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RESEARCH ON PRODUCTS AND DEVICES

Reinventing the wheel for a manual wheelchair

Claire L. Flemmer[a] and Rory C. Flemmer[b]

[a]School of Built Environment, Massey University, Palmerston North, New Zealand; [b]Nimbl Inc, Palmerston North, New Zealand

ABSTRACT

Purpose: Standard manual wheelchairs (MWCs) are inefficient and pushrim propulsion may cause progressive damage and pain to the user's arms. We describe a wheel for a MWC with a novel propulsion mechanism.

Methods: The wheel has two modes of operation called "Standard" mode and "Run" mode. In Run mode, the wheelchair is propelled forward by pushing a compliant handle forward and then pulling it back, both strokes contributing to forward propulsion. We report the propulsive force and preliminary testing on a rough outdoor circuit by three able-bodied participants.

Results: In Run mode, the peak applied force is reduced to 30% and the maximum force gradient is reduced to 10% of that for standard pushrim propulsion, for the same work output. The travel time for the 1.06 km outdoor circuit is about 60% of that for a brisk walk and about 40% of that for pushrim propulsion. At a propulsion speed of 1 m/s, the cardiovascular effort in Run mode is 56% of that for pushrim propulsion. Automatic hill-hold in Run mode improves safety when ascending slopes. The mechanism has three gears so that it can be used by people with widely varying strength and fitness. Folding the handle away converts the operation to Standard mode with the conventional pushrim propulsion, supplemented by three gears.

Conclusions: Despite the increased weight, width and friction, the bimodal geared wheels facilitate wheelchair travel on challenging paths. This may bring significant improvement to the quality of life of MWC users.

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KEYWORDS
Manual wheelchair; bidirectional stroke; epicyclic; handles; propulsion

➤ IMPLICATIONS FOR REHABILITATION

- The novel bimodal geared propulsion may benefit users with impaired upper extremity function.
- The push–pull propulsion on handles is less strenuous than pushrim propulsion and may reduce repetitive strain injuries.
- Run mode has significantly reduced peak force and force gradient compared with standard pushrim propulsion, for equal work.
- The bimodal geared propulsion facilitates outdoor travel, providing exercise that may benefit the user's strength and health.

Introduction

The fundamental design of the standard manual wheelchair (MWC) has remained unchanged for over 100 years. The user grasps pushrims, pushes them forward, releases and then re-positions the arms for the next propulsion cycle. At a travel speed of 0.8–1.3 m/s, the push part of the cycle lasts about 0.4 s or about 30–40% of the cycle [1–3]. The jerking grasp and release each last about 0.1 s and slightly slow the MWC [4,5]. Gripping the pushrim puts a constraint on the wrist orientation. The applied push force consists of tangential, radial and medial–lateral components. The tangential component is 55–75% of the applied force and is the only component that contributes to propulsion [3,6]. The fraction of effective force (FEF) is defined as the ratio of the tangential force to the applied force and that ratio determines mechanical efficiency; the lower the value of FEF, the greater the wasted energy. FEF decreases with increase in propulsion speed; this means that propelling a MWC becomes progressively less efficient as the speed is increased [7]. Jahanian et al. [8] describe MWC use as a "low efficiency and physically straining form of mobility". This has two consequences for MWC users; first, they need to have adequate strength and fitness and, second, the repetitive straining, jerky propulsion progressively damages the arm joints, causing pain [9,10]. Thirty-one to seventy-three percent of MWC users with spinal cord injury (SCI) report shoulder pain and 49–73% report carpal tunnel syndrome [5,11]. The onset of shoulder problems for MWC users varies from 5 to 20 years depending on a host of factors such as the age of the user, the level of injury, the user's fitness and the length of time using the MWC [12]. Shoulder problems such as rotator cuff tears are estimated to be about 3–4 times higher for MWC users than for able bodied people of the same age [8,13].

There is general consensus that MWC users should do regular aerobic exercise and strength training to reduce the risk of upper limb problems [14,15] and secondary problems such as obesity, diabetes, respiratory problems and cardiovascular problems [16,17].

CONTACT Claire L. Flemmer c.l.flemmer@massey.ac.nz School of Built Environment, Massey University, Private Bag 11 222, Palmerston North 4442, New Zealand

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Community participation is much lower for MWC users than for ambulatory people and pain makes it harder for MWC users to stay mobile [18]. Data from Best and Miller [19] show that older community-dwelling wheelchair users are six times less physically active compared with ambulatory people of similar age. Sol et al. [20] cite studies showing that young MWC users are also significantly less physically active than their ambulatory peers. Morgan et al. [21] cite studies showing that less than 50% of people with SCI do any physical activity and that only 15% do enough to see health benefits. Alongside physical health benefits, Herring et al. [22] report that exercise helps alleviate depression in WC users. In conclusion, the average MWC user is likely to develop upper extremity pain, leading to less exercise, less community participation, more secondary health problems and a steadily worsening quality of life [8,10,23].

The standard MWC has other problems when it is used outdoors. Outdoor paths have a cross-slope to drain rainwater. The MWC user must push harder on the downslope pushrim to stay straight on the path, which means that one arm gets fatigued. The pushrim gets dirty, wet and cold, making it slippery and unpleasant on the user's hands. It can also burn the user's hands when used for braking [24,25]. Finally, ascending ramps is challenging; extra effort is needed to prevent the MWC from rolling downslope between push phases. Wieczorek et al. [26] describe this as "one of the most difficult and dangerous activities" for MWC users. They note that a reversing lock module can be fitted to prevent roll-back, improving overall safety at the expense of the slightly greater muscular effort needed to overcome the added friction from the device [26].

Exercise using a standard MWC is more straining to the musculoskeletal system than hand cycling, the latter using a continuous force application and lower peak loads [27,28]. Kraaijenbrink et al. [29] review studies on handcycling and comment that the alternating use of push and pull muscles over the cycle spreads the task load over time and over larger muscles, reducing overall loads and peak loads and ultimately reducing the risk of injury.

