Balancing manual wheelchair stability and ‘ tippiness’ for functional independence – Lynne Hills (OT)

1 Abstract

This study investigated the influence of the Rear Axle Position (RAP) on both the hand rim propulsion forces and the castor weight distribution when performing functional mobility tasks.

When the RAP is set forwards (known as a “tippy” or less stable position), a smaller tip angle is created and there is a greater tendency for the wheelchair to tip backwards.

Laboratory studies have shown that more stable wheelchairs apply more load to the front castors, in turn increasing the rolling resistance of the wheelchair (WOWSUP 2005). During a propulsion stroke inertial forces tend to tip the wheelchair and unload the castors. It is not known what affect the RAP has on propulsion forces generated during functional mobility, or how these forces are altered to overcome rolling resistance. In this study it was hypothesised that:

Hypothesis 1:

H0: Moving the rear axle forward (tippy) does not change the castor forces during functional mobility.

H1: Moving the rear axle forward (tippy) decreases castor forces during functional mobility.

Hypothesis 2:

H0: Moving rear axle forward (tippy) does not change the push rim forces (Peak Mz) during functional mobility.

H1: Moving rear axle forward (tippy) decreases the push rim forces (Peak Mz) during functional mobility.

This study showed that setting the RAP forwards (tippy) does not significantly influence propulsion forces on three terrians pushing in a straight line. This result differs from what is widely believed. Castor loading is influenced by RAP and terrain, yet it does not increase rolling resistance sufficiently to influence propulsion forces. However, RAP does significantly influence propulsion forces when negotiating a kerb for experienced wheelchair users.

2 Introduction

The UK environment is extremely challenging for wheelchair users. About 3-4% of (manual) wheelchair users have a spinal cord injury with the majority of these sustaining their injuries between 15 and 30 years old. As a result, they will be using a wheelchair for many years and careful wheelchair selection is important to promote the highest level of independence, with all the benefits this brings, both socially and economically.

Such high levels of independence will not only depend on the user's ability to negotiate a range of environments and terrains, but will also depend on their wheelchair set up. A key factor in achieving optimal wheelchair set up is the stability of the wheelchair, which is determined in part by adjusting the rear axle position. Many wheelchair manufacturers offer models where the axle position can be adjusted to suit the individual. It is assumed that moving the axle towards the front of the wheelchair will make the wheelchair significantly easier to push and turn, as it reduces the weight through the front casters. However, little objective evidence has been provided to demonstrate the benefits of such a feature, nor has evidence-based guidance been provided for its effective use.

Kirby 1996 describes static rearward stability as the angle away from the horizontal surface. Therefore a larger angle indicates greater wheelchair stability.The Department of Health and Social Security (DHSS) Technical Bulletin TB/SA/6 set a standard of 12° (manual wheelchairs) as a safe angle of stability for a manual wheelchair. However, the Medicines and Healthcare Regulatory Advisory Service (MHRA) have since set guidelines that do not reference these standards, advising instead that referrals should be made to the manufacturer's guidelines (as cited in Rehabilitation Engineers Handbook, Stability Testing 2005)

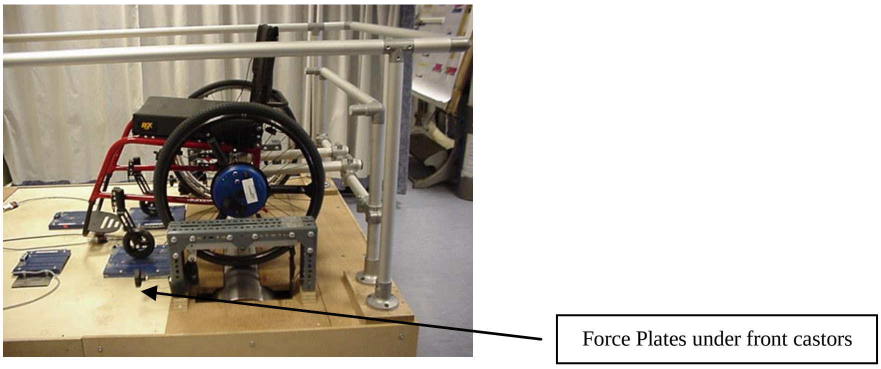
There have been a number of studies measuring the static stability of manual wheelchairs and their high reliability is well documented (Kirby et al 1989, Kirby, Sampson, Thoren and MacLeod 1995). However, very little research has so far been carried out on dynamic manual wheelchair stability. Dynamic or functional stability could be best described as; "how change in the weight distribution of the wheelchair (adjusting the RAP) and user kinematics affects rolling resistance and stability when users perform functional mobility tasks in their wheelchair"

A smaller tip angle is normally associated with wheelchair instability. However, experienced wheelchair users with advanced wheelchair skills can manage such angles effectively and safely, thus increasing their functional performance (ability to manage different terrains). A key aim of the project was to measure dynamic functional performance over different terrains typical of everyday wheelchair use. The goal was to increase awareness around the implications of axle adjustment and provide some insight into how a less stable wheelchair performs on everyday terrains.

3 Background

Some early work at ACDS using a wheelchair Ergometer (**Figure 1**), with force plates beneath the front castors showed that there is a substantial weight shift between castors, and rear wheels during the propulsion cycle. When the rolling resistance was increased on the rear wheels, the front castor force was increased due to the changing body posture.

Figure 1- **Wheelchair Ergometer**



This study aimed to look at these findings in more detail in an attempt to understand what happens during functional mobility, such as ascending a kerb or slope and propelling on varying surfaces on level ground.

4 Methodology

The study took place at the Stanmore Clinical Research Facility at the Royal National Orthopaedic Hospital (RNOH), Stanmore. Full ethical approval was granted by the joint RNOH and Institute of Orthopaedic and Musculoskeletal NHS Local Research Ethics Committee.

4.1 Participants

Inclusion criteria for the participants were as follows;

1) Use of a manual wheelchair was the primary mode of mobility;
2) To have been using a wheelchair for 2 or more years;
3) To have a spinal cord injury of the level T1 or below.

Spinal Cord Injury level was determined in all participants using the American Spinal Injuries Association Classification (ASIA). Participants were excluded from participating in the study if they reported a history of trauma to the upper limb or had experienced upper limb pain on pushing the wheelchair.

Seven men and one woman volunteered for the study. All participants provided written consent before they participated in the study. **Table 1** provides the characteristics of the subjects.

