What Factors Really Affect the Efficiency of a Manual Wheelchair?

Presented by Curt Prewitt, MS, PT, ATP

A wheelchair user wants a chair that performs for them . . .A wheelchair that doesn't take too much effort

- To just be in
- or to maneuver

How Do We Provide a High-Performance Machine (wheelchair)?
First, we Need to Understand How A Wheelchair Works.

How do researchers determine how a wheelchair works and performs?

Component-level testing

- Drums
- Force plates

<u>Limitations of Component-level testing</u>

"…component-level information does not fully translate to clinically useful knowledge because it does not reflect the complex interactions between wheelchair components at a systems level." (Sprigle & Huang, 2015)

"Component-level tests are repeatable and offer a valid means to compare different components. However, they often cannot capture the complex interactions that take place at the system-level during over-ground maneuvering, which limits their direct clinical relevance." (Misch, J., Huang, M., & Sprigle, S. (2020).

Systems-level testing

Systems-level tests of Manual Wheelchair propulsion characteristics and energy losses expand on component testing to permit assessment of various wheelchair configurations in more realistic usage conditions.

These include tests both with and without human operators.

<u>With human operators</u>

- Treadmills and rollers
- Overground

<u>Limitations of Systems-level testing with human operators – **treadmills and rollers**</u>

"Systems-level testing with human operators has been dominated by focus on steady-state velocity, often using treadmills and rollers, which are not well positioned to assess the propulsion effort required to maneuver a wheelchair over-ground." (Sprigle and Huang, 2020)

<u>Systems-level testing with human operators – **overground**</u>

Tests using human operators during overground maneuvers offer a much more realistic representation of propulsion forces and effort, as the system is endowed with changes in momentum and travels over common surface types. These studies have assessed the impact of different surfaces, wheelchair mass, weight distribution or axle position, and push forces at different speeds.

<u>Systems-level testing **without human operators**</u> – wheelchair propelling robot, AMPS

The most direct way to measure mechanical system efficiency is to study the mechanical system. Propulsion effort or propulsion efficiency is best studied by studying the mechanical system. For a manual wheelchair, propulsion effort is critically important.

Wheelchair propelling robot, AMPS. It reports work/distance in Joules/meter J/m

- The robot has Consistency - Humans simply cannot impart consistent energy into a mechanical system
- The robot has Sensitivity - If mechanical testing cannot discern a difference, no way that humans could

To maneuver a manual wheelchair, one must overcome 2 principals of physics
Friction and Inertia

<u>Friction</u> - resistance to relative motion between two bodies in contact

Rolling Resistance: the frictional force that slows down a rolling wheel

- Rolling Resistance is a frictional force
  - Friction is resisting relative motion
    - Resisting relative motion results in Energy Loss

That Energy Loss occurs where the wheel meets the surface – at the tire

An example of Energy Loss:

Tire Traction

- Traction is the friction between tires and the ground that allows a vehicle to move forward.
- We need tire traction to move, BUT it's a necessary force that results in energy loss

In wheelchairs… Energy loss due to wheelchair tires is influenced by:

Tire material
Contact patch and air pressure
Tire type

This all affects Rolling Resistance

<u>Tire Material</u>

Rebound - Elasticity

- Rebound: The ability of an object or material to resume its original shape after being deformed
- When a material is deformed and rebounds, energy is consumed in the process
  - Tires deform, and the energy consumed by deformation is greater than the energy recovered by returning to its original shape
  - This effect is a significant contributor to an increase in rolling resistance

<u>Contact patch and pressure</u>

Contact Patch – the deformed area in contact with the support surface

Includes:

- Surface area (length x width)
- Shape (how long, or how wide)

Contact Patch (area) is a function of Pressure and Load

Pressure = Load / Area if load remains the same, then an increase in Pressure results in a decrease in area, and vice-versa

PSI = Pounds / Square Inch - - - Tire Pressure in PSI = System Weight in Pounds / Area in Square Inches

We said tires deform under load.

On a completely smooth surface the following applies:

- The higher the inflation pressure,
- The less the tire deformation (smaller the contact patch)
- The less the tire deformation (smaller the contact patch)
- Thus, less rolling resistance.