The alternatives to the MWC include power-assist rear wheels, powered front attachments and the Segway Wheelchair or Seated Segway (e.g., supplied by Omeo Technology[1]). These use electrical power to supplement the user's physical exertion, which does not address the need for cardiovascular exercise. They have the further disadvantage of higher weight which makes them harder to lift and transport in cars [29]. For example, the average weight of standard pushrim MWC wheels is 3.5 kg, while the weight of Quickie® Xtender® power-assist wheels and battery is 17 kg [8]. Nevertheless, power-assist devices are useful for overcoming common outdoor barriers such as curbs, rough/uneven surfaces, side slopes and steep ascending/descending inclines and thus facilitate community participation [30]. Another alternative is manual geared wheels, for example, IntelliWheels, which can operate with gear ratios of 1:1 and 1.5:1 and which weigh 7 kg [8]. When operated in low gear (1.5:1), they have lower propulsion demands and are thus particularly beneficial for strenuous propulsion on carpeted surfaces or for ramp ascension [8]. Crank- and lever-propelled wheelchairs are less strenuous on the arm joints, provide exercise and are more efficient [31–36] but are worse for transferring, less manoeuvrable and unsuited to indoor travel [1]. Thus, despite its severe limitations, the standard MWC remains the most commonly used mobility device for people who use wheelchairs [10].

Figure 1. Quickie® QRi® manual wheelchair fitted with bi-modal wheels.

The first objective of this work is to describe the features of our novel propulsion mechanism and compare these with the standard pushrim propulsion. The second objective is to present data on the measured force of the mechanism's propulsion cycle and compare this with the measured force of the standard pushrim propulsion cycle. Finally, we present preliminary biometric data on the performance of the wheel mechanism on a rough outdoor path.

Methods

The design of the novel propulsion mechanism for a manual wheelchair

The main effort of this research involved the iterative design and development of a rear wheel for a MWC that would address many of the inherent problems of the standard wheel. The requirements for the wheel were that it had to fit quickly to a standard MWC frame, look aesthetically pleasing, retain the manoeuvrability of the standard MWC and, most importantly, provide more "user-friendly" propulsion. User-friendly propulsion means less strain on the arms and shoulders, suitable for users with widely varying strength/fitness, facilitating outdoor accessibility and providing the safety of anti-rollback during ramp ascent. The design passed through 23 prototypes and many years of effort and culminated in the bi-modal wheel (BMW) design described below.

Figure 1 shows the BMW fitted to a Quickie® QRi® MWC frame and Table 1 lists the wheelchair specifications. The BMW has a spigot and latching mechanism that allows quick attachment to or removal from the frame. Each wheel weighs about 7 kg.

The wheels operate in one of two modes called Standard mode and Run mode. When the wheels are in Standard mode, the handles

Table 1. Wheelchair specifications.

Parameter	Specification
Wheelchair make and model	Quickie® QRi®
Frame weight (without rear wheels)	8 kg
Length	87.5 cm
Height	82.5 cm
Seat height	49.5 cm
Seat width	46.5 cm
Seat depth	39.5 cm
Seat angle to the horizontal	10°
Angle of backrest to the vertical	6.5°
Rear wheel camber angle	0°
Rear axle distance from caster shaft	42.5 cm
Rear wheel specification	Pneumatic Marathon Plus, 100 psi
Caster specification	Semi-pneumatic, 35 psi

are furled (Figure 2) and the MWC is propelled with the pushrim, as usual, but with the addition of three gears. The gear is changed with a lever and this is described below. Low gear facilitates mobility for those with limited arm strength or on resistive surfaces such as a thick pile carpet. Standard mode is primarily used for indoor mobility, where the user regularly needs to be able to move both forward and backward. The BMWs in Standard mode increase the overall width of the chair by 35 mm a side compared with a normal wheel. For a 711 mm (28 in.) wide MWC, the BMWs would increase the overall width to 781 mm, leaving a clearance of 31 mm on a standard 812 mm (32 in.) wide door.

Figure 2. Bi-modal wheel in Standard mode with the handle furled.

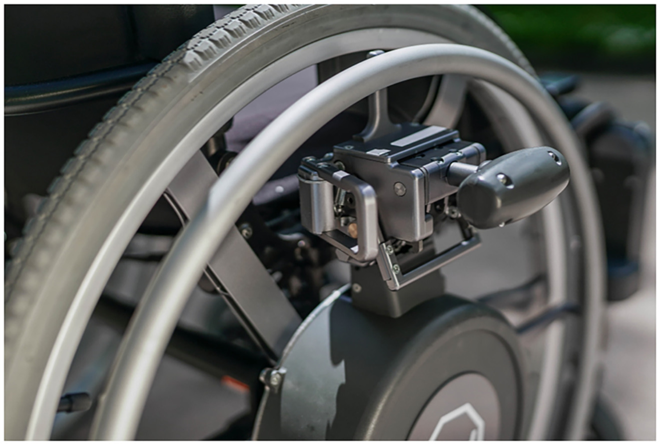


Figure 3. Bi-modal wheel in Run mode with the handle unfurled.

When the handles are raised (Figure 3), the wheel operates in Run mode.

In Run mode, the user grasps the handles and pushes them forward to the position shown in Figure 4(a), propelling the wheelchair forward. They then pull the handles back towards the hips, to the position shown in Figure 4(b) and rectification again propels the wheelchair forward. Thus, the complete oscillating push–pull stroke cycle propels the wheelchair forward. Figure 5 is a schematic representation of the two modes of operation.

In Run mode, the MWC can only move in the forward direction. This mode is suitable for long distance travel on challenging paths such as those found outdoors with uneven and sloped surfaces. If the user wants to move backwards, they need to furl the handles and switch to Standard mode. With the handles unfurled, the BMWs are 90 mm wider on each side than standard MWC wheels, increasing the total width of a 711 mm wide standard MWC to 891 mm. However, since outdoor paths and ramps are a minimum of 1200 mm wide, the additional width is not problematic. Run mode is useful when ascending ramps; the drive mechanism prevents rollback so that the user can propel up the ramp at their own speed, stopping midway to rest or to change to a lower gear if needed. Further, the bi-directional stroke is continuous, using both agonist and antagonist muscles in the push and pull phases of the propulsion cycle. The hands remain on the handle and propulsion is similar to that used in handcycling which has been shown to facilitate outdoor mobility and provide exercise with reduced risk of upper extremity damage compared with pushrim propulsion [29]. The BMW has a compliant handle (it swivels freely) that is easy to grasp compared with the constrained grasp required to provide friction on the pushrim in standard MWCs. The control mechanism has a manually operated gear lever, shown in Figure 6(a) with three gears; low gear has a gear ratio of 1:1.6, middle gear has a gear ratio of 1:1 and high gear has a gear ratio of 1.6:1. Users with average strength would use low gear to travel slowly over rough terrain or steep slopes and high gear to travel fast on smooth, flat paths. The control mechanism also has a lever-type brake, shown in Figure 6(b) operated with the base of the palm. This removes the risk of burns and dirt from braking on the pushrim or tyre of the standard MWC.

