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Measurement of wheelchair rolling resistance with a handle bar push technique

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The purpose of this study was to evaluate a technique of pushing a wheelchair at the level of the handle bars as a method for measuring rolling resistance of wheelchair-user systems under different field conditions. Under standardized conditions on a motor driven treadmill, rolling resistance was determined using a 2D strain gauge-based push technique at the level of the handle bars and a commonly used 1D strain gauge-based wheelchair drag test using an adapted push wheelchair and ISO dummy at several velocities and using different push handle heights. After verification of the method, rolling resistance of six different floor surfaces was measured with the experimental push wheelchair in a centre for rehabilitation. Using an analysis of variance for repeated measures, small but significant differences in rolling resistance were found between the drag and push tests on a motor driven treadmill. Belt velocity and push handle height significantly affected rolling resistance. In the field study in the rehabilitation centre, tiles and tarpaulin had the lowest rolling resistance, while high piled carpet had the highest values. It is concluded that the wheelchair pushing method described in this study is usable for the determination of (relative) differences in rolling resistance of different floor materials if performed under standardized conditions and procedures, such as a stable velocity (within a small range of variation), using an ISO-dummy and a constant pushing handle bar height.

Introduction

Manual wheelchair propulsion is generally viewed as straining and inefficient [1,2]. The physical work capacity of wheelchair users is generally not high. Long-term wheelchair use seems to be associated with overuse injuries in the upper body, primarily shoulders and wrists [3–6]. It is therefore important that the external forces and power output, which the wheelchair user needs to generate during actual propulsion, are as low as possible.

One important way to minimize these external stresses is to reduce the resisting forces during wheelchair propulsion. These forces are generated in the interaction between the wheelchair and the environment. Theoretically, the total drag force (or external power output which is the product of external force times speed) during wheelchair propulsion consists of rolling resistance, internal friction in the wheelchair, air resistance and resistance due to inclination and other obstacles. Rough and uneven surfaces, obstacles, curbs, ramps and side slopes clearly are physically straining, not only from a purely mechanical perspective [7–13], but also from a physiological standpoint [14–16].

Additionally the wheelchair itself plays an important role in the experienced strain and comfort of propulsion [17]. During propulsion on flat surfaces in daily wheelchair use, rolling resistance will generally be the dominant resisting force (at higher speeds this role is overtaken by air resistance [18,19]). As far as the wheelchair-user system is concerned, rolling resistance depends on a number of wheel and tyre related characteristics, i.e. tyre pressure, form, surface and material of the tyre, wheel diameter, castor shimmy, wheel alignment and toe-in/toe-out, but also on wheelchair and occupant characteristics, such as weight and weight distribution [2,10,19–28]. A review of wheelchair rolling resistance from a more theoretical as well as empirical perspective is presented by Kauzlarich [29].

As stated above, rolling resistance is also highly dependent on environmental characteristics, i.e. the nature of the floor surface and material [19,20,30]. Physical strain and energy cost not only vary considerable with different obstacles [16], but also with different floor surfaces and materials, as was already suggested with straightforward cardio-respiratory experiments by Wolfe *et al.* [14], Glaser and Collins [31] and Glaser *et al.* [15].

Understanding the effect of floor surface on rolling resistance is therefore of practical relevance to designers of the built environment. Also, a ready to use technique may help evaluate different (and newly developed) floor surfaces. Different methods for measurement of rolling resistance in wheelchairs have been used in the literature, including wheelchair drag tests, most frequently used in association to wheelchairs

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on a treadmill [1,20]; deceleration or coast down tests with [8,32] or without [33–35] the use of accelerometry; or wheelchair push technique [15,30,31]. A fairly recent, highly versatile technique that (also) can be used to measure rolling resistance under practical conditions or in the lab is the instrumented wheel [11–13], but this is a very costly and, for this purpose, over-dimensioned technology.

More sophisticated strain gauge-based laboratory techniques are also used, in combination with a treadmill or rotating drum, to evaluate effects of wheel and tyre materials [19,22,29], but also bearing friction—which essentially can be defined as internal friction—onto rolling resistance. Internal friction is not only a consequence of bearing resistance, but also of deformation of the wheelchair frame (components), and cannot be separated from rolling resistance in experiments where complete wheelchair–user combinations are tested†. To evaluate the rolling friction of a complete wheelchair–user combination on different floor surfaces and variable terrain conditions in the field, the strain gauge based instrumented handle bar, as previously described by Glaser and colleagues [15,30,31], seems very appropriate. Glaser *et al.* were the first to use a uni-dimensional strain gauge based handle bar technique to evaluate effects of different floor surfaces on rolling resistance. They also used the technique to determine external power output in wheelchair exercise experiments on different tracks. However they did not systematically study the validity and reliability of this technology. Although mentioned in [30] as possible confounders, they did not systematically evaluate handle bar height or velocity effects, as far as the current authors know. Also, the strain gauge was uni-dimensional and it was not possible to evaluate the effect of a vertical force component.

The major purpose of the current study is therefore to evaluate the usability of a two-dimensional strain gauge-based wheelchair handle bar push technique and to measure rolling resistance (and the vertical force component) of different floor surfaces in a rehabilitation centre under realistic daily use conditions. This study has therefore the following main objectives:

- To evaluate the usability of the wheelchair handle bar push method for determination of the wheelchair drag force, and its two dimensional components. For this purpose, the two-dimensional strain gauge-based push technique was used on a motor driven treadmill and results were compared with the results of a more common wheelchair drag test with the same wheelchair set-up.
- To evaluate effects of different velocities and slopes of the treadmill in the handle bar push technique push (and wheelchair drag) tests.
- Since handle bar height may affect the direction of the push force in the plane of ambulation, especially influencing the vertical force component, different push handle heights were evaluated in the wheelchair push technique.
- The magnitude and variation in rolling resistance of six different floor surfaces in a rehabilitation centre was subsequently evaluated with the wheelchair push technique for the horizontal and vertical force components.