Table 1- Subject Characteristics

Experienced User	Injury	ASIA	Time since Injury	Male	Female	Age
1	T12	C	35 yrs	Y		54
2	T5	A	6 yrs	Y		52
3	T11	A	10 yrs	Y		45
4	L3	A	3 yrs		Y	43
5	T6	A	12 yrs	Y		41
6	T12	A	2 yrs	Y		27
7	T8	A	11 yrs	Y		37
8	T9	A	12 yrs	Y		49

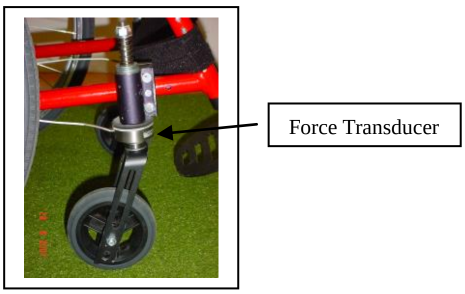
4.2 Equipment & Terrain

Each participant was set up in the Laboratory's test wheelchair. The chosen model was a 17" Quickie GPV, rigid frame lightweight wheelchair. Only one wheelchair could be used as the instrumentation was not interchangeable between wheelchairs. A 17" wheelchair was chosen as the most adaptable size for most test participants. This was then configured to suit each individuals needs.

Figure 2 - Quickie GPV Wheelchair

Force sensors, integral to the castors, measured weight distribution during functional mobility tasks in order to gather dynamic data (**Figure 3**). These were calibrated and validated by the research team (WOWSUP 2007).

Figure 3 - **Castors**



The wheelchair was set up with a Smart$^{\text{WHEEL.TM}}$. The Smart$^{\text{WHEEL.TM}}$ (produced by Three Rivers Holdings, Mesa, Arizona), is an instrumented wheel, fitted to the wheelchair to gathers data on pushrim forces, moments, speed and acceleration. The Smart$^{\text{WHEEL.TM}}$ is a calibrated and commercially available device (see **Figure 2**) (SmartWheel Users Guide 2005)

<u>Terrain Tested</u>

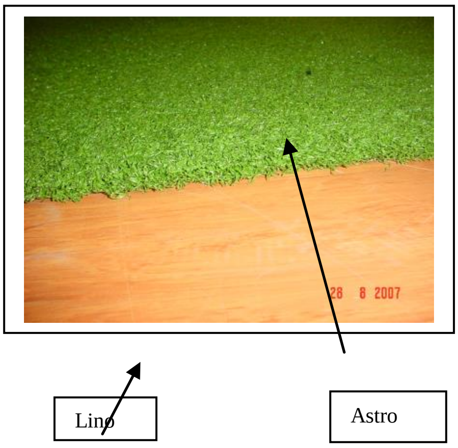
The functional mobility tasks included the following terrain types: (**Figure 4)**

A) Straight push along 12m Lino (level ground)
B) Straight push along 12m Astro Turf (level ground)
C) Ascending a 1:12 Ramp
D) Ascending a 3” Kerb

Figure 4 - <u>Functional mobility tasks/terrains</u>

Terrain C

Terrain A & B



Terrain D

4.3 Experimental Procedure

Rear Axle Position (RAP) was altered to give the most stable (back) and most tippy (forwards) position. In each axle position the following procedure was completed:

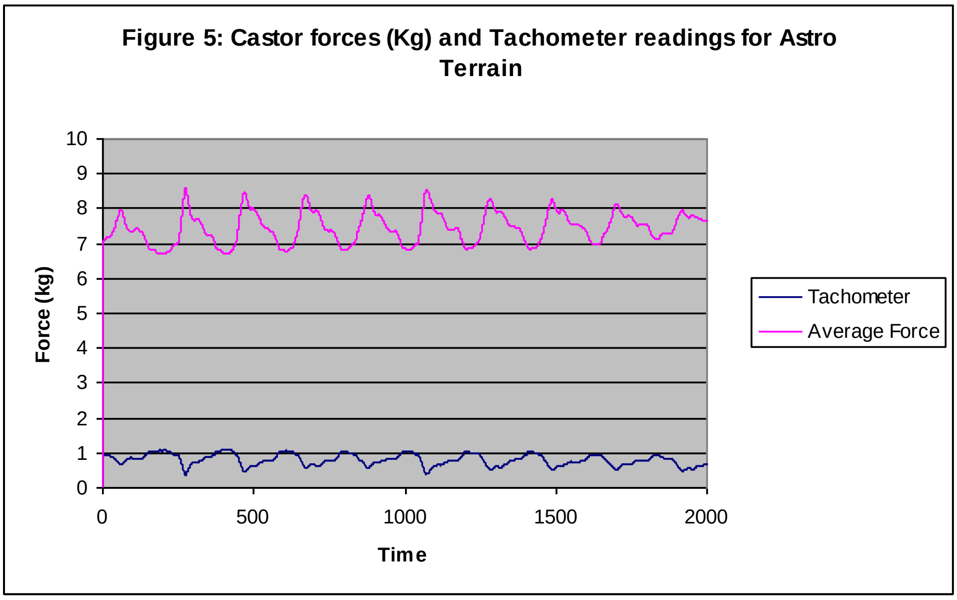
Participants performed the series of functional mobility tasks as outlined above at self selected speeds, which were repeated three times. The terrains reflect those advised by the Smart$^{\text{WHEEL.TM}}$, with the additional task of ascending a kerb. This was included as it is an everyday barrier encountered by active wheelchair users. The course was completed in the same order for each of the participants. All participants completed the mobility course without difficulty, with the exception of one subject, who was unable to perform the kerb run in the tippy set up.

4.4 Data Collection & Analysis

4.4.1 Castor Data

Castor data was gathered using a bespoke programme (written in LabView 7.0) for a PDA which stored the data onto an SD card. Once all the testing was completed, the raw binary files were downloaded onto a desktop computer and converted into a readable form using a LabView programme (**Figure 5**). All readings were then converted from voltage units to Newtons in an Excel (spreadsheet) format. Data was collected for each test to establish the output at zero loading. Any offset was subtracted. A tachometer attached to one of the rear wheels was used to determine exactly when the wheelchair started to move.

Figure 5 - Castor Force (Kg) and Tachometer output during propulsion on Astro.
Note the Castor force has not been converted into Newtons and the zero offset (6.7 kg) has not been removed



4.4.2 Smart^WHEEL.TM Data

The data saved on the memory card fitted in the Smart^WHEEL.TM was transferred to the desktop computer and analysed using the Smart^WHEEL.TM 2006 analyser software. The data was then transferred to a prepared Microsoft template written specifically for the programme by Graham Nicholson (2005) (**Figure 6**). Selected biomechanical variables were analysed, which included;

Stroke Angle - This is the average length of the participants push, in degrees.

Cadence –This is how many times per second, on average, the participant pushes on the SmartWheel.