<u>Tire Type</u>

1 - **Pneumatic / Air-Filled** – an outer tire, with an air-filled rubber inner tube

Two types of solid tires:

2 - **Airless Insert, aka Flat Free Insert** – an outer casing, same tire as the pneumatic, but instead of being filled with air, it has a low-density foam insert inside it
3 - **Fully Solid tire** - solid tire material throughout the core of the tire
The solid tire options are often selected because they is considered to be maintenance free

Pneumatic tires exhibit lower rolling resistance than solid tires
Sawatsky, et al, 2004; Kwarciak, et al, 2004; https://www.wheelchairstandards.pitt.edu

<u>Inertia</u> - Resistance to motion due to mass

Examples of Inertia in the world around you

- When you're in a car that makes a sharp curve, inertia causes you to lean
- When you're skateboarding down the sidewalk, and your skateboard hits the grass, inertia causes you to fly forward off the skateboard

<u>Rotational Inertia</u> (aka Moment of Inertia)
A wheel with more mass will have more rotational inertia than one with less mass
Where the mass is located matters
How much mass matters

How should a manual wheelchair rider deal with inertia?
Utilize good technique for: • Accelerating • Decelerating • Turning

There is also rotational inertia of a turning wheelchair, and where the mass is located on the wheelbase matters

>A wheelchair has Mass
    >Wheelchair seating has Mass
        >A person has Mass
            >Combined, they represent System Mass

For average adults, the ultralightweight wheelchair may represent 10 – 20% of system mass
    >A 2-pound difference in chair weight would represent less than 1% difference in system mass

<u>Distribution of Mass - commonly called Weight Distribution</u>
Where the Mass is located on the wheelbase matters

- In turning the wheelchair, which also involves rotational inertia
- In straight line movement

Wheelbase

- The position of the drive wheels and caster wheels including their ability to be adjusted.

Weight Distribution - the proportion of system mass over the rear wheels as compared to that over the front wheels

- Weight Distribution influences Rolling Resistance,

therefore

- Weight Distribution influences propulsion effort

Wheelbase is affected by

- Horizontal Axle Position of rear wheel

Center of Gravity (CoG) adjustment

- Front wheel (caster wheel) position

Adjustable caster position possible?

Importance of CoG Optimization, or Optimizing Weight Distribution

Weight distribution affects friction

- Rolling Resistance is an energy loss parameter, a reflection of friction in the system.
- That friction can be influenced by weight distribution.
- So, not how much mass, but how is that mass distributed will influence this energy loss parameter
- Weight Distribution is thus influential in the cost of propulsion

Overall system mass has little impact on cost of propulsion not already accounted for by the energy loss parameters. Shifting weight from the casters to the drive wheels results in an overall decrease in the cost of propulsion.

Weight Distribution is not only affected by changes to the Wheelbase

It is affected by postural changes due to Seating Adjustment

- Back angle – e.g. opening the back angle shifts the mass of the trunk rearward
- Seat angle – e.g. lowering the rear seat height lower the mass of the trunk, and without a concurrent close in the back angle can also shift that mass rearward.

How much does a small increase in Mass of the chair matter?

Consider the Bouts of Mobility study: How do manual wheelchair users move about during their daily life?

2012 Bouts of Mobility, Sonenblum, Sprigle and Lopez – lots of frequent short bouts of movement, don't go very far or very fast, but execute lots of starts, stops and turns (think straight-line inertia and rotational inertia)

2017 study: Wheelchair Use in Ultra-lightweight Wheelchair Users – Sonenblum and Sprigle

2017 study suggests that Ultralightweight Manual WC users perform about 90 bouts/day, and propel about 1.7Km/day

-Using that usage data, 1 pound (.45 Kg) was added to a frame, to see how much extra work it requires

Over the course of an average day, that additional 1 pound of weight added to the frame resulted in an additional 14.4 Joules of work.

What does an additional 14.4 J equate to? - - Equal to the work of lifting a 2L bottle of soda from floor to table 1 time

Source: Dr. Stephen Sprigle, PhD, PT

Summary: What Factors Really Affect the Efficiency of a Manual Wheelchair?

"When considering propulsion effort within ULW manual wheelchairs, ample scientific evidence suggests that wheels, tires and weight distribution are the most impactful. So, by focusing solely on suggests that wheels, tires and weight distribution are the most impactful. So, by focusing solely on mass, one neglects the most important factors affecting propulsion effort."

Dr. Stephen Sprigle, PhD, PT

Wheel and Tire Selection is very important because it will influence Friction

- Friction represents Energy Loss

Weight Distribution is very important because it can influence Friction

- Friction represents Energy Loss