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Trunk motion influences mechanical power estimates during wheelchair propulsion

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ABSTRACT

In wheelchair sports, there is an increasing need to monitor mechanical power in the field. When rolling resistance is known, inertial measurement units (IMUs) can be used to determine mechanical power. However, upper body (i.e., trunk) motion affects the mass distribution between the small front and large rear wheels, thus affecting rolling resistance. Therefore, drag tests – which are commonly used to estimate rolling resistance – may not be valid. The aim of this study was to investigate the influence of trunk motion on mechanical power estimates in hand-rim wheelchair propulsion by comparing instantaneous resistance-based power loss with drag test-based power loss. Experiments were performed with no, moderate and full trunk motion during wheelchair propulsion. During these experiments, power loss was determined based on 1) the instantaneous rolling resistance and 2) based on the rolling resistance determined from drag tests (thus neglecting the effects of trunk motion). Results showed that power loss values of the two methods were similar when no trunk motion was present (mean difference [MD] of 0.6 ± 1.6 %). However, drag test-based power loss was underestimated up to −3.3 ± 2.3 % MD when the extent of trunk motion increased (r = 0.85). To conclude, during wheelchair propulsion with active trunk motion, neglecting the effects of trunk motion leads to an underestimated mechanical power of 1 to 6 % when it is estimated with drag test values. Depending on the required accuracy and the amount of trunk motion in the target group, the influence of trunk motion on power estimates should be corrected for.

1. Introduction

In manual wheelchair propulsion, wheelchair athletes produce mechanical power to overcome resistance forces and to accelerate their wheelchair (van Dijk et al., 2023; van Ingen-Schenau and Cavanagh, 1990). Mechanical power is therefore crucial to performance in wheelchair sports. In addition, monitoring mechanical power on a regular basis can provide insight into training load, physical capacity, and fatigue, which is useful for coaches, athletes, and sport scientists. During hand-rim wheelchair propulsion, mechanical power can be monitored by determining the power lost due to resistance forces and the change in kinetic energy (de Vette et al., 2022; van Ingen-Schenau & Cavanagh, 1990).

To determine resistance force and, consequently, power during ergometer-, treadmill- and wearable sensor-based measurements of wheelchair propulsion, drag or deceleration tests are commonly used (de Groot et al., 2013; de Klerk et al., 2020; Mason et al., 2014; van der Woude et al., 1986; Veeger and van der Woude, 1989). However, in our previous study, deviations of −4.6 to 0.9 % were found between the drag test-based resistance force and the reference resistance force (van Dijk et al., 2023). Also, deviations were much larger for some participants than for others. As during drag tests, the user is instructed to maintain a static position (Rietveld et al., 2021), while during wheelchair propulsion most wheelchair users incline their upper body – mainly trunk –

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within a push cycle, these deviations may be due to the (neglected) effects of trunk motion on the rolling resistance (Sauret et al., 2013). In this regard, larger deviations are expected when larger trunk inclinations are observed. However, the relation between trunk motion and deviations in rolling resistance (and thus power) estimates during wheelchair propulsion is not yet known.

During wheelchair propulsion, trunk inclination influences the rolling resistance in two ways. First, rolling resistance coefficients of the small castor wheels on the front are usually larger than that of the – much larger – rear wheels (Sauret et al., 2013). Thus, the rolling resistance increases when the load (or COM) is shifted towards the castor wheels and vice versa. Second, trunk motion causes vertical accelerations of the COM such that the total load on the wheels increases when the COM accelerates upward and vice versa. In practice, forward trunk inclination will thus cause a varying rolling resistance force due to two different mechanisms.

Sauret et al. (2013) investigated the 'effects of users actions on rolling resistance' in everyday wheelchairs and investigated both changes in forward-backward load distribution, and vertical COM accelerations. Based on three participants, they found the total load to vary from 80 to 130 % of the gravitational force, indicating the effect of the vertical acceleration of the COM. In addition, the forward and backward shift of the COM, mainly due to inclination resulted in a castor wheel load ranging from 24 to 31 % (minimal values) to 61–83 % (maximal values) of the total load within each push cycle. However, they did not quantify the relative contribution of the two mechanisms. Once this is known, the effects of trunk motion could be corrected for when estimating rolling resistance, such that more accurate power values are obtained. Therefore, the relative contribution of the two mechanisms that cause a varying rolling resistance during wheelchair propulsion should be investigated.

The first aim of this study was to investigate the relation between trunk motion and the difference between the reference power loss (calculated from instantaneous rolling resistance), i.e., P_{IR}, and drag test-based power loss, i.e., P_{drag}, during wheelchair propulsion. The second aim of this study was to quantify the relative contributions of 1) changes in forward-backward load distribution, and 2) vertical COM accelerations, to the difference between P_{IR}, and P_{drag}. To this end, wheelchair propulsion experiments were performed while load on the front wheels was measured with custom-made load pins, and trunk and wheelchair kinematics were obtained from inertial sensors. P_{IR} and P_{drag} were compared for three levels of trunk motion: no trunk motion, moderate trunk motion and full trunk motion.

2. Methods

2.1. Data collection

2.1.1. Outline of the study

Twenty-four able-bodied individuals (18 females and 6 males, mean age: 25±13 years, mean body mass: 76±13 kg, mean body height: 1.70 ±0.07 m) without wheelchair experience propelled the hand-rims of a wheelchair on a large treadmill in three different conditions; 'no trunk motion', 'moderate trunk motion' and 'full trunk motion'. During the 'no trunk motion' condition, participants were instructed to keep the trunk static, whereas the other two conditions were imposed by following a metronome making participants to propel with long strokes accompanied by (natural) trunk motion (Goosey et al., 2000). During this experiment, trunk and wheelchair kinematics were measured using three IMUs attached to the participants' sternum, the wheelchair's frame, and right wheel axle. Custom-made load pins in the castor wheel axes measured the vertical load on the castor wheels (see Fig. 1). Before the treadmill session, participants received a 10-minute overground wheelchair training to get familiar with the wheelchair, a force plate session in which they stationary performed 'fake' wheelchair strokes on a force plate, and a 10-minute training on the treadmill (see Fig. 2). After the treadmill session, drag tests were performed on the