Velocity –This is the average speed of the Smart[WHEEL.] during each push. This can be used as an index of function. Average walking velocity is 1.4 m/s

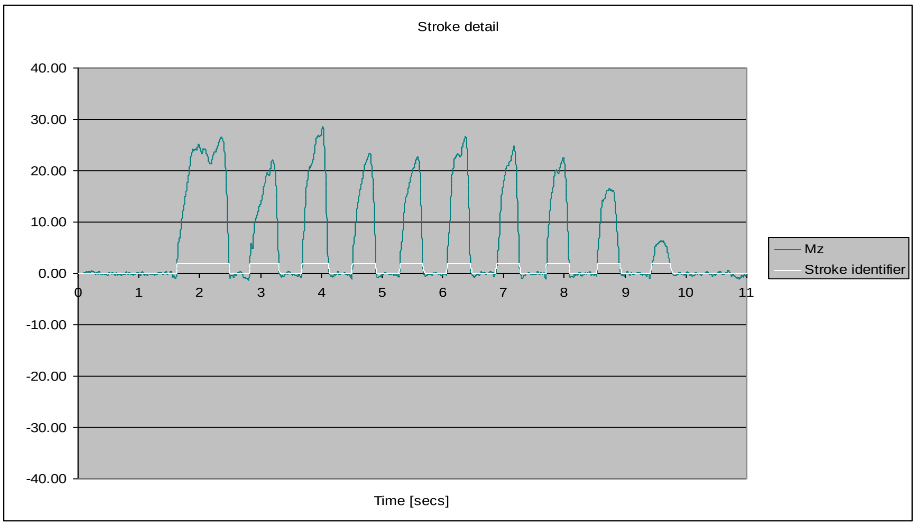
Peak Mz –This is the peak propulsion moment that the participant applies to the Smart[WHEEL.] during each push. This is the moment that turns the wheel.

Peak Average Force Ratio –This is the ratio between the peak force during a push, and the average force during a push. It provides an indication of how smoothly pushes are applied to the SMART[WHEEL]'s handrim. A lower ratio indicates the peak force is more close to the average force, which can indicate a smoother push. Large peak forces are associated with the development of upper extremity pain and dysfunction

Impulse – Is determined by calculating the change in momentum of the wheelchair resulting from the prolusion moment. Impulse indicates the change in wheelchair velocity generated for each stroke.

Energy per stroke – Is determined by calculating the integral of the propulsion force with respect to distance for each stroke.
(Definitions provided by, SmartWheel Users Guide 2005 and WOWSUP/ACDS 2005)

Figure 6 - **<u>Smart[WHEEL.TM.] – Propulsion moment Mz plotted against time (s) generated by the SMART[WHEEL] software. Also the graph indicates stroke phase which is used to calculate the parameters defined in the text.</u>**



4.4.3 Smart[WHEEL] and Castor Data Synchronisation

Once all data had been converted from the castor and the Smart[WHEEL.TM] it was important for the propulsion cycle to be defined. The same event had to be detected in both data recording systems so that they could be synchronised for analysis. Synchronisation was completed through visually matching:

a) When wheel movement was first detected from the Tachometer signal by the PDA, and;

b) When the Smart$^{WHEEL.TM}$ data indicated evidence of movement (velocity >0) using the 1/20s running average velocity parameter (**Figure 7**) (SmartWheel Users Guide 2005).

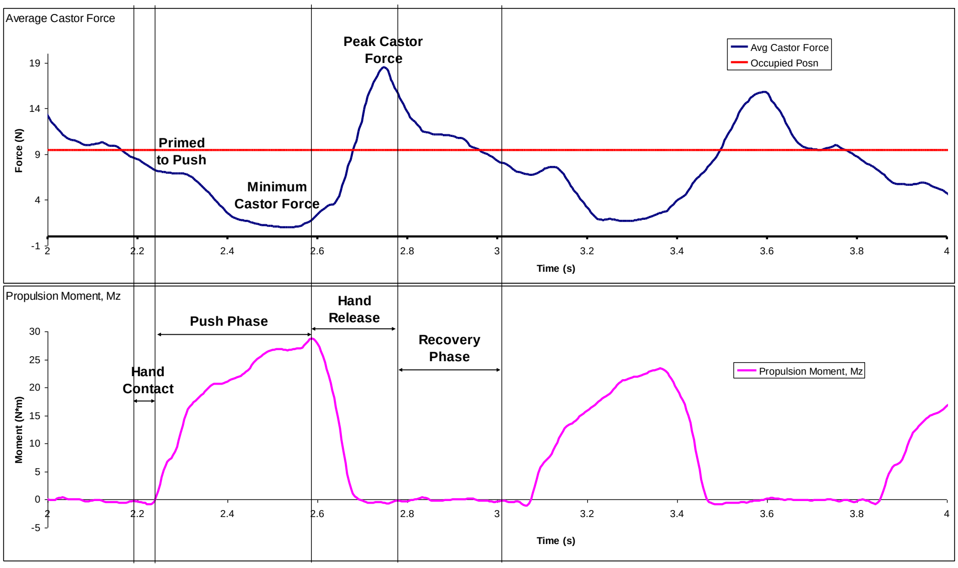
Following this and consulting other studies, the propulsion cycle was determined as:

1. **Primed to Push** – hands on the rim, push phase beginning
2. **Minimum Castor Force** – lowest castor force recorded during the propulsion cycle
3. **Maximum Castor Force** – highest castor force recorded during the propulsion cycle
4. **Push Phase** – starts with a positive propulsion moment (Mz) and is completed at hand release usually identified immediately after reaching the peak propulsion force
5. **Recovery Phase** – starts immediately after hand release and is completed at hand contact.
6. **Hand Contact** – when the hand makes contact with the rim
7. **Hand Release** – when the hand releases all contact with the rim

Figure 7 - **Synchronised propulsion readings**

NB. Max castor force replaces Peak Castor Force

Astro- Stable Chair



4.4.4 Statistics

Excel (spreadsheet) and SPSS (statistical analysis) programmes were used to analyse the data. For the main parameters a Univariate Analysis Of Variance (ANOVA) was performed to determine whether a significant difference in propulsion forces and castor loading occurred for extremes in chair tippiness, when performing the different functional mobility tasks.

This was then followed by a 'Post Hoc Bonferroni' test to explore the interaction between the different terrains. A statistician was consulted to assist with identifying the most effective methods for reading and presenting the data. Significance level was set at ($p < 0.05$) for all statistical procedures.

5 Results

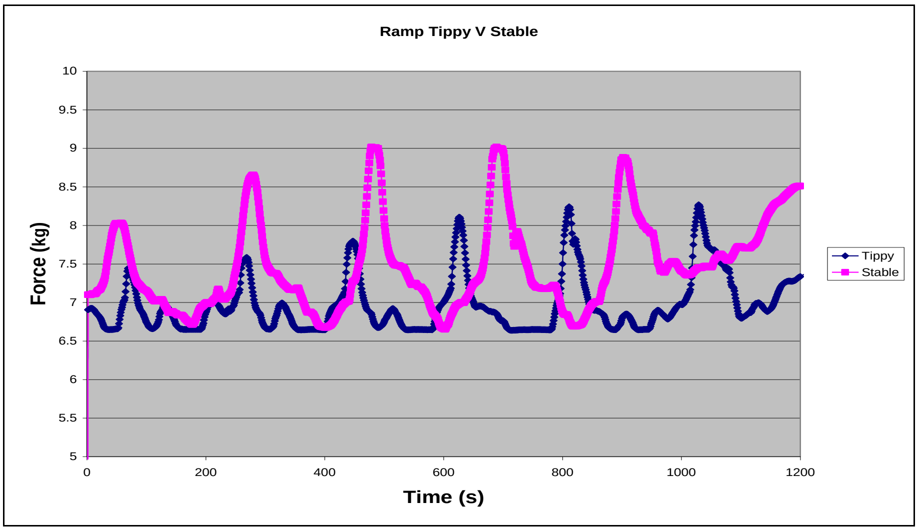
In relation to RAP there was found to be significant effect for the type of terrain ($p = 0.009$) and weight on the front castors ($p<0.0004$).