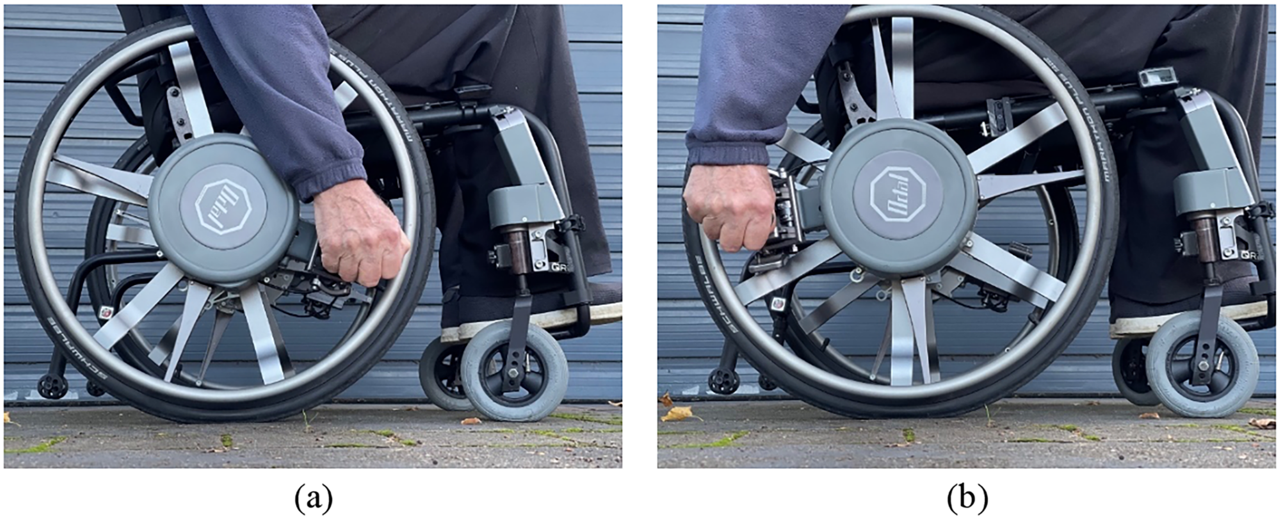


Figure 4. Bi-modal wheel in Run mode showing the handle in (a) the forward-most propulsion position and (b) the rear-most propulsion position.

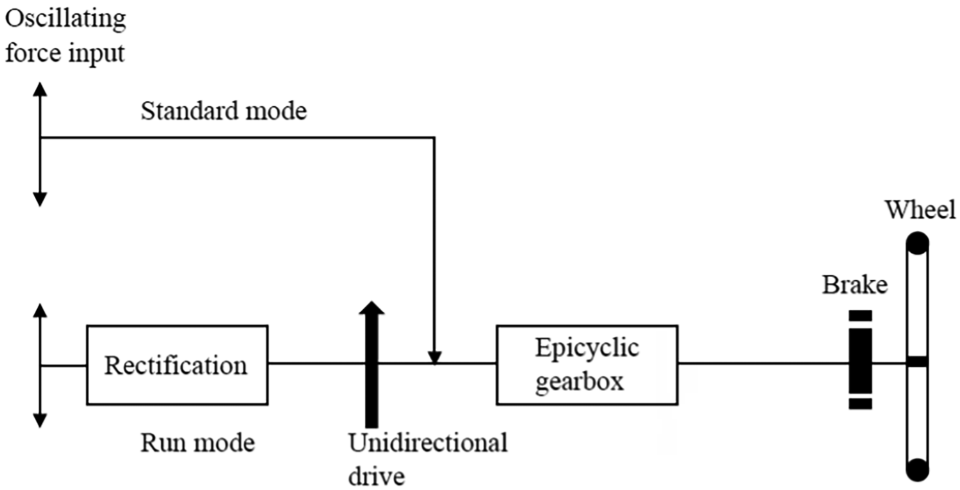


Figure 5. Schematic diagram showing the two modes of operation of bi-modal wheels.

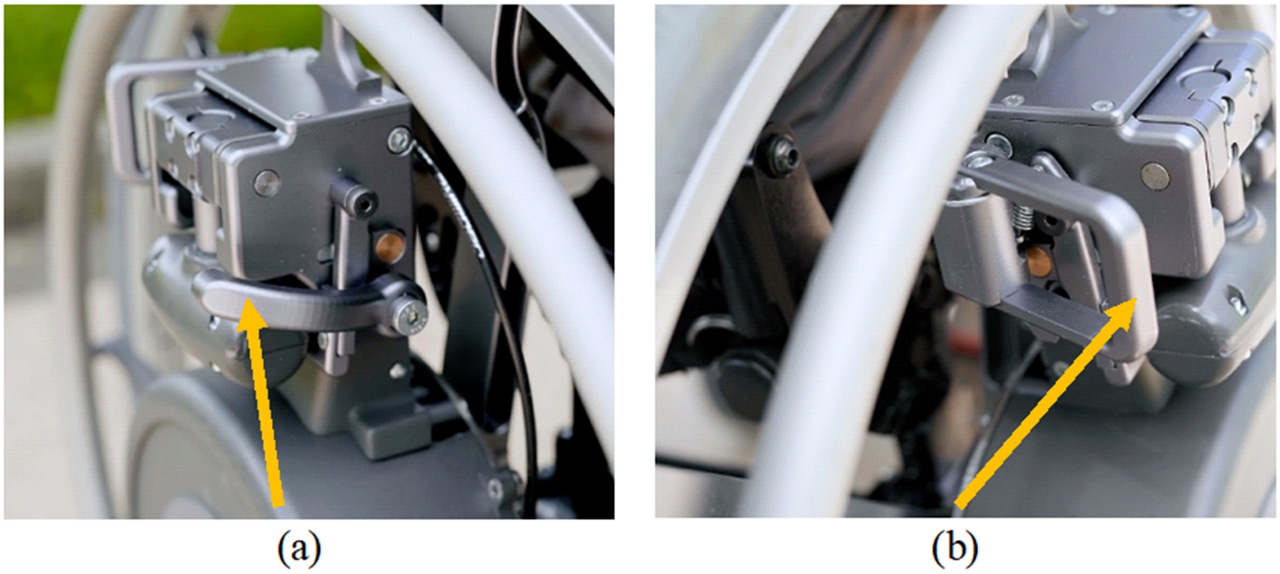


Figure 6. Control mechanism showing (a) the gear lever and (b) the brake.