† *Rolling resistance will be used as the outcome of both the wheelchair push and wheelchair drag tests. Thus, rolling friction as well as internal friction components, are included in this measure.*

Methods

To evaluate the consistency of the wheelchair push handle technique for the determination of rolling resistance, a wheelchair push and a wheelchair drag test were performed on a motor-driven treadmill. Rolling resistance is defined as the required push (F_{push}) or drag force (F_{drag}), that has to be exerted parallel to the floor surface and in the line of coasting of the wheelchair.

To evaluate the possible effect of velocity of the treadmill belt upon F_{push} and F_{drag}, both tests were conducted at velocities of 0.28 m, 0.56, 0.83, 1.11, 1.25 and 1.39 m s^{-1}. Each test was repeated three times to obtain a more accurate estimate.

Subsequently, the effect of push handle height on rolling resistance was determined on the treadmill at five different push handle heights (0.9, 1.0, 1.1, 1.2 and 1.3 m from the floor) and at a velocity of 1.25 m s^{-1}. Based on the results of these tests, the field measurements for the rolling resistance of different floor surfaces in the rehabilitation centre were conducted with the wheelchair push technique.

Theory

Theory of rolling resistance in the context of the current study is fairly simple. Rolling resistance can be described as:

$$F_{roll} = cN \quad \text{(N)} \qquad (1)$$

where c is the coefficient of friction and N is the normal force; in wheelchairs c is dependent on tyre and floor characteristics. Frequently the important role of wheel diameter (r) leads towards a somewhat modified equation 1:

$$F_{roll} = c_w r^{-1} N \quad \text{(N)} \qquad (2)$$

Since wheelchairs have different characteristics for the front and rear wheels, F_{roll} in equation 1 can be extended to:

$$F_{roll} = c_f N_f + c_r N_r \quad \text{(N)} \qquad (3)$$

When propelling up an incline, the total drag or push force becomes:

$$F_{drag/push} = F_{roll} + mg\sin(\alpha) \quad \text{(N)} \qquad (4)$$

where gravitational acceleration (g) acts upon the total mass (m) of wheelchair and occupant under the angle of inclination (α) of the treadmill.

For a more thorough discussion of the theoretical concepts underlying the physics of rolling resistance, the reader is referred to [29].

Experimental wheelchair

All tests were conducted with a standard attendant push wheelchair that was modified to accommodate the measurement equipment (figure 1). The experimental wheelchair was a typical attendant push wheelchair (type: Poirier 3A-42; mass: 30 kg; front castor wheel: radius = 0.1 m, width = 0.05 m; rear wheel: radius = 0.15 m, width = 0.06 m; tyre pressure front: 400 kPa, rear: 250 kPa). A speedometer (Shimpo DT-4AG) was mounted to the right rear wheel. Every two seconds the velocity of the wheelchair was displayed. During the field measurements the displayed velocity values were dictated on an audiotape and used to verify the consistency of the push velocity during the field experiment. The wheelchair was loaded with a 75 kg standardized dummy in reference to ISO/DIS 7176-11 [36].

Force transducers

A two-dimensional strain gauge-based force transducer was fixed to the frame at the back of the wheelchair. The transducer was fixed in the sagittal plane such that it measured both the horizontal (F_x, i.e. F_{push}) and vertical force components (F_z). A uni-dimensional strain gauge-based force transducer on the treadmill measured F_{drag}, parallel to and in the middle of the belt of the treadmill. Prior to each experiment the force transducers were calibrated statically with a set of reference weights. Calibration equations were obtained through linear regression analyses.

During the experiments the force transducers were connected to bridge amplifiers, an analogue filter (Krohn Hite) and an Olivetti microcomputer. The analogue signals of the force transducers were amplified and low-pass filtered (18 dB/octave) at a cut-off frequency of 25 Hz (Krohn-Hite). Subsequently, the signals were digitized by a 12-bit AD converter and processed with an Olivetti PC. The signals were sampled at 100 Hz at an interval of 5 seconds. Data of the measured forces were filtered afterwards with a digital low-pass second-order Butterworth filter with a cut-off frequency of 0.4 Hz.

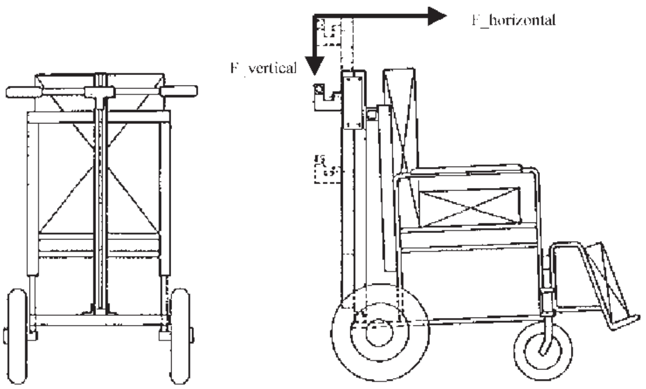

Figure 1. Experimental attendant push wheelchair with the height adjustable handle bar, equipped with a two-dimensional strain gauge-based force transducer. The forces acting on the wheelchair during the push test are exemplified.

Treadmill

The push tests and drag tests were conducted on a motor driven treadmill (Enraf Nonius 3446; 1.25 × 3.0 m) at 10 different slopes, ranging from 0.38 to 3.66 degrees. The drag test was conducted as previously described by van der Woude *et al.* [1] with the experimental wheelchair-dummy combination fixed (at 0.3 m from the floor) with a rope (10% elasticity; [37]) to the force transducer. The transducer hinged in the horizontal plane to a height-adjustable bar that was fixed to the frame of the treadmill [1].

The wheelchair push tests were conducted by the trained experimenter (male, 25 years; body mass: 70 kg; length: 1.83 m; shoulder height: 1.51 m), who pushed the wheelchair at the handle bar bimanually at the speed of the treadmill belt. During the push tests the two-dimensional force transducer was fixed to an adjustable frame at the back of the experimental wheelchair. To avoid a vertically directed force component as much as possible, the left and right hands applied a symmetrical and horizontal force in the walking direction onto the handle bar through two pointers that were held between index finger and thumb. A similar set-up and procedure was used in the field tests.