Table 2 - **<u>Castor Forces for Prime, min and max push over all terrains and their significance in relation to RAP and terrain (NS = Not significant)</u>**

Terrain Stability	Lino Stable	Lino Tippy	Astro Stable	Astro Tippy	Ramp Stable	Ramp Tippy	Terrain F Value	Terrain p Value	Terrain Lino Astro	Terrain Lino Ramp	Terrain Astro Ramp	RAP F Value	RAP p Value
Prime1A	134.6003	81.01249	169.7507	108.2933	139.3026	74.55465	$F(2,32) = 7.6$	0.002	0.003	NS	0.005	$F(1,32) = 63.2$	<.001
Min1A	61.77368	28.52988	68.08869	39.85804	56.25533	25.63344	$F(2,32) = .111$	NS	NS	NS	NS	$F(1,32) = 15.0$	<.001
Max1A	234.3387	172.8425	284.3341	230.0273	260.7646	153.4992	$F(2,32) = 6.17$	0.005	0.003	NS	0.013	$F(1,32) = 35.7$	<.001
Prime2A	145.2484	87.50238	160.1713	121.448	140.9931	74.97658	$F(2,32) = 5.83$	0.007	0.022	NS	0.004	$F(1,32) = 50.06$	<.001
Min2A	73.1407	33.15441	68.24414	46.54224	61.38506	17.30595	$F(2,32) = .76$	NS	NS	NS	NS	$F(1,32) = 16.48$	<.001
Max2A	226.508	198.7243	283.9455	247.8454	279.0101	201.4434	$F(2,32) = 5.55$	0.009	0.001	NS	NS	$F(1,32) = 17.33$	<.001
Prime3A	137.1458	96.55713	161.8229	102.6778	142.1978	84.34778	$F(2,32) = 1.63$	NS	NS	NS	NS	$F(1,32) = 41.29$	<.001
Min3A	71.02274	40.94617	60.64669	49.12654	49.08536	31.8735	$F(2,32) = .287$	NS	NS	NS	NS	$F(1,32) = 3.92$	NS
Max3A	240.0707	203.5237	297.7414	261.9716	277.6111	230.2232	$F(2,32) = 7.48$	0.002	<.001	NS	NS	$F(1,32) = 12.08$	<0.001
PrimeL1A	134.8918	93.00129	171.4217	130.7359	147.7356	73.17784	$F(2,32) = 6.35$	0.005	0.015	NS	0.014	$F(1,32) = 23.99$	<0.001
MinL1A	73.29615	39.62487	65.93187	44.15225	56.39135	19.52661	$F(2,32) = .773$	NS	NS	NS	NS	$F(1,32) = 9.55$	0.004
MaxL1A	238.0111	194.1969	302.8128	241.8801	274.1912	191.7391	$F(2,32) = 6.52$	0.004	0.004	NS	NS	$F(1,32) = 22.41$	<.001
PrimeL2A	143.9466	108.9314	178.4751	124.8872	132.6961	88.87793	$F(2,31) = 2.72$	NS	NS	NS	NS	$F(1,31) = 13.28$	0.001
MinL2A	79.96091	55.51927	63.05611	49.6706	58.83963	24.34545	$F(2,32) = .79$	NS	NS	NS	NS	$F(1,32) = 4.13$	NS
MaxL2A	231.8127	174.3775	291.4458	241.3749	270.4411	223.1837	$F(2,32) = 9.20$	0.001	<.001	0.005	NS	$F(1,32) = 121.67$	<.001
PrimeL3A	140.9348	85.51534	164.2129	125.0816	155.197	108.1977	$F(2,31) = 2.36$	NS	NS	NS	NS	$F(1,31) = 15.15$	<.001
MinL3A	98.53676	50.23409	68.90479	57.6178	87.24747	43.70964	$F(2,32) = .334$	NS	NS	NS	NS	$F(1,32) = 6.50$	NS
MaxL3A	227.8293	171.424	275.396	238.7518	259.385	205.9513	$F(2,32) = 6.52$	0.004	<.001	NS	NS	$F(1,32) = 19.43$	<.001

The castor forces were significantly higher when the RAP was set rearwards into the stable position. These forces were consistently higher over all terrains in the stable position (**Figure 8**)

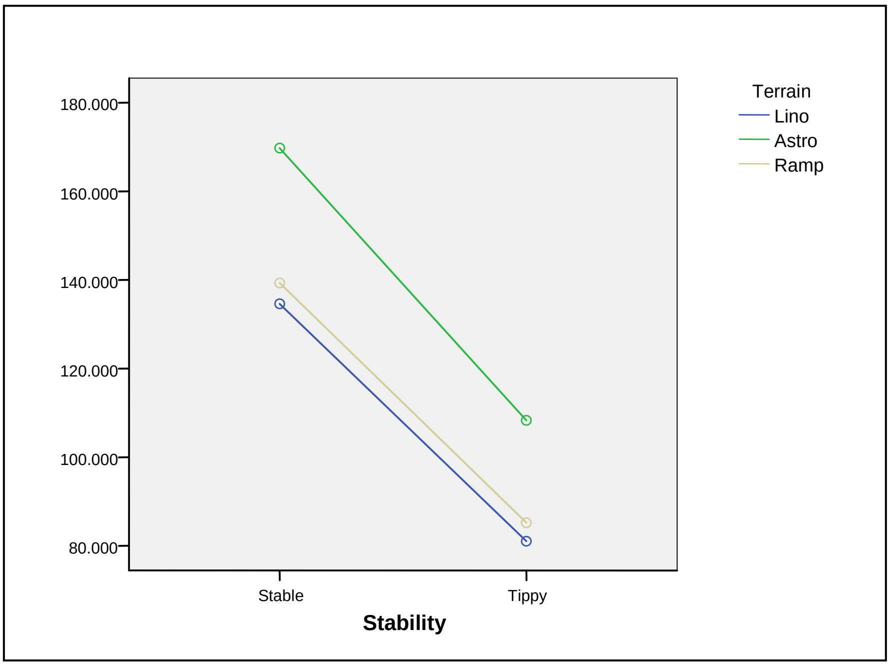
Figure 8 - **Comparing castor forces (Kg) in the tippy and stable setup during propulsion on the ramp. Note the Castor force has not been converted into Newtons and the zero offset (6.7 kg) has not been removed**



There were no significant differences seen for the castor forces when subjects performed on the ramp, compared to astro or lino. The main differences were found between lino and astro which are predominantly associated with the prime and the max push parameters. The propulsion cycle can be broken down as detailed below;

Prime push; shows significant differences between the astro surface and the ramp (p=0.014). **(Figure 9)** Castor forces are lower with the RAP set forwards in the tippy position. Prime push castor forces also show similar levels on the ramp and the lino, with the greatest reading on the astro terrain.