Caster modification for flutter control and cross-slope compensation

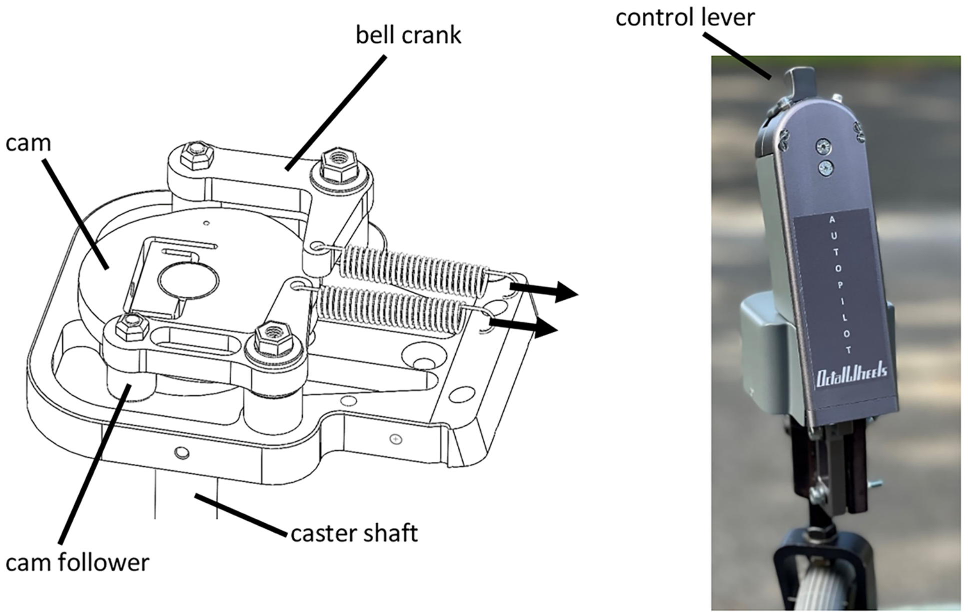
During the development, two additional problems related to the MWC casters became apparent, namely the problem of caster flutter or shimmy at high speed and the problem of cross-slope on paths leading to overuse of one arm. Caster flutter was reduced by adding a friction washer to each caster shaft to provide friction damping as described in Kauzlarich et al. [37]. The problem of cross-slope arises because most outdoor paths are sloped to shed rainwater. On a cross-slope, the wheelchair casters swivel towards the downslope and the user counteracts this by propelling the downslope pushrim more than the upslope pushrim. This means that a user travelling in one direction over a long outdoor path will overuse the downslope arm. A cross-slope compensation (CSC) device was designed to address this problem.

The CSC device (Figure 7) attaches to the right-hand caster and counteracts the average path cross-slope as follows. The user sets the control lever to the left side, the middle or the right side and this varies the loading on the two springs, adjusting the force on the two cam followers. They, in turn, operate on the cam that is attached to the vertical caster shaft. In the mid-position, neither cam follower is engaged, and the caster can rotate freely, without any cross-slope compensation. In the side positions, one or other of the springs applies a load to the associated cam follower, which biases the caster to turn in one or other direction. The left caster moves freely to match the right caster bias, which counteracts the path cross-slope. The user must still compensate for small variations in the path cross-slope but not for the average path cross-slope, so that the use of both arms during propulsion is more balanced.

The CSC device weighs 0.75 kg, extends 25 mm from the frame (i.e., it is narrower than the standard pushrim wheel) and is positioned below the seat plane (see Figure 4) so that it does not interfere with transferring. The design of the BMW and the CSC device are protected intellectual property [38,39].

Propulsive force for bi-modal wheels in Run mode and comparison with pushrim propulsion

To measure the propulsive force on the wheel, an instrumented handle with a force transducer was fitted to the handle of the wheel (Figure 8).



(a) (b)

Figure 7. Cross-slope compensation (CSC) device showing (a) the schematic diagram of the mechanism and (b) the control lever and attachment to the caster wheel.

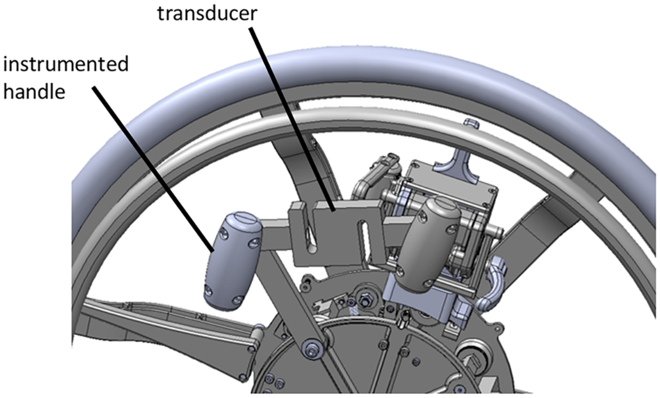


Figure 8. Measurement of propulsive force.

The transducer was a Honeywell S beam load cell, with strain gauge bridge, monitored using a Measurement Computing Corporation Data Acquisition (DAQ) logger. The signal was read at 50 ms intervals.

To compare the propulsive force of BMWs in Run mode with standard pushrim propulsion, a suitable source of pushrim propulsion data had to be found and the experimental method chosen to be as similar as possible for the two types of propulsion. The only published source of tangential force data for pushrim propulsion was Boninger et al. [3], who tested athletic MWC users propelling at a speed of 1.3 m/s on a dynamometer and show an average force trace for paralympic athlete participants (in Figure 2 of [3]). In our test, the MWC fitted with BMWs was operated in Run mode and middle gear (1:1 ratio) on a smooth sloped concrete surface and was propelled by an able-bodied participant. The participant trained over several 90 s trials to achieve a consistent travel speed of approximately 1.3 m/s to match the pushrim propulsion speed reported in Boninger et al. [3]. Fifteen full cycles were extracted from the steady state portion of the full recorded force trace. The average cycle time (push stroke plus pull stroke) was calculated to be 2.0 ± 0.4 s. Each of the 15 cycles was divided into 100 time increments and the average measured force, $F_{i,BMW}$, was computed at each time increment. This average measured force is reported in "Results" section.

The test conditions in [3] are very different from those reported in this work. Differences include the surface type (dynamometer roller versus concrete path), expertise of the participants, weight of the participants, distribution of weight between the propulsion wheels and the caster wheels, specification and configuration of the MWCs, tyre type and pressure, etc. One way to accommodate these differences is to adjust the raw measured BMW propulsive forces so that the work done is the same as that for the pushrim propulsion reported in [3]. The analysis of the force comparison for equal work is as follows:

- The propulsive work done, W, is the product of force, F, and distance. Distance is the product of speed, v, and time, t. Since the average speed is constant (and the same for both sets of data) at 1.3 m/s, the propulsive work done over time is:

$$W = \sum_i F_i \Delta x_i = v \sum_i F_i \Delta t_i \tag{1}$$

From Equation (1), the work done in each test is proportional to the area under the force–time graph, providing that the total time and speed for the test is the same in both BMW propulsion and pushrim propulsion.

- The actual propulsive work done with the BMWs at a speed of 1.3 m/s, W_{BMW}, is the sum of the absolute average measured force at each time increment, $\left|F_{i,BMW}\right|$, multiplied by the time increment, Δt, of 0.01 s:

$$W_{BMW} = v \sum_{i=1}^{100} \left|F_{i,BMW}\right| \Delta t \tag{2}$$

- The tangential force, F_{PRP}, at 0.01 s increments for the push phase of the pushrim propulsion (which lasted 0.4 s) was extracted from Figure 2 of Boninger et al. [3]. The work done with pushrim propulsion, W_{PRP}, was computed as:

$$W_{PRP} = v\sum_{i=1}^{40} F_{i,PRP}\Delta t \tag{3}$$

- Since one pushrim cycle lasts approximately 1 s, there will be two pushrim cycles in the two-second cycle of BMW propulsion and the work done will be $2W_{PRP}$.
- In order to do the same propulsive work for the BMW test and for the pushrim test, the equivalent force for BMW propulsion, $F_{i,BMWeq}$, would be:

$$2W_{PRP} = v\sum_{i=1}^{100} \left|F_{i,BMWeq}\right|\Delta t \tag{4}$$

Dividing Equation (4) by Equation (2) and noting that Δt is constant gives the scaling factor for the equivalent propulsive force for BMWs, $F_{i,BMWeq}$:

$$F_{i,BMWeq} = \frac{2W_{PRP}}{W_{BMW}} F_{i,BMW} \tag{5}$$

Both the raw average measured force ($F_{i,BMW}$) and the equivalent force ($F_{i,BMWeq}$) for the same propulsive work as the pushrim propulsion are reported in "Results" section.

As mentioned, there are many limitations in comparing the force data for BMW propulsion ($F_{i,BMW}$) with that for pushrim propulsion ($F_{i,PRP}$) from Boninger et al. [3]. An attempt to minimise the differences was made by performing the propulsion at the same speed for both tests, by removing the gearing effect in the BMW propulsion (using middle gear with a 1:1 gear ratio) and by the assumption that the same propulsive work was done in the two different tests. However, it is recognised that only an approximate comparison can be made.

Preliminary biometric performance of bi-modal wheels

Ethics approval for biometric performance testing was obtained from the Human Ethics Southern A Committee of New Zealand (ID SOA 18/02).

The heart rate of three able-bodied, fit participants (Table 2) was monitored with a Polar H10 device, at one-second intervals, while travelling on a 1.06 ± 0.11 km outdoor path. Participants started and ended with the front caster wheels touching a line marked on the path and were instructed to aim for the centre of the path. The path length was measured with a Cateye Velo 7[2] digital odometer/speedometer fitted to the right-hand BMW. It is recognised that the approximately 2% path length variation over the trials is a source of error in the results. The path surface was weathered, unswept tarmac with regular concrete driveway crossings, occasional raised and cracked portions from tree roots and variable cross-slope. An outdoor path was chosen because several studies have shown that field testing provides more relevant measurement than laboratory testing, on a treadmill or ergometer [40,41].

Table 2. Able-bodied participant characteristics.

Participant	Gender	Age (years)	Height (m)	Mass (kg)	HRrest (bpm)
1	M	30	1.88 m	103	60
2	M	75	1.93 m	100	72
3	F	61	1.57 m	60.0	70

HRrest: resting heart rate; bpm: beats per minute; M: male; F: female.

Heart rate is commonly used to predict energy expenditure, for both able-bodied participants [42,43] and for MWC users [44,45]. The resting heart rate was measured when each participant had been supine for five minutes, in accordance with the Polar H10 protocol. Cardiovascular effort was computed from:

$$\text{Cardiovascular effort} = \left(HR - HRrest\right) / \left(HRmax - HRrest\right) \tag{6}$$

where *HR* is the average heart rate in beats per minute (bpm) over the test, *HRrest* is the resting heart rate and *HRmax* is the maximum or peak heart rate, calculated from the age of the participant in years. Shookster et al. [46] review the many equations predicting age-based maximal heart rate and opine that the most commonly used and accurate one for general populations is:

$$HRmax = 220 - subject\ age \tag{7}$$

The participants were timed doing five circuits of the path under different conditions (Table 3). The participants practised pushrim and bi-directional propulsion beforehand. Tyre pressure affects energy expenditure [47], so this was set at 100 psi and 35 psi for the rear tyres and caster tyres, respectively.

Conditions for circuits 1, 2 and 3 were used to investigate the cardiovascular effort involved in brisk walking, brisk pushrim propulsion and brisk BMW Run mode propulsion. Conditions for circuits 2 and 4 were used to compare the cardiovascular effort involved in pushrim propulsion and BMW propulsion at the same speed (1 m/s). Conditions for circuits 2 and 5 were used to investigate the effect of CSC on travel time during pushrim propulsion.

Results

A video of the operation of the MWC with BMWs in Run mode is shown here.

Propulsive force for bi-modal wheels in Run mode and second gear

Boninger et al. [3] report the average tangential force trace ($F_{i,PRP}$) for a standard MWC propelled by an athlete travelling with a steady state speed of 1.3 m/s on the level smooth surface of a dynamometer roller. The trace is shown in blue in Figure 9. It is repeated at a one-second interval and the area under the graph is proportional to the propulsive work done by Equation (3). The force trace for the right handle of the BMW in Run mode and second (1:1) gear was measured at a similar speed on a smooth concrete path, averaged over 15 cycles ($F_{i,BMW}$) and is shown as the discrete points on

Table 3. Conditions for five circuits of the 1.06 km outdoor path.

Circuit	Travel condition
1	Self-selected, at a brisk walk
2	Pushrim propulsion: in a standard MWC at a self-selected, brisk speed
3	Bi-directional propulsion: in a MWC fitted with BMWs in Run mode, top gear, CSC device engaged, at a self-selected, brisk speed
4	Bi-directional propulsion: in a MWC fitted with BMWs in Run mode, CSC device engaged, at an average speed of 1 m/s (the same as the average speed of circuit 2)
5	Pushrim propulsion: in a MWC fitted with BMWs in Standard mode, no gearing (middle gear), CSC device engaged, at a self-selected, brisk speed

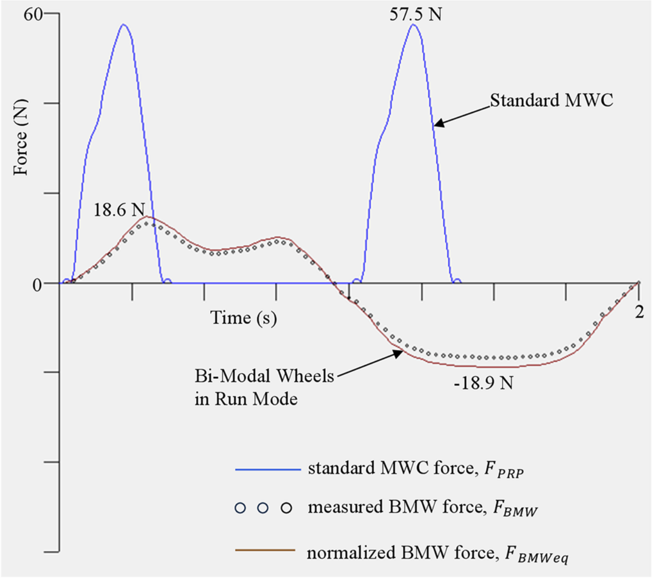


Figure 9. Comparison of propulsive force for standard pushrim propulsion and bi-modal wheels propulsion.

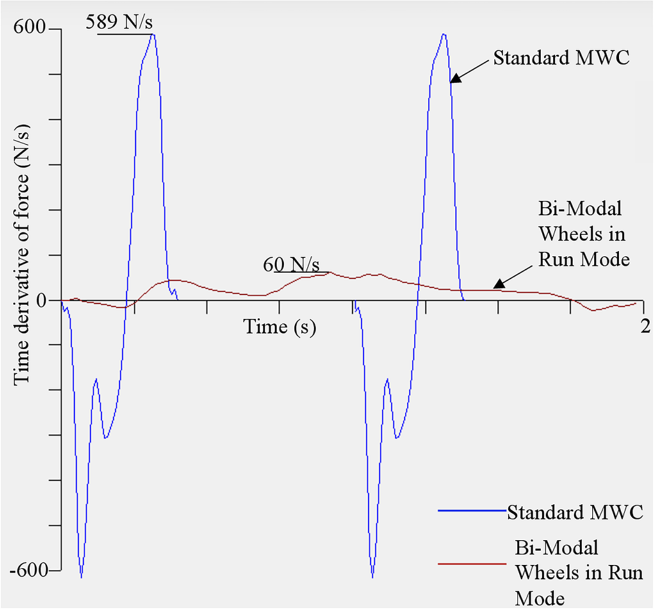


Figure 10. Comparison of force gradient for standard pushrim propulsion and bi-modal wheels propulsion.

Figure 9. The first half of the trace is the push stroke and the second half is the pull stroke. Also shown in brown in Figure 9 is the equivalent force for the BMWs ($F_{i,BMWeq}$), normalised to give the same work done as the pushrim propulsion from [3].

The blue trace in Figure 9 shows the repeating short, push stroke used for standard pushrim propulsion. The brown trace shows the push–pull stroke of the BMWs. The area under each trace (proportional to the propulsive work done) is the same for both types of wheels (at equal speed). The peak force for the standard MWC is 57.5 N, while the peak force for the MWC fitted with BMWs is 18.6 N (pushing) and −18.9 N (pulling). Thus, for equal work, BMW propulsion uses about 33%, or just one-third, of the peak force for pushrim propulsion. In addition, the push–pull BMW propulsion uses both agonist and antagonist muscles, moving the synovial fluid in the joint, which keeps the joints lubricated [48]. A further benefit of the BMW propulsion is its smooth force trace compared with standard propulsion. The gradient of the force with respect to time is shown in Figure 10 for the two modes of propulsion; the blue trace for the standard MWC and the brown trace for the BMWs in Run mode. Beirens et al. [9] suggest that shoulder damage and pain may result from large rate of rise of the applied force.

The maximum force gradient for the standard MWC propulsion is 589 N/s while that for BMW propulsion is 60 N/s, just 10% of the standard MWC peak force gradient.

Arnet et al. [34] compared handcycling with pushrim propulsion and demonstrated that handcycling reduced the peak force to 37%. Handcycling has a smooth force trace that is very similar to the force trace for BMWs in Run mode.

Finally, the user’s hands remain on the BMW handle, applying a continuous and fairly even force without the idle period and grip-release period of pushrim propulsion.

Biometric performance: preliminary energy expenditure assessment

Figure 11 compares the cardiovascular effort, defined in Equation (6), of the three AB participants completing the circuit by self-selected brisk walking (at an average speed of 1.4 m/s), brisk standard MWC pushrim propulsion (at an average speed of 1 m/s), brisk BMW Run mode (top gear) propulsion (at an average speed of 2.6 m/s) and BMW Run mode propulsion (at an average speed of 1 m/s), corresponding to circuits 1–4 (Table 3).

For all participants, BMW operation in Run mode at a self-selected brisk speed (2.6 m/s) requires far greater cardiovascular effort than either brisk walking (at 1.4 m/s) or brisk standard MWC pushrim propulsion (at 1.0 m/s). The three participants completed the circuit in the standard MWC at an average self-selected brisk speed of 1 m/s with an average cardiovascular effort, defined by Equation (6), of 30.0%. When the participants completed the circuit at the same average speed (1 m/s) using BMWs in Run mode, their average cardiovascular effort was 16.8%, or just 56% of the effort required when using the standard MWC.

Figure 12 shows the time taken to complete the circuit at a self-selected brisk speed by walking, standard MWC propulsion and BMW (in Run mode and top gear) propulsion (circuits 1–3, respectively). Completing the circuit takes an average of 17.4 s with standard MWC pushrim propulsion, compared with an average of 7.1 s with BMWs in Run mode (41% of the time taken for standard pushrim propulsion).

The average speed for walking, standard MWC propulsion and BMW propulsion, all done at a brisk pace, is 1.4 m/s, 1.0 m/s and 2.6 m/s, respectively. The measured average walking and jogging speeds reported in Aghabayk et al. [49], for mixed gender participants aged 18–84 years on a level asphalt path are 1.35 m/s and 2.77 m/s. The results show that BMWs allowed the participants to travel at close to jogging speed on rough outdoor paths.

It is difficult to compare the propulsion speed in different types of wheelchairs because there is a wide variation in the configuration and specification of different models, as well as in the testing methodology and capability of the participants. For standard pushrim propulsion by able-bodied participants, Chaikhot et al. [50] cite an average comfortable speed of 0.85 m/s in able-bodied participants with no wheelchair experience while Rupf et al. [51] cite sprint speeds of about 3 m/s in elite wheelchair court sports players. Speeds of 1.11 m/s and 1.66 m/s are common for tests on pushrim propulsion and hand cycling respectively with able-bodied participants [34].

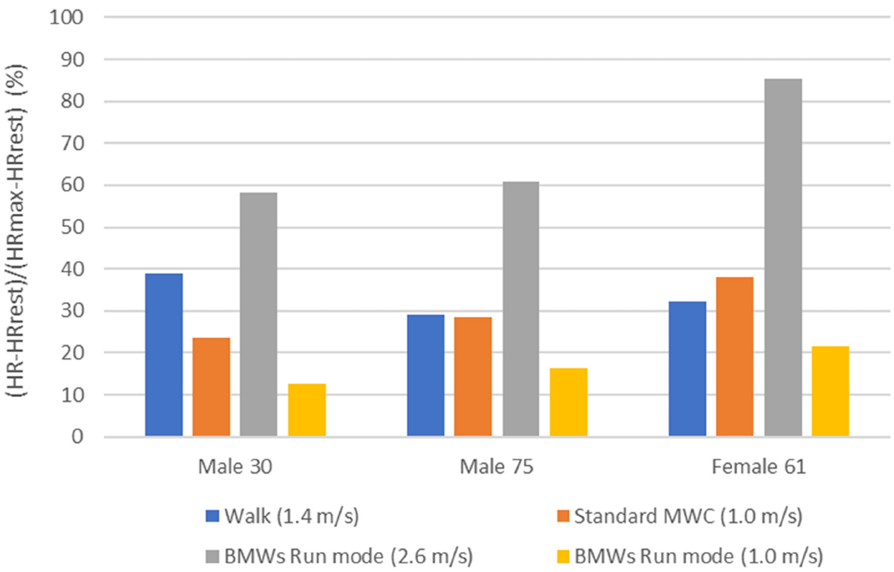


Figure 11. Effect of travel type on cardiovascular effort for the three participants.

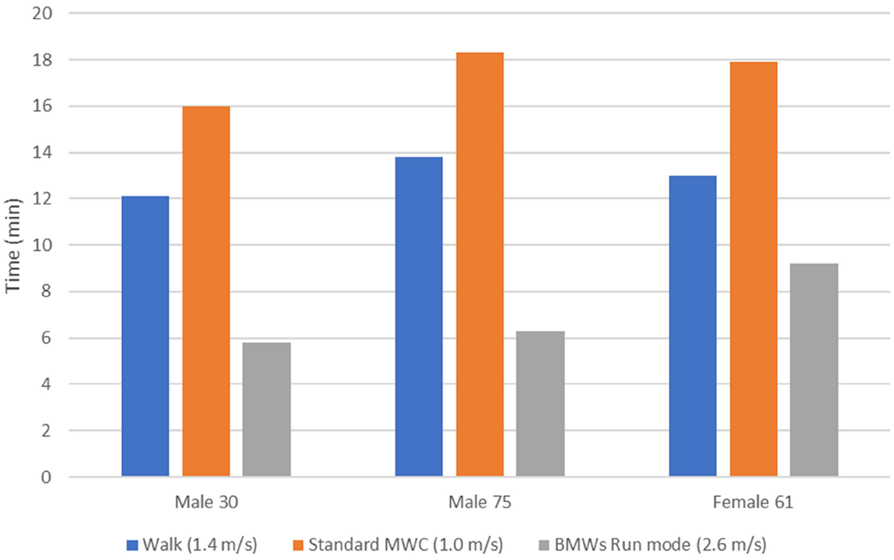


Figure 12. Effect of exercise type on circuit time.

Figure 13 shows the effect of path cross-slope on pushrim propulsion, comparing the time to complete the circuit with standard lightweight wheels with that for BMWs in Standard mode, middle gear and with the CSC device engaged to counter the effect of path cross slope.

Despite the additional 14 kg of weight and the slightly increased friction from the BMW mechanism, the CSC reduced the circuit time to 71–75% and all three participants reported that left and right arm use seemed approximately equal, based on their subjective perception. Without the CSC, in the standard MWC, the arm on the downslope of the path had to push far more strongly than the upslope arm to stay on a straight path. Participants experienced some muscle pain in this arm, which limited their speed.

Discussion

The first aim of this work was to present the design features of the MWC fitted with BMWs and draw comparisons with standard pushrim propulsion. BMWs have two modes of operation; Standard mode and Run mode. In Standard mode, the MWC is propelled with the pushrim, in the same manner as a conventional pushrim MWC, except that the BMWs have three gears. A user can select the gear that best suits their own strength and the particular environment, selecting a high gear for smooth, level paths and a low gear for rougher, more challenging paths. In this mode, the wheels are similar to other geared wheels. Extending the BMW handles changes the wheels to Run mode, where the user holds the handles and applies a continuous push–pull propulsion stroke that propels the MWC forward. The same three gears are available in this mode and the mechanism provides automatic anti-rollback when ascending sloped paths. The ergonomic handle is comfortable on the user’s hand and stays clean and dry. A lever brake close to the handle replaces the hand braking with friction on the wheel/pushrim for standard MWCs. The MWC with BMWs has the same manoeuvrability and ease of transferring as standard MWCs. The BMWs have the disadvantage of weighing 7 kg each, which is much more than standard pushrim wheels but less than power assist wheels. They are 35 mm wider

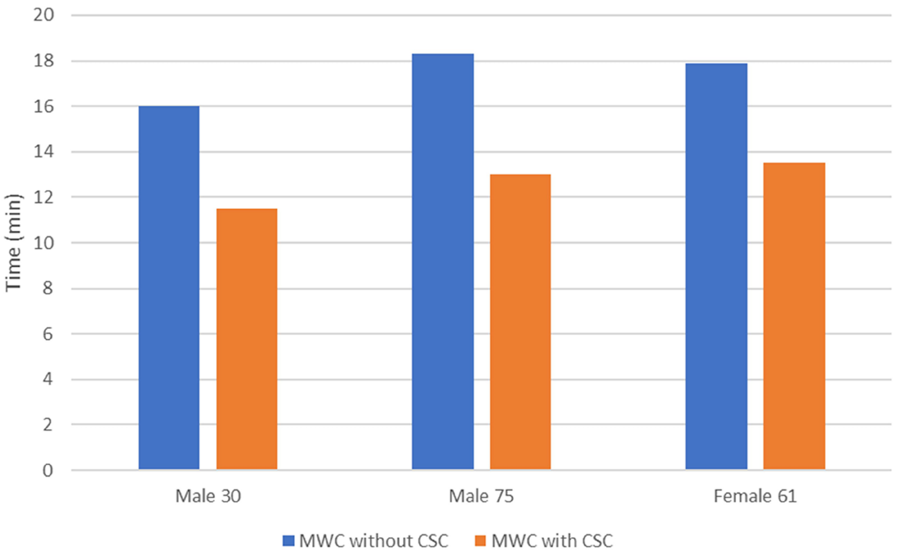


Figure 13. The effect of path cross-slope on pushrim propulsion.

with the handle furled, so there is less clearance in doorways. A final disadvantage is that the BMW mechanism has more friction than standard pushrim wheels.

The second aim of the work was to present preliminary force measurement data. In Run mode, the applied force is continuous and fairly even without the idle period and repeated grasp-release stages of the standard pushrim propulsion cycle. Run mode peak forces are about 30% of pushrim peak force and the maximum force gradient is reduced to about 10% of that for pushrim propulsion. These results are not precise since there are limitations in comparing measured force data for tests conducted with different methodologies, wheelchair specifications and participants. However, BMW propulsion in Run mode appears to use considerably lower propulsive forces and Beirens et al. [9] suggest that this less strenuous propulsion may reduce the risk of damage to the upper extremities.

The third aim of the work was to report preliminary biometric data using BMW propulsion on a rough outdoor path and to compare these data with standard pushrim propulsion and walking. In the first three tests, three able-bodied participants, from 30 to 75 years in age, traversed a 1.06 km rough outdoor path at their self-selected brisk pace while walking, using standard pushrim propulsion and using BMWs in Run mode and top gear. On average, using BMWs reduced the circuit time to 41% of the time for standard pushrim propulsion, despite the additional 14 kg of weight and the increased friction in the BMW wheels. The participants could sustain an average travel speed of 2.6 m/s, which is close to jogging speed for ambulatory people [49]. In the fourth test, the participants traversed the same path using BMWs in Run mode at an average speed of 1.0 m/s (the average speed of standard pushrim propulsion). The cardiovascular effort for BMW propulsion was 56% of that for standard pushrim propulsion at the same speed. The biometric data are not precise; only three able-bodied participants were used and the wheelchair configuration was not optimised for the different sized participants. However, the findings suggest that cardiovascular effort for BMW propulsion in Run mode is much lower than for standard pushrim propulsion at the same speed.

The final set of biometric tests demonstrated the advantage of CSC during MWC propulsion. The participants first propelled the BMWs in Standard mode (pushrim propulsion mode) with CSC along the path and then propelled a standard MWC along the same path, without CSC. Despite the additional 14 kg of weight and the slightly increased friction from the BMW mechanism, the CSC reduced the average circuit time to 73% and all three participants reported that left and right arm fatigue was approximately equal and slight. Like all of the biometric test data reported here, these findings are limited by the small number of participants.

Conclusions

The standard MWC is light and manoeuvrable and is easy to use on even, smooth surfaces. It is more difficult to use on challenging paths, such as those with uneven and sloped surfaces, and extended pushrim propulsion can lead to repetitive strain injury. Other minor disadvantages are the user's hands getting dirty through contact with the pushrims and the user needs to apply friction to the wheel and pushrim for braking. The alternatives to standard MWCs use crank/lever, geared and power assist propulsion. Each of these offers both advantages and disadvantages. The crank type has less strenuous propulsion, but it is heavier, has poorer indoor manoeuvrability and is harder for transferring. Geared and power assist options allow users to access more challenging environments, but they are heavier and use pushrim propulsion, which may damage the upper extremity joints.

The bimodal wheel design described here is a novel alternative to the current MWC options. It switches between standard pushrim propulsion (Standard mode) and lever propulsion (Run mode) by furling and unfurling a handle and it has three gears in both modes. Run mode is used for travel over long distances outdoors or on challenging environments (such as ramps). In this mode, the user alternately pushes and pulls an ergonomic handle in a continuous, smooth cycle that propels the MWC forward. The design includes lever brakes and automatic anti-rollback when ascending sloped paths. The propulsive forces are much lower than those for standard pushrim propulsion and this may reduce the risk of joint damage. Preliminary testing indicates that in Run mode the user can travel outdoors at a jog pace. At a slower, sustained travel speed of 1 m/s on outdoor paths, Run mode requires considerably less cardiovascular effort than pushrim propulsion at the same speed. Standard mode is used indoors or when the user needs to reverse. It has the same pushrim propulsion and braking as the traditional MWC, but the addition of gearing makes it easy to use even for those with weaker arms. The bimodal wheels are heavier and wider than standard MWC wheels, but they do not affect manoeuvrability or transferring.

The novel design appears to facilitate wheelchair movement on challenging paths, and this has the potential to broaden the environments that wheelchair users can access. This, in turn, may benefit their health and quality of life through increased community participation and social interaction. A shortcoming of the research is that the biometric performance is based on very limited testing; just three able-bodied adult participants and one outdoor path. Further testing is needed to confirm the findings reported here and to assess the extent of any long-term health benefits to MWC users. Future work will look at the development of a paediatric version of the wheels and the development of an overdrive system, raising the top speed to 20 kph.

Notes

1. Omeo technology: https://omeotechnology.com/
2. https://www.cateye.com/intl/products/computers/CC-VL520/

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Author contributions

Rory C. Flemmer did the design and development of the novel propulsion mechanism with review by Claire L. Flemmer. Both authors contributed equally to the testing, writing and editing of the manuscript.

Disclosure statement

The authors disclose that they own intellectual property associated with this research and that they intend to commercialise the products developed in the research.

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Notes on contributors

Dr. Claire L. Flemmer is a Senior Lecturer at Massey University's School of Built Environment. Her primary research area includes improvements in the mechanical design of manual wheelchairs and in accessibility in the built environment. She is a member of the International Standards Organization ISO/T C 173 SC 1 Wheelchairs New Zealand International Review Group.

Dr. Rory C. Flemmer is a mechanical and chemical engineer, inventor and retired academic. He spent 20 years in the USA producing and patenting industrial robotic and artificial vision systems. He then moved to New Zealand, won the IP ENZ Innovator of the Year award, and has focussed on innovations in wheelchairs.

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