The push and drag force at 0 degrees slope was defined as rolling resistance (F_{roll}), but obviously includes internal friction components of the wheelchair. Based on previous experience [1] in wheelchair drag tests (and given the inherent instability of the wheelchair during a drag test on the treadmill at a zero slope) the resistance force at zero degrees is not measured directly, but determined through extrapolation on the basis of a linear regression analysis on the measurements at the slopes from 0.38 to 3.66 degrees.

Field tests

The effect of floor surface in the Rehabilitation Centre Amsterdam (RCA) on rolling resistance was evaluated in a series of push tests on six different floor surfaces at a fixed handle height and within a fixed velocity range. All push tests were conducted with the same experimenter who conducted the treadmill tests. Before testing, the experimenter was made familiar with the testing procedure and conditions and was trained in a steady and more or less fixed walking pace and horizontal push direction. All experiments were conducted indoors and at a low but comfortable and steady walking velocity to reduce effects of air resistance and an instable walking pattern. The experimenter repeatedly pushed the wheelchair with dummy across the six different surfaces in six different areas of the centre: tiles (café), tarpaulin (fitness), low pile carpet (corridor), vinyl (gym), high pile carpet (entrance) and tarpaulin (living). Where possible, the wheelchair was pushed up and down so that the even and odd trials were in opposite direction to each other in an attempt to compensate for variations within a given floor surface. In every trial the wheelchair was pushed across the same section of the surface. The experimenter received audible feedback on the velocity of the wheelchair. Also, a metronome was used to help the subject to maintain a given step frequency and thus a more or less constant pushing velocity between 1.11 and 1.25 m s^{-1}. The frequency of the metronome was the same as the preferred step frequency of the experimenter on the treadmill at a velocity of 1.25 m s^{-1}. The signals of the force transducer were measured at the moment that the wheelchair reached a more or less constant velocity. Each floor surface was tested with a minimum of forty times. Afterwards a selection of the most stable trials was made, based on the quality of the signals: a more or less constant velocity during the interval of measurement, between 1.11 and 1.25 m s^{-1}.

Statistics

Apart from descriptive statistics, linear regression analyses were used for the calibration data as well as to relate slope and force in the treadmill push and drag tests, using equation 4. As stated above, the rolling resistance on the treadmill was thus estimated as the force at zero degrees slope (the intercept in equation 4), according to van der Woude *et al.* [1].

The influence of velocity and push handle height on push force and drag force were tested by means of an analysis of variance for repeated measures. The level of significance for all tests was $p < 0.05$.

Results

Instrumentation

The linearity of the force transducers appeared to be good ($r^2 = 0.998$). The resolution of the AD conversion during sampling was 0.17 N bit^{-1} in the horizontal direction and 0.51 N bit^{-1} in the vertical direction with a calibration range of 193 N. The cross talk between the vertical and horizontal force of the two-dimensional force transducer was low: less than 1% when a mass of 19.7 kg was imposed purely horizontally or vertically. The uni-dimensional transducer for the drag test on the treadmill had similar quality characteristics. Moreover, based on a repeated coast down test (5 ×) [33], the directional stability of the instrumented wheelchair with test dummy appeared to be good.

Push test versus drag test

The analysis of variance for repeated measures (main factors $F_{drag/push}$ and speed) for the drag and push tests on the treadmill showed significant main effects for the factors F_{push}/F_{drag} ($p < 0.000$; figure 2), speed ($p = 0.05$), as well as for the interaction term ($F_{push}/F_{drag} \times$ speed) ($p < 0.000$).

The difference between drag and push force, averaged over the different speeds, is to the benefit of the drag test over the whole range of slopes. At zero degrees of slope the estimated F_{roll} for the drag test (= 10.8 N ± 0.8) is 1.3 N lower than push test (= 12.1 N ± 2.1), a 10.7% difference. F_{roll} in the drag test ranged from 9.7 to 11.7 N and from 9.0 to 14.5 N in

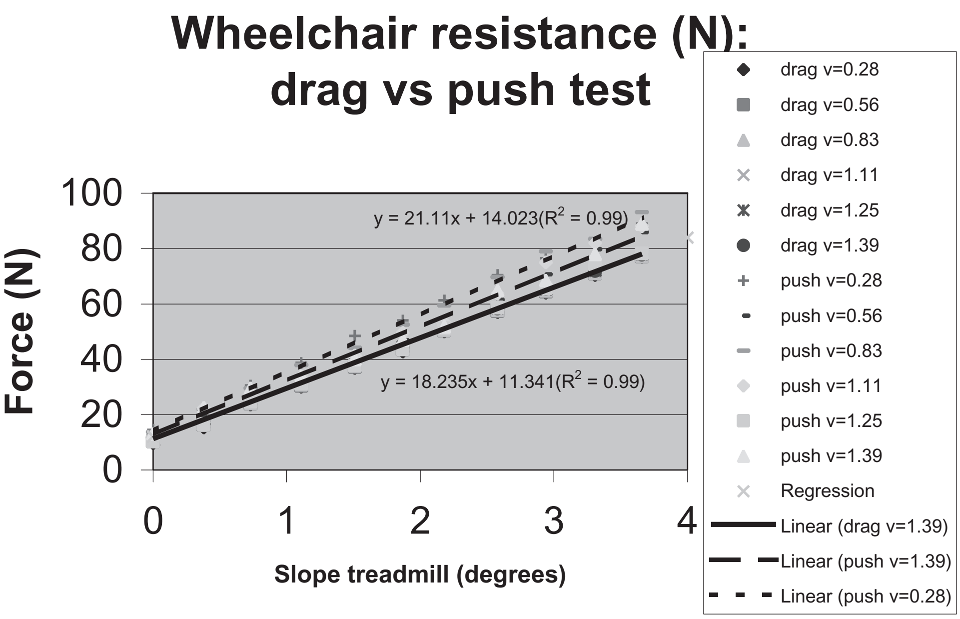

Figure 2. Results of drag and push test on the treadmill in relation to slope and speed of the treadmill. Three typical trendlines (linear regression; two for the push and one for the drag test) and their significance are shown.

the push test for the different velocities. F_{roll} in the push test expectedly showed a systematically larger variance compared to the drag test, as is expressed in the standard deviation (ranging from 0.3 to 0.8 for F_{drag} vs. 2.1–5.0 for F_{push} at the different slopes on the treadmill). For the drag test a slight but systematic increase in F_{drag} is seen with increasing velocity, whereas this trend is less consistent for the push test. Over the range of slopes a systematically increasing difference is seen between the mean F_{push} and F_{drag} ($r = 0.96$), ranging from 1.3 N at zero slope (F_{roll}) to 9.7 N at the highest slope of 3.66°, averaged over speed.