Figure 9 – **Estimated Marginal Means of Average Castor Force (N) Prime First Push**



Min castor forces; generate no significant difference for any of the terrains.

Max castor forces; Significant differences (p=0.009) can be seen between lino and astro terrains with astro generating greater castor forces compared to lino. These forces are significantly greater in the stable position compared to the tippy position (p=<0.001) (**Figure 10**).

Figure 10 - **<u>Estimated Marginal Means of Average Castor Force (N) Max Third Push</u>**

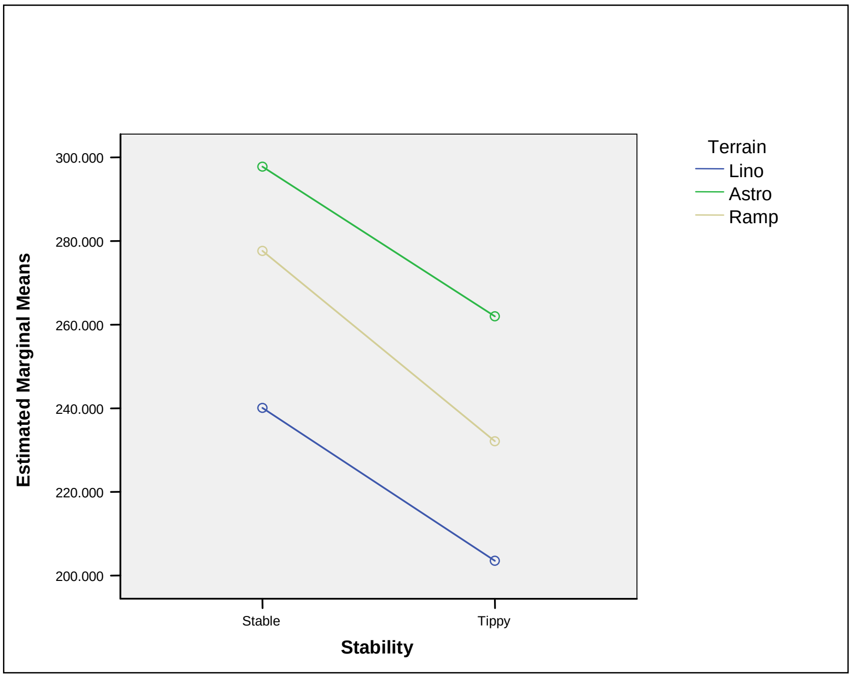


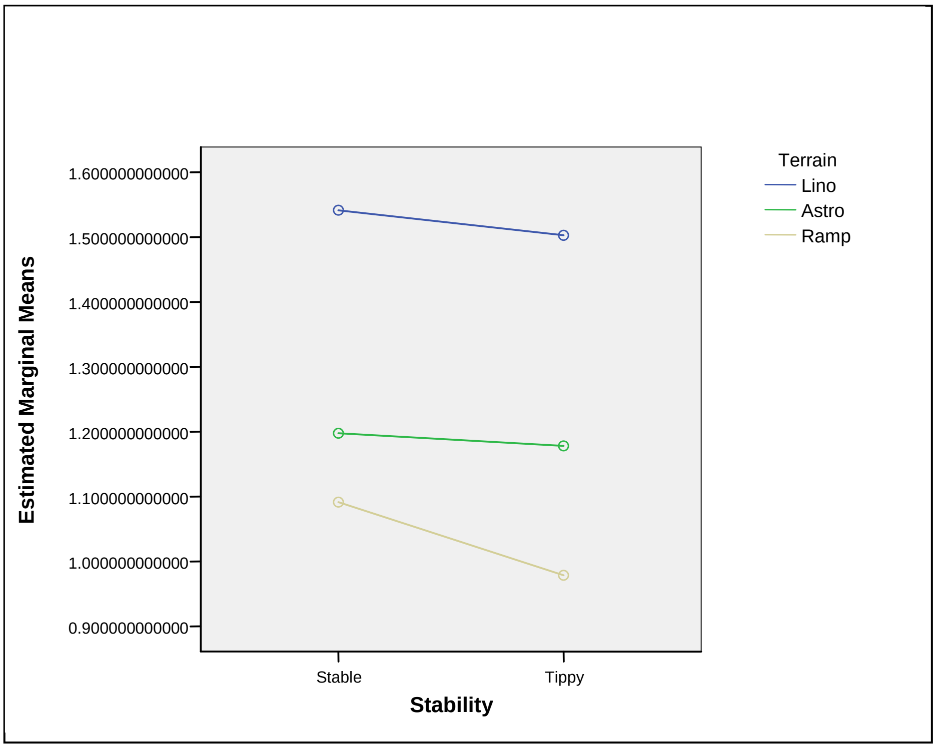
Table 3 – Analysed Smart$^{\text{WHEEL.TM}}$ variables over all terrains and their significance in relation to RAP and terrain (NS = Not significant)

Terrain Stability	Lino Stable	Lino Tippy	Astro Stable	Astro Tippy	Ramp Stable	Ramp Tippy	Terrain F Value	Terrain p Value	Terrain Lino Astro	Terrain Lino Ramp	Terrain Astro Ramp	RAP F Value	RAP p Value
StrAng1	79.508	80.935	79.4575	70.20143	86.77875	85.8375	$F(2,32) = 0.983$	NS	NS	NS	NS	$F(1,32) = .414$	NS
StrAng2	81.201	89.77	75.235	87.76571	91.0975	88.6375	$F(2,32) = 0.300$	NS	NS	NS	NS	$F(1,32) = 1.38$	NS
StrAng3	80.378	86.81375	83.475	88.89429	92.66125	82.50625	$F(2,32) = .136$	NS	NS	NS	NS	$F(1,32) = 0.02$	NS
StrAng12	80.35438	85.3525	77.34625	78.98357	88.93813	87.2375	$F(2,32) = .85$	NS	NS	NS	NS	$F(1,32) = 0.33$	NS
StrAng13	80.362	85.83958	79.38917	82.28714	90.17917	85.66042	$F(2,32) = .576$	NS	NS	NS	NS	$F(1,32) = 0.212$	NS
StrAngsteady	74.168	73.77167	73.13583	109.2076	92.33417	76.20792	$F(2,32) = 2.90$	NS	NS	NS	NS	$F(1,32) = 1.07$	NS
Cad1	0.416	0.423775	0.416038	0.367574	0.454372	0.449444	$F(2,32) = 0.98$	NS	NS	NS	NS	$F(1,32) = 0 .41$	NS
Cad2	0.425	0.470035	0.39393	0.45954	0.476985	0.464105	$F(2,32) =0 .300$	NS	NS	NS	NS	$F(1,32) = 1.38$	NS
Cad3	0.421	0.454556	0.437074	0.465449	0.485173	0.432002	$F(2,32) = 0.14$	NS	NS	NS	NS	$F(1,32) =0.02$	NS
Cad12	0.421	0.446905	0.404984	0.413557	0.465679	0.456774	$F(2,32) = 0.85$	NS	NS	NS	NS	$F(1,32) =0.33$	NS
Cad13	0.421	0.449455	0.415681	0.430854	0.472177	0.448517	$F(2,32) = 0.58$	NS	NS	NS	NS	$F(1,32) =0.21$	NS
Cadsteady	0.388342	0.386268	0.382938	0.57181	0.483461	0.399024	$F(2,32) = 2.90$	NS	NS	NS	NS	$F(1,32) =1.07$	NS
Vel1	0.767	0.637422	0.646698	0.531925	0.71337	0.592919	$F(2,32) = 0.77$	NS	NS	NS	NS	$F(1,32) =8.21$	0.007
Vel2	1.270	1.245233	1.017158	0.982018	1.006164	0.910857	$F(2,32) = 14.57$	<.001	<.001	<.001	NS	$F(1,32) =0.73$	NS
Vel3	1.541	1.502718	1.197528	1.125225	1.091306	0.97852	$F(2,32) = 42.17$	<.001	<.001	<.001	0.049	$F(1,32) =1.90$	NS
Vel12	0.952	0.879248	0.795795	0.741727	0.842299	0.720825	$F(2,32) = 4.21$	0.024	0.004	0.008	NS	$F(1,32) =4.66$	0.038
Vel13	1.118	1.04186	0.911239	0.852572	0.914615	0.787076	$F(2,32) = 12.04$	<.001	<.001	<.001	NS	$F(1,32) =5.01$	0.032
Velsteady	1.841	1.96762	1.327296	1.04236	1.102039	1.023567	$F(2,32) = 49.31$	<.001	<.001	<.001	NS	$F(1,32) =0.72$	NS
PeakMz1	22.148	24.5475	27.46	23.9	28.37875	32.435	$F(2,32) = 1.46$	NS	NS	0.049	NS	$F(1,32) =0.43$	NS
PeakMz2	20.475	23.89375	26.995	26.78857	34.58625	35.105	$F(2,32) = 3.40$	0.046	NS	0.003	NS	$F(1,32) =0.38$	NS
PeakMz3	17.9675	21.8525	25.72375	26.85857	28.94	28.26375	$F(2,32) = 1.43$	NS	NS	NS	NS	$F(1,32) =0.23$	NS
PeakMz12	21.31125	24.22063	27.2275	25.34429	31.4825	33.77	$F(2,32) = 2.82$	0.074	NS	0.006	NS	$F(1,32) =0.466$	NS
PeakMz13	20.19667	23.43125	26.72625	25.84905	30.635	31.93458	$F(2,32) = 2.69$	0.084	NS	0.007	NS	$F(1,32) =0.453$	NS
PeakMzsteady	11.33125	13.50792	19.49917	18.09381	25.31167	27.80375	$F(2,32) = 11.14$	<.001	0.076	<.001	0.025	$F(1,32) =0.343$	NS
Energy1	23.84848	26.6342	31.68995	26.91856	32.12384	37.4163	$F(2,32) = 1.46$	NS	NS	0.048	NS	$F(1,32) =0.330$	NS
Energy2	19.79907	24.52293	25.85935	28.9772	35.57218	37.66665	$F(2,32) = 4.29$	0.022	0.001	NS	NS	$F(1,32) =1.48$	NS
Energy3	16.90832	19.5426	24.85132	26.48944	32.01862	29.78854	$F(2,32) = 2.75$	NS	NS	0.015	NS	$F(1,32) =0.033$	NS
Energy12	21.82377	25.57857	28.77465	27.94788	33.84801	37.54147	$F(2,32) = 3.26$	0.051	NS	0.003	NS	$F(1,32) =0.998$	NS
Energy13	20.18529	23.56658	27.46687	27.46173	33.23821	34.95716	$F(2,32) = 3.87$	0.031	NS	0.002	NS	$F(1,32) =0.592$	NS
Energysteady	9.490258	11.07602	17.44792	18.49454	25.94726	26.61296	$F(2,32) = 12.37$	<.001	0.035	<.001	0.019	$F(1,32) =0.265$	NS
Impulse1	46.67161	50.60735	57.8963	47.73004	51.23725	57.57452	$F(2,32) = 0.211$	NS	NS	NS	NS	$F(1,32) =0.020$	NS
Impulse2	19.684	23.86198	33.49829	37.55845	43.98407	50.27606	$F(2,32) = 9.16$	0.001	0.033	<.001	NS	$F(1,32) =1.35$	NS
Impulse3	12.94485	15.39106	27.86111	27.97945	38.42774	40.1026	$F(2,32) = 9.94$	<0.001	0.019	<.001	NS	$F(1,32) =0.060$	NS
Impulse12	33.17781	37.23466	45.6973	42.64425	47.61066	53.92529	$F(2,32) = 3.67$	0.037	NS	0.005	NS	$F(1,32) =0.517$	NS
Impulse13	26.43349	29.95346	39.7519	37.75598	44.54969	49.31773	$F(2,32) = 6.46$	0.004	0.055	<.001	NS	$F(1,32) =0.372$	NS
Impulsesteady	6.404115	6.548609	18.29316	19.10639	29.41533	33.12325	$F(2,32) = 29.25$	<.001	0.001	<.001	<.001	$F(1,32) =0.310$	NS
Peakaveforce1	1.603026	1.815751	1.643553	1.777433	1.738817	2.133426	$F(2,32) =0.926$	NS	NS	NS	NS	$F(1,32) =7.05$	0.012
Peakaveforce2	1.545814	1.504439	1.513359	1.56125	1.658923	1.704508	$F(2,32) =1.20$	NS	NS	NS	NS	$F(1,32) =0.332$	NS
Peakaveforce3	1.398088	1.548513	1.566737	1.600088	1.552992	1.7164	$F(2,32) =1.422$	NS	NS	0.018	NS	$F(1,32) =7.49$	0.01
Peakaveforce12	1.57442	1.660095	1.578456	1.669342	1.69887	1.918967	$F(2,32) =1.189$	NS	NS	NS	NS	$F(1,32) =4.26$	0.047
Peakaveforce13	1.515643	1.622901	1.57455	1.646257	1.650244	1.851444	$F(2,32) =1.368$	NS	NS	0.044	NS	$F(1,32) =5.68$	0.023
Peakaveforcesteady	1.494513	1.592155	1.46565	1.447292	1.493013	1.613186	$F(2,32) =3.80$	0.033	NS	NS	NS	$F(1,32) =3.22$	NS

Stroke Angle and **Cadence** are not affected by terrain or stability.

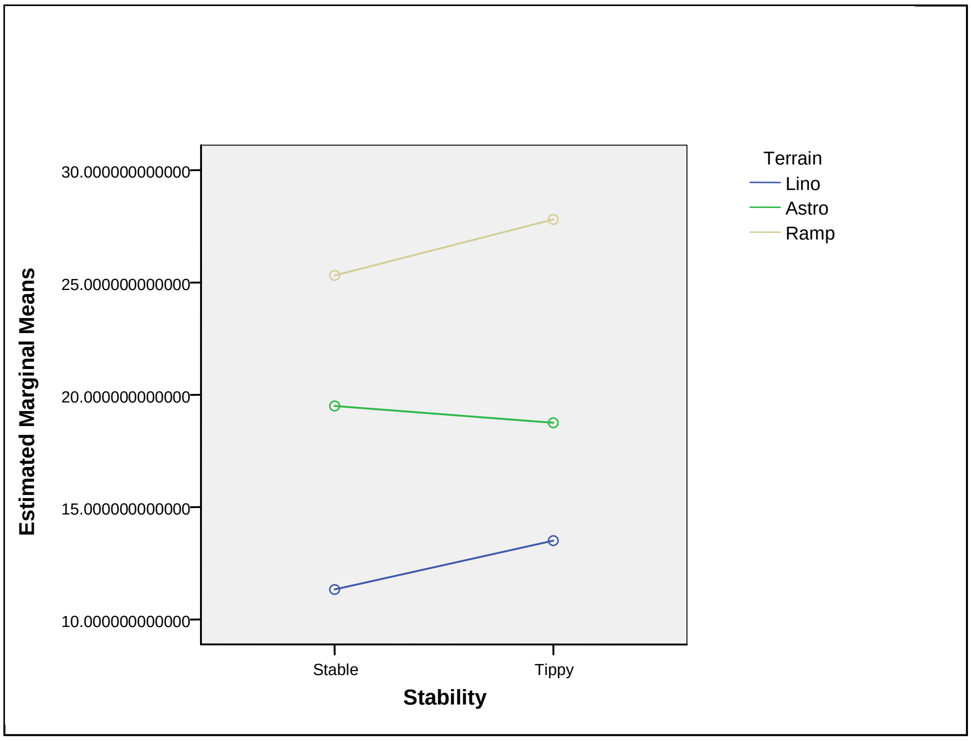
Velocity is influenced by terrain showing a significance following the first push. The greatest difference is between lino and astro (p<0.001) and lino ramp (p<0.001). There is no significant difference between astro and ramp. Velocity was higher when performing on lino compared to the other terrains in both the stable and tippy set-up (**Figure 11**). Velocity was influenced by stability, but only in half of the scenarios with the most significant being at first push.

Figure 11 - <u>**Estimated Marginal Means of 1/20 Second Running Average Velocity Third Push**</u>



Peak Mz shows significant differences in the steady state terrain (p=<.001) but not stability. The greatest difference is seen in lino compared to ramp. (**Figure 12**) The RAP showed no significance.

Figure 12 - Estimated Marginal Means of Peak Propulsion Moment Last Three Pushes



Impulse is influenced by terrain (p=0.037), the results show a significant difference between lino and astro (p= 0.033) and lino and ramp (P=0.005) but no significance between astro and ramp.

Peak Average Force shows no significant difference over the different terrains though is one of the only values to be influenced by stability (0.047). This shows a greater reading in the tippy position compared to the stable position.

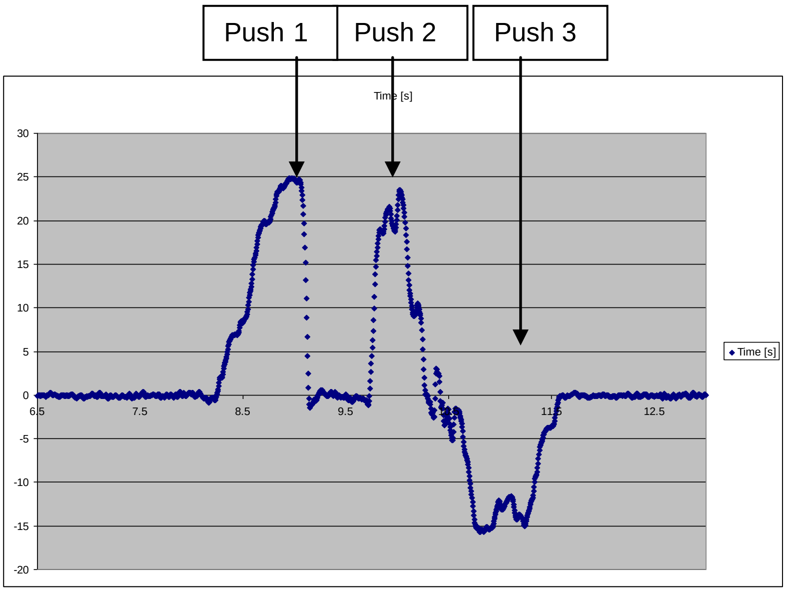
Kerb data
When performing the Kerb test, data were collected from the Smart$^{WHEEL.TM}$. The castor data was not considered to have any relevance in this test. The propulsion parameters for the wheelchair user performing the kerb test can be split into three push phases (**see Figure 13)**

Push 1 – initial moment generated to flip the castors up the kerb.

Push 2 – moment generated to get over the kerb

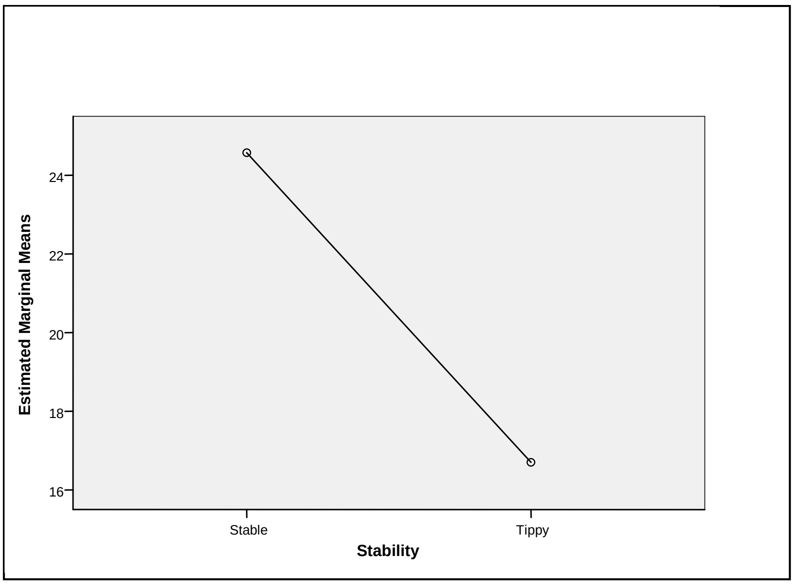
Push 3 – moment required to stop the wheelchair moving forwards (braking)

Figure 13 - **Smart**[WHEEL.TM.] **– Propulsion moment Mz for kerb plotted against time (s) generated by the SMART**[WHEEL] **software defining the pushes.**



Peak Mz shows a significant difference (p =.023) in **Push 1** between the tippy and stable set up with a greater Peak Mz performed to flip the castors with the wheelchair in the stable position (**see Figure 14)**

Figure 14 - Estimated Marginal Means of Max Propulsion Moment First Kerb Push



Push 2 analysis found no significant difference in **Peak Mz** between the two RAP's.

6 Discussion

By changing the RAP and hence stability of the wheelchair, we have been able to measure the effect of wheelchair RAP on the push stroke forces during wheelchair propulsion. We highlighted earlier that most clinician's assume that moving the axle towards the front of the wheelchair will make the wheelchair significantly easier to push and reduces the weight through the front casters. However, the results of this study do not fully support this assumption. Although castor weight is reduced in a less stable setup this does not translate into reduced propulsion forces, it is only terrain that influences these propulsion forces.

6.1 Hypothesis 1 Revisited

It was shown in this study that there is a significant difference between the castor forces when the RAP is adjusted and thus the null hypothesis can be rejected. So, moving the rear axle forward (less stable) reduces the amount of castor forces during functional mobility.

An interesting finding was that when ascending the ramp and pushing on the lino the results show that castor forces are similar. It is thought this can be explained by the subjects tendency to lean forwards on the ramp in order to maintain the stability of the wheelchair therefore achieving a similar level of stability to that achieved on the lino. When performing on the Astro the castor forces are greater, which points to the effect of an increase in the rolling resistance on this surface.

6.2 Hypothesis 2 revisited

This study shows that the position of the rear axle does not significantly affect the propulsion forces of the wheelchair on any of the terrains. Thus, the null hypothesis cannot be rejected in this case. These results were surprising and contrary to current clinical practice, which suggests that setting up a wheelchair in a less stable configuration assists in achieving optimal propulsion efficiency.

However, as expected there is a significant difference between the forces necessary to propel over various terrains.

6.3 Additional results

Some of the additional data recorded by the Smart$^{WHEEL.TM}$; indicates that Velocity and Peak Average Force do give some significant results when the RAP is adjusted.

It was anticipated that the subjects may perform certain terrains faster with the RAP forwards but this is not supported by the velocity data. In this study we allow participants to self-select their speed (this is common practice in gait analysis research too). In using the readings as an index of function, on average, average walking velocity of 1.4 m/s was not achieved. There is very little difference between tippy and stable velocity.

Peak average force is higher in the less stable position compared to the more stable position in all terrains. This shows that the peak force reading is close to the average force reading resulting in a less smooth push in the less stable configuration. Higher values for Peak average force have been associated with the development of upper extremity pain and dysfunction (WOWSUP 2005)

Terrain does significantly affect some of the propulsion forces generated from the Smart$^{WHEEL.TM}$, particularly velocity, energy and impulse.

The average velocity for each surface was calculated and indicated that participants pushed at a slower average speed on the ramp and astro terrains (1.0 m/s) than on the lino (1.2 m/s). Similar results were found by Koontz et al (2005). One may expect to see more strokes required on the ramp to keep the wheelchair moving forwards but cadence does not show any significance in the results.

Impulse was not influenced by RAP during the first push and when comparing the Astro and ramp, except for the steady state condition. Differentiation between start up and steady state were not explored in this study. This could be investigated further as there are reported changes in users adapting to surface type between the two phases (Kootz 2005). However, the results did indicate some significance over the different terrains, which implies that there are significant differences in the ways subjects change the velocity of the wheelchair depending on the terrain, after the first push.

Higher Peak Mz readings were expected when subjects propelled on surfaces that imposed greater resistance to propulsion. This was supported by the results with a greater Peak Mz on the ramp (34.6Nm) compared to the lino (20.5Nm) (push 2 average). However, what was surprising was the limited difference seen in the Peak Mz over the other terrains.

This study also supports Koontz et al (2005) findings in that greater propulsion force is needed for users to start pushing the wheelchair from a dead stop compared with maintaining a constant self-chosen pace. First push Lino Stable 22.1 Nm compared to Steady State Lino 11.3 Nm.

The kerb analysis showed a greater first propulsion moment was needed with the RAP rearwards (stable) compared to the less stable configuration. For a clinician this makes sense, when teaching users to flip their castors it is much easier for them to achieve this with a less stable configuration. This is the only propulsion moment data to show any significant difference with the adjustments made to the RAP ($p = .023$).

This reinforces the importance of configuring a wheelchair for a full range of tasks anticipated for the user rather than simply those used for forward movement whilst also considering the frequency of such tasks as part of their daily routine. It is pertinent to note that the Peak Mz recorded during the kerb task were not dissimilar to those readings on the other terrains. This indicates that kerb's are not more challenging than the other terrains for the participants and that it is skill and technique which is influential. It would be interesting to repeat such a test with less experienced wheelchair users.

Very little difference can be seen in any of the Smart$^{WHEEL.TM}$ data when comparing the ramp and astro terrains. This may tell us that there is very little difference between performance on the two terrains and a similar technique is used on both terrains.

7 Conclusion

From this study, we can see that when the RAP is set forwards (tippy) on an experienced users wheelchair it does not necessarily translate into lower propulsion forces, as has been widely believed. Care needs to be taken in translating laboratory test results into wheelchair performance within functional environments. Additionally, these tests were performed for straight line activities and therefore did not include the influence of real-life manoeuvrability tasks, apart from that of the kerb.

This study recognises that the user of a less stable wheelchair may lean forwards during each propulsion stroke to maintain stability therefore, it was expected that castor force may increase over terrains with greater resistance However, although this is the case for the Astro what also appears to occur is that users generate similar castor forces for extreme differences in terrain such as on the lino and ramp. Further work is needed to understand the complexities of postural changes used intuitively by experienced wheelchair to assist in optimising wheelchair set up and possibly endurance.

From clinical experience we can assume that an individual's level of injury and technique can profoundly affect the balance between stability and tipability of the wheelchair. This study did not examine the level of injury and the effects of posture during propulsion. This would require further analysis incorporating use of a motion analysis system such as CODA.

The next stage in this research should look at rolling resistance and its relationship with the castor loading when performing functional tasks. Some preliminary data using a test dummy indicates that RAP does not substantially affect rolling resistance ($p = 0.383$). This supports the results from the Smart$^{WHEEL.TM}$ in that there is little change in propulsion forces when comparing a less stable wheelchair to a more stable one.

8 References

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