thirds of the work was produced in the pull phase and only one third in the push phase of the propulsion cycle. These results show that, with increasing resistance, people with no or limited triceps function tend to favour the start of the wheelchair propulsion cycle.

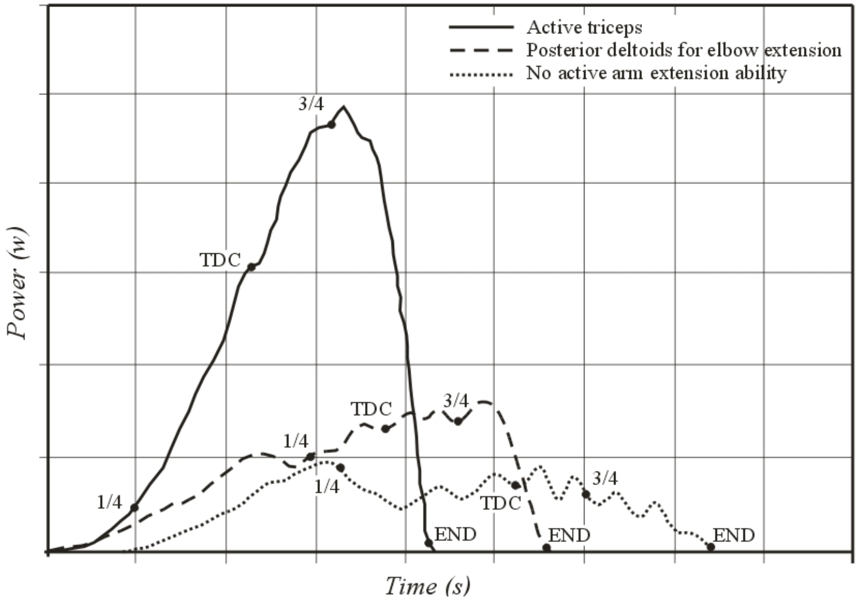


Figure 8. Power output during the high resistance test

6. Conclusion

A wheelchair dynamometer was found to be the most appropriate method for measuring human power output during wheelchair propulsion. Methods such as instrumented pushrims are not universally suitable for measuring maximum power output because they may require the wheelchair user to change their technique in order to measure the actual output forces.

Under normal wheelchair propulsion conditions, two thirds of the work is done during the push phase of the wheelchair propulsion cycle. Under higher resistance conditions people with limited or no active elbow extension favour the earlier pull phase of the propulsion cycle.

Despite the differences in wheelchair propulsion techniques, there is currently no consideration given either in the design of wheelchairs or the configuration of these wheelchairs to better suit a person with weak or no triceps function.

The authors are currently working with A.J. Medland of the University of Bath, UK on the creation of a constraint based model of a human that is designed to interact with machines and products. An initial parametric model of a wheelchair, shown in Figure 9, has been created that can incorporate the motions and forces derived from the above studies. The research will investigate the ability to individualise a chair to take into account the disabilities of users.

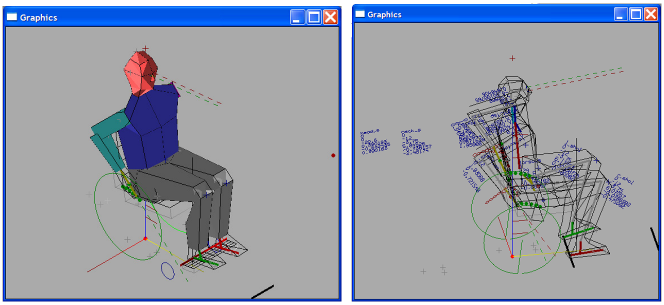


Figure 9. Initial parametric model of a wheelchair

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