F_z *versus* F_x

The average vertical component (F_z) during the push test ranged between 0.5 N and 7.4 N over the different slopes and speeds and also appeared significantly related to speed (figure 3). Overall, however, this component was not larger than 1% of the total mass of the wheelchair and dummy (105 kg). It was hypothesized that the resistance force measured during the push test can be considered as being mainly rolling resistance if the vertical push force component is less than 1%.

Handle bar height

Based on the personal preference of the experimenter the tests at the different handle heights were conducted at $v = 1.25$ m s^{-1} of the treadmill. At zero degrees slope, F_{push} was 10.2 N (± 2.5 N) at a velocity of 1.25 m s^{-1} and a push handle height of 1.2 m. The mean vertical component for all handle bar heights was 0.9 N. The mean F_z for all handle bar heights and slopes was 3.3 N (± 1.4 N). As was to be expected, push handle height had a significant effect on the horizontal push forces ($p < 0.05$). At zero degrees the push force at a handle height of 0.90 m was the lowest, but only slightly less than at the 1.1 and 1.3 m height (table 1). In terms of F_z, the 1.0 m condition proved the least consistent.

Based on the results a push handle height of 1.20 m was selected for the field studies: at this handle height the vertical push force component was the smallest and the experimenter indicated that this height was his personal preference.

Field tests

The field tests were conducted with the push technique and similar to the procedures on the treadmill. Six different floor surfaces in the RCA were evaluated within a velocity range of 1.11–1.25 m s^{-1} and at handle height of 1.2 m.

The total number of trials on each of the different floor surfaces in the RCA was 70 with the exception of the floor surfaces in the cafe and fitness room, where respectively 50 and 40 trials were performed. Where possible, the measurements were conducted in two directions over the same trajectory. In the cafe and

Table 1. Effect of handle height (0.9–1.3 m from the treadmill surface) on the horizontal (Fx) and vertical force (Fz) components at zero degrees of slope.

Handle bar height (m)	F_x at zero degrees (F_{roll} (N))	F_z at zero degrees (N)	Mean F_z for all slopes
0.9	9.5 ± 1.3	− 0.8 ± 1.0	− 8.6 ± 2.9
1.0	10.5 ± 0.3	− 5.0 ± 3.4	2.0 ± 14.4
1.1	9.6 ± 0.9	+0.2 ± 0.7	− 4.4 ± 1.2
1.2	10.2 ± 2.5	+0.9 ± 0.4	− 3.3 ± 2.7
1.3	9.6 ± 2.3	− 0.0 ± 0.6	− 2.0 ± 1.1

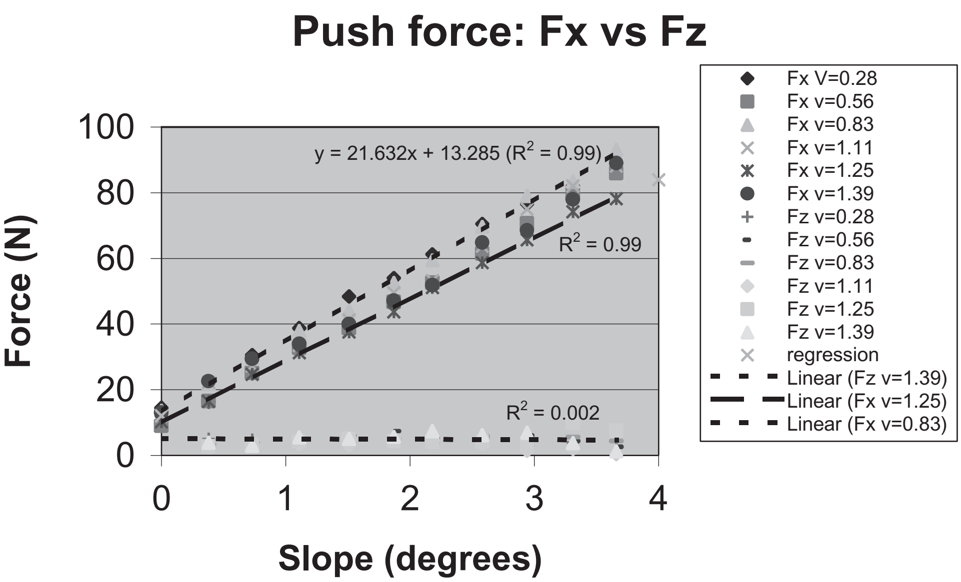

Figure 3. The horizontal (F_x) *and vertical force* (F_z) *components during the push test on the treadmill at different slopes and speeds. Three typical trendlines (linear regression; two for* F_x *and one for* F_z) *are shown with their characteristics.*

entrance the measurements were made in one direction only because of lack of space. Due to the selection criteria of valid runs—predominantly too much variation in velocity—only 10% of the trials could be taken into account. The mean rolling resistances of six different floor surfaces are presented in figure 4.

On the high pile carpet in the entrance, it was very difficult to push the wheelchair in a straight line and with a constant velocity. Subsequently, the vertical push force was considerably larger under this surface condition: more than 10% of the horizontal push force, but only 0.3% of the total weight of the wheelchair with dummy. The tarpaulin or linoleum in the 'living' was somewhat uneven, but this apparently had no effect on the standard deviation.

Rolling resistance (F_x or F_{push}) of tile and tarpaulin in the living was the lowest. Tarpaulin and low pile carpet had an almost equal mean value between 16 and 17 N. F_{push} of high pile carpet was approximately 3 times higher than tarpaulin in the living and tile. The rolling resistance of the vinyl floor in the gymnasium was higher than expected (20.3 N $\pm$ 1.2) and appears the second to most straining of all floor surfaces.

Based on the equation for rolling resistance and the mass of wheelchair and dummy the mean rolling friction coefficient c ($F_{roll} = cN$); [22] for the different floor surfaces ranged from 0.0105 for tarpaulin in the living to 0.0292 for the high pile carpet.

Discussion

Instrumentation

The wheelchair drag test on a motor driven treadmill is frequently used as part of a protocol of wheelchair exercise experiments as well as in studies that evaluate aspects of vehicle mechanics of wheelchairs [1,2,20,22,37]. The drag test, in combination with wheelchair exercise experiments, will determine external power output (the product of the drag force and the actual belt velocity) as a measure of performance, or—in association with oxygen uptake—a measure for gross mechanical efficiency [2]. When conducted accurately, different mechanical characteristics of wheelchair design and material can also be evaluated with a treadmill drag test (i.e. weight, weight distribution, camber, toe-in/out, wheel size and alignment, tyre characteristics, and also effects of maintenance [2]). Obviously, treadmills also allow simulation of different ramps. A treadmill is, however, hard to use for the study of rolling resistance of different surface materials. A wheelchair push technique at the level of the handle bars was experimentally introduced by Glaser *et al.* [15,30]. However no detailed analyses of reliability and validity of this technique for determination of rolling friction were performed. A similar handle bar push technique was later used by van der Woude *et al.* [38] to evaluate the mechanical strain onto the upper body through biomechanical modelling of different handle bar heights in wheelchair pushing. This same device was used in the current study on the treadmill and in the field tests.

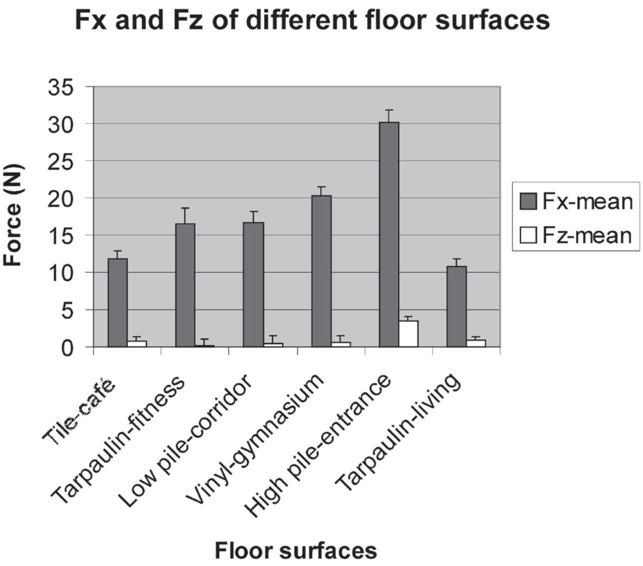

Figure 4. Mean and standard deviation of the horizontal (F_x) *and vertical* (F_z) *force components for different floor surfaces in the RCA.*

Given the relative mobility of the experimental set-up, the major advantages of the push technique in determining resisting forces of different floor surfaces on the experimental wheelchair—especially after implementing suggested modifications—include the possibility to provide quick results, and to measure rolling resistance in many different field conditions. The technology basically uses a two-dimensional force transducer and additional electronics, thus is quite cheap. The current equipment proved technically appropriate for the tests on the treadmill as well as in the field tests, but the current set-up was not highly practical. For data acquisition, there was a fixed (extended) cable connection between the force transducers and the electrical and computer equipment. Although giving sufficient manoeuvrability for the current experiments, it does not allow free movement of the push wheelchair in field experiments. This would require for instance a battery-based data logging system, mounted to the wheelchair, which are available on the current market today, also in the context of rehabilitation (engineering) [39]. The feedback of the walking velocity in the current study should be improved in terms of direct visibility for the experimenter.

The handle bar push technique clearly has its limitations, however. The experimenter must be experienced and very aware of the importance of the different requirements of 'a good push technique' (horizontal, stable and constant velocity, especially on soft floor surfaces). A relatively long track is required to accelerate and decelerate the wheelchair and maintain a constant velocity for a sufficiently long trajectory in between. Despite the expertise of the experimenter in the current study, many trials are needed to obtain a sufficient number of acceptable trials to generate an average resisting force. The attachment of the measurement frame to the wheelchair affects the characteristics of the wheelchair to some degree by a shift of the centre of gravity and an increase of the total mass. This will have affected the results of the push technique to some extent—both with respect to F_x and F_z. For future experiments, light weight and overall reduction of material will help reduce the effect on rolling resistance. Clearly, the current absolute results can only be applied to this wheelchair/experimenter combination and as an indication of rolling resistance of different floor surfaces in relation to each other. The relative values for instance with respect to the more common material like tarpaulin or linoleum are certainly indicative.

An alternative for measurement of rolling resistance of wheelchair characteristics as well as different floor surfaces is the coast down technique [33–35]. Practical use however requires a horizontal surface, a stable wheelchair and accurate measurement of the distance travelled as well as of the velocity changes during that trajectory. Moreover, speed must be limited to exclude effects of air resistance [18,40,41]. Currently, a good alternative technique to measure manual wheelchair rolling resistance is the instrumented wheel. This technology is not only expensive but also requires sophisticated data processing and is therefore not widely available or applicable. It will however enable the measurement of rolling friction during actual wheelchair propulsion under virtually all conditions [5,11–13]. As well as measurement of rolling resistance and obstacle forces, they can be used to study propulsion technique and mechanical strain to the upper extremity.

Other resisting forces

The force needed to push a wheelchair on a smooth surface with a constant velocity is dependent on rolling friction, internal resistance, air drag and resistance due to an inclination. Air resistance is absent during the measurements on the treadmill. The remaining resisting forces are measured in both the drag and the push test. Based on the figures at the different slopes of the treadmill the resistance at zero degrees slope was extrapolated through linear regression. Direct measurement of the drag force at zero degrees slope is not common, since the hand rim wheelchair is rather unstable in the medio-lateral direction at zero degrees slope, which makes accurate measurement difficult [1].

As stated above, strictly speaking the measured push force consists of the internal friction (bearing, frame deformation) and the rolling resistance. According to Frank and Abel [22] however, bearing resistance can be assumed negligible (0.001 of the friction coefficient) if the bearings are in good condition and properly adjusted and lubricated. Effects of frame deformation are difficult to determine and will have be minimal in the current experimental wheelchair, since the folding mechanism of the chair was ‘overruled’ by the frame for the push handle bar that was securely fixed to the (back rest) frame of the chair.

In the field experiment the air drag was considered to be negligible since the measurements were performed indoors and again at a relatively low velocity [22]. Air resistance is defined by frontal plane area, air density and the drag coefficient and the square of air velocity. While Hedrick *et al.* [40] evaluated different posters—and thus frontal plane area—in relation to wheelchair drag in coast down tests, Coe [18] performed a wind tunnel experiment with a wheelchair. Coe indicated that at a speed of close to 2.5 m s^{-1}, air resistance equals rolling drag and due to its squared dependence, air speed increases exponentially with riding speed. At speeds little above 1 m s^{-1} air resistance will be limited to 1 N or less [42]. At a speed of 5 m s^{-1}, air resistance was estimated to be around 14 N.

Push test versus drag test

From experience in the current experiments it may be concluded that the push technique in its current technical form may not be highly practical, but it is certainly usable. One should indeed bear in mind, that in order to generate useful data, the current tests required a considerable degree of experience from the experimenter as well as standardization and control of (walking) speed, dummy positioning and force application. Despite the measures of standardization taken, a more than two-fold higher standard deviation was observed for the overall F_{push} versus F_{drag} at zero degrees slope(2.1 versus 0.8 N). This indicates that the push technique indeed is less reproducible than the drag test. Also despite the measures of standardization, an (overall) small vertical component in the push force is still hard to prevent—both in the more controlled conditions on the treadmill as well as in the field tests—due to the nature of human posture and movement. As a consequence of that and possibly other causes, a relatively small but significantly higher F_{push} is seen on the treadmill compared to the F_{drag} (on average 1.3 N, i.e. 10.7% of F_{push}). The small but systematic difference in drag and push resisting force may be explained in two ways.

The vertical force component in the push test essentially will enhance the resisting force since it acts perpendicular to the floor surface and thus will lead to a small increase in the reaction force of the floor to the tyre and thus to rolling resistance (see forces and torque in figure 1).

Moreover, the horizontal component of the push force is applied at a level above the rear wheel axis. This force will generate a (small) torque around the rear wheel axis, which will lead to an additional (small) reaction force of the floor to the smaller castor wheels, thus increasing the rolling friction force of the smaller castor wheels (the smaller air filled tyres of the front castors essentially will have a higher rolling resistance at equal levels of loading). In the drag test the cord was fixed to the frame of the wheelchair little above the rear wheel axis (0.3 m from the floor) and thus has a much smaller moment arm. Theoretically, this results in a smaller additional torque around the wheel axis that acts onto the castor wheels.

Handle bar height

The same combination of the applied push force and the moment arm with respect to the rear wheel axis explains the significant effect of handle height upon the resisting force. Above that, the height of the handle bar seems associated with a gravitational effect of the trunk, head and arms. Glaser *et al.* [30] made the assumption, after only a small pilot, that the push force was unaffected by the height position of the force transducer. Their pilot was conducted, however, on a horizontal surface while in the current study the effect on pushing height was determined on a treadmill at several inclines up to 3.66°. van der Woude *et al.* [38] also did not find a significant difference in the horizontal push force between five pushing heights in the task of pushing the attendant wheelchair on a flat surface. The main difference between their study and this study was that not only the task differed, but also that the subjects were not instructed to push as horizontal as possible and the subjects were not required to push with a constant velocity. In the task in which the wheelchair had to be pushed up on an inclined surface, a significant effect of pushing height on the push force was found. An explanation for this effect can be found in the fact that the distance between the rear (rotating) axis and the force transducer (moment arm) increases as the pushing height increases. Due to the torque around the centre of the rear wheels, which will increase with handle height, the front wheels are increasingly loaded and a larger resistance of the smaller front castor wheels will be the consequence.

Velocity effect on the treadmill

In contrast to the theory of rolling resistance, in the current results a significant effect of velocity was found on the treadmill, both for the drag test and the push technique. The theory of rolling resistance however holds for ideal testing conditions, which evidently is not the case here. Frank and Abel [10] also found a velocity effect while determining rolling resistance of a wheelchair on a treadmill.

The effect of velocity on the results of the push test seem partly associated with the greater constraints that are imposed upon the experimenter and his 'push' technique, which may introduce larger perturbations of force application and thus deviations of applied forces to control the task and the wheelchair-dummy combination with increasing belt velocity. Above that the step frequency of the experimenter goes up with speed, introducing a more frequent impact on the belt surface. Also the effects of un-roundness of the wheels as well as the roughness of the belt surface and tyre surface will increase over time with increasing belt velocity and as such may influence the impact on the rolling characteristics of the tyres and thus the resisting force. These factors will influence the rate of deformation of the tyre and belt/floor surface material and thus have an impact on the degree of hysteresis that is primarily responsible for the phenomenon of rolling resistance [26].

Above this level, the trail of the castor wheels may be affected by the irregularities of the belt surface and the perturbations of the belt surface by the experimenter. For instance, a slight increase in the degree of castor shimmy has a considerable effect on rolling resistance [25]. These experimenter-related causes may affect resisting forces in the push test and partly explain the differences seen between the drag and push technique.

Clearly, speed conditions must be standardized in both the drag and push technique for the measurement of rolling resistance, especially in the field test.

Field test

The trials in the RCA were conducted on a flat surface. Effects of an uneven floor surface were outbalanced as far as possible by taking the trials in both directions. This was however not always possible. This will have affected the F_x and F_z values for the various surfaces to some, unknown, extent.

When interpreting figures from the field test, it clearly needs to be taken into account that the push technique is a less standardized and thus cruder technique to determine the resisting force of a wheelchair. To reach an acceptable data sample in the field test, a large number of repetitions were needed to finally have a sufficiently large number of trials to met the inclusion criteria. Indeed, only 10% of the field test measurements were included in the analysis, since the majority of the trials did not meet the inclusion criteria of a stable velocity within the boundaries of 1.11 and 1.25 m s^{-1}. Despite this, the standard deviations seen for the different floor surfaces overall still only vary between 1 and 2 N, i.e. 10 to 20% of F_{push}. Despite all the technical and experimental limitations one may conclude that the push technique renders information closely mimicking the resistance force experienced during the pushing of a wheelchair.

As expected the tile and tarpaulin in the living surface had the lowest rolling resistance and the high pile carpet the highest. Glaser *et al.* [30] found, pushing on a tiled surface, a rolling resistance of 11 N (total mass = 105 kg). In the present study rolling resistances of 10.8 and 11.9 N were found for tarpaulin (living) and tile, respectively. The high pile carpet was located at the entrance and had a cleaning function; the carpet piles work as brushes. This particular function not only causes steering problems, but also increases the rolling resistance.

Surprisingly, the rolling resistance in the gym was relatively high compared to the other surfaces. This floor surface consists of a quite soft and elastic material that helps to prevent injury in the event of a fall. Due to mobility related impairments, falling is a serious hazard for many patients in rehabilitation. Given their age and limited co-ordination, a fall can have serious physical consequences. A more elastic floor surface will help to prevent these.

The down-side is that wheelchairs will experience more resistance. This may impair different wheelchair users in their mobility. The maximal power output of subjects with tetraplegia is about 25 Watt [16]. This means that for these wheelchair users the maximal velocity on the gymnastic floor will be about 1.25 m s^{-1}. If only the rolling resistance is taken into account it can be argued that it is better to apply harder surfaces in a gymnastic room. However, in view of the fact that during wheelchair sports, like basketball and quad rugby, crashes are quite common, the protection function of a soft surface is useful for wheelchair users.

Conclusions

Horizontal resistance measured during a strictly standardized (push height, velocity, force direction training; vertical component less than 1% total weight) handle bar push test can be considered as a reasonable indicator of rolling resistance plus internal friction, and the described push method is a usable method to measure rolling resistance in field conditions. The results only hold for the current experimental wheelchair. With some adjustments—direct feedback of velocity and data logging in a unit on the wheelchair, but also the use of lightweight materials and reduction of materials for the push frame—the method will generate even more useful information on rolling drag.

Since pushing height and velocity had an effect on rolling resistance, both must be standardized in future experiments as well as in practical use later.

Comparing the six different floor surfaces, high pile carpet had the highest rolling resistance and tiles the lowest, more attention should be paid to floor surface as an environmental barrier for wheelchair users (especially in clinical situations).

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References

1. van der Woude, L. H. V., de Groot, G., Hollander, A. P., van Ingen Schenau, G. J., and Rozendal, R. H., 1986, Wheelchair ergonomics and physiological testing of prototypes. *Ergonomics*, **29,** 1561–1573.
2. van der Woude, L. H. V., Veeger, H. E. J., Dallmeijer, A. J., Janssen, T. W. J., and Rozendaal, L. A., 2001, Biomechanics and physiology in active manual wheelchair propulsion. *Medical Engineering and Physics*, **23,** 712–733.
3. Burnham, R. S., and Steadward, R. D., 1994, Upper extremity peripheral nerve entrapments among wheelchair athletes: prevalence, location and risk factors. *Archives of Physical Medicine and Rehabilitation*, **75,** 519–524.
4. Pentland, W. E., and Twomey, L. T., 1994, Upper limb function in persons with long term paraplegia and implications for independence (part I). *Paraplegia*, **32,** 211–218.
5. Boninger, M. L., Cooper, R. A., Baldwin, M. A., Shimada, S. D., and Koontz, A., 1999, Wheelchair pushrim kinetics: body weight and median nerve function. *Archives of Physical Medicine and Rehabilitation*, **80,** 910–915.
6. Boninger, M. L., Towers, J. D., Cooper, R. A., Dicianno, B. E., and Munin, M. C., 2001, Shoulder imaging abnormalities in individuals with paraplegia. *Journal of Rehabilitation Research and Development*, **38,** 401–408.
7. Wawzrinek, A., 1981, Rollstuhl am Hindernis: Ermittlung der erforderlichen Antriebs-momente. *Orthopaedie Technik*, **1,** 1–7 (in German).
8. Munaf, M., Wawzrinek, A., and Boenick, U., 1983, Experimentelle Ermittlung des Einflusses von Fahrbahnoberflaechen und Hindernissen auf die Beanspruchung von Rollstuhlen. *Biomed Technik*, **28,** 44–48 (in German).
9. Brubaker, C. E., McLaurin, C. A., and McClay, I. S., 1986, Effects of side slope on wheelchair performance. **23,** 55–58.
10. Frank, T. G., and Abel, E. W., 1989, Measurement of the turning, rolling and obstacle resistance of wheelchair castor wheels. *Journal of Biomedical Engineering*, **11,** 463–466.
11. Chesney, D. A., and Axelson, P. W., 1996, Preliminary test method for the determination of surface firmness. *IEEE Transactions in Rehabilitation Engineering*, **4,** 182–187.
12. VanSickle, D. P., Cooper, R. A., and Bonninger, M. L., 2000, Road loads acting on manual wheelchairs. *IEEE Transactions in Rehabilitation Engineering*, **8,** 371–384.
13. van Drongelen, S. A., Veeger, H. E. J., Angenot, E., van der Woude, L. H. V., and Janssen, T. W. J., 2002, *Mechanical strain in the upper extremity during wheelchair related activities.* (Cleveland: ISG).
14. Wolfe, G. A., Waters, R., and Hislop, H. J., 1977, Influence of floor surface on the energy cost of wheelchair propulsion. *Physical Therapy*, **57,** 1022–1027.
15. Glaser, R. M., Sawka, M. N., Wilde, S. W., Woodrow, B. K., and Suryaprasad, A. G., 1981, Energy cost and cardiopulmonary responses for wheelchair locomotion and walking on tile and on carpet. *Paraplegia*, **19,** 220–226.
16. Janssen, T. W. J., van Oers, C. A. J. M., Veeger, H. E. J., Hollander, A. P., van der Woude, L. H. V., and Rozendal, R. H., 1994, Relationship between physical strain during standardised ADL tasks and physical capacity in men with spinal cord injuries. *Paraplegia*, **32,** 844–859.
17. DiGiovine, M. M., Cooper, R. A., Boninger, M. L., Lawrence, B. M., VanSickle, D. P., and Rentschler, A. J., 2000, User assessment of manual wheelchair ride comfort and ergonomics. *Archives of Physical Medicine and Rehabilitation*, **81,** 490–494.
18. Coe, P. L., 1979, Aerodynamics characteristics of wheelchairs. NASA technical Memorandum 8019, NASA Scientific and Technical Information Branch, 1, Hampton, Virginia, pp. 1–17.
19. O'Reagan, J., Thacker, J., Kauzlarich, J., Mochel, E., Carmine, D., and Bryant, M., 1981, Wheelchair dynamics. In *Wheelchair Mobility 1976–1981*, edited by C. E. Brubaker and C. A. McLaurin, (REC, University of Virginia), pp. 33–41.
20. Bennedik, K., Engel, P., and Hildebrandt, G., 1978, *Der Rollstuhl. Experimentelle Grundlagen zur technischen und ergometrischen Beurteilung handbetriebener Krankfahrzeuge.* (Rheinstetten: Schindele-Verlag) (in German).
21. Brubaker, C. E., and McLaurin, C. A., 1982, Ergonomics of wheelchair propulsion. In *Wheelchair* III, edited by F. L. Golbranson and R. W. Wirta, (Bethesda: RESNA), pp. 22–41.
22. Frank, T. G., and Abel, E. W., 1993, Drag forces in wheelchairs. In *Ergonomics of manual wheelchair propulsion; state of the art*, edited by L. H. V. van der Woude, P. J. M. Meijs and de Y. A. Boer, (Amsterdam: IOS Press), pp. 255–267.

23. GORDON, J., KAUZLARICH, J. J., and THACKER, J. G., 1989, Tests of two new polyurethane foam wheelchair tires. *Journal of Rehabilitation Research and Development*, **26,** 33–46.
24. WEEGE, R. D., 1989, Aktiv-Rollstuhl: nicht nur für aktive Rollstuhlfahrher. *Med. Orth. Tech*, **109,** 170–176 (in German).
25. KAUZLAURICH, J. J., BRUNING, T., and THACKER, J. G., 1984, Wheelchair caster shimmy and turning resistance. *Journal of Rehabilitation Research and Development*, **20,** 15–29.
26. KAUZLARICH, J. J., and THACKER, J. G., 1985, Wheelchair tire rolling resistance and fatigue. *Journal of Rehabilitation Research and Development*, **22,** 25–41.
27. KAUZLAURICH, J. J., BRUNING 3RD, T. E., and THACKER, J. G., 2000, Wheelchair caster shimmy II: damping. *Journal of Rehabilitation Research and Development*, **37,** 15–29.
28. MCLAURIN, C. A., and BRUBACKER, C. E., 1991.
29. KAUZLARICH, J. J., 1999, Wheelchair rolling resistance and tyre design. In *Biomedical aspects of manual wheelchair propulsion: state of the art II*, edited by L. H. V. van der Woude, M. T. E. Hopman and C. van Kemenade), (Amsterdam: IOS Press), pp. 158–172.
30. GLASER, R. M., STEVEN, R. C., and STEPHEN, W., 1980, Power output requirements for manual wheelchair locomotion. *NAECON, IEEE*, 502–509.
31. GLASER, R. M., and COLLINS, S. R., 1981, Validity of power output estimation for wheelchair locomotion. *American Journal of Physical Medicine*, **60,** 180–189.
32. BOOSFELD, C., 1988, Messung der Belastung von Rollstuehlen im Labor und Feld mit einem ortsunabhaengigen Mikrocomputer-system, Biomedizinische Technik, Forschungsberichte fuer die Praxis Band I Schiele & Schoen. (in German).
33. MCLAURIN, C. A., 1983, *Determination of rolling resistance of manual wheelchairs*. (University of Virginia).
34. FRANK, T. G., and ABEL, E. W., 1988, A technique for the accurate measurement of low values of rolling resistance. *Proceedings of the Institute of Mechanical Engineering*, **202,** 251–255.
35. SAWATZKY, B. J., DENISON, I., and KIM, W. O., 2002, Rolling, rolling, rolling. *Rehab Management*, **9,** 36–39, (www.rehabpub.com/features/892002/7.asp).
36. ISO, 1992, *Wheelchairs Part 11: Test dummies*. International Standard ISO-7176-11.
37. MOLINO, L., 1992, *Use of a treadmill to determine the force required to roll a wheelchair*. (Baltimore: Department of Veteran Affairs, Prosthetics Assessment and Information Centre).
38. VAN DER WOUDE, L. H. V., VAN KONINGSBRUGGEN, C. M., KROES, A. L., and KINGMA, I., 1995, Effect of push handle height on net moments and forces on the musculo-skeletal system during standardized wheelchair pushing tasks. *Prosthetics and Orthotics International*, **19,** 188–201.
39. BUSSMANN, J. B., HARTGERINK, I., VAN DER WOUDE, L. H. V., and STAM, H. J., 2000, Measuring physical strain during ambulation with acelerometry. *Medicine and Science in Sports and Exercise*, **32,** 1462–1471.
40. HEDRICK, B., WANG, Y. T., MOEINZIDAH, M., and ADRIAN, M., 1990, Aerodynamics positioning and performance in wheelchair racing. *Adapt Phys Act Quart*, **7,** 41–51.
41. HIGGS, C., 1992, Wheeling in the wind: the effect of wind velocity and direction on aerodynamic drag of wheelchairs. *Adapt Phys Act Quart*, **9,** 74–87.
42. ABEL, E. W., and FRANK, T. G., 1991, The design of an attendant push wheelchair. *Prosthetics and Orthotics International*, **15,** 38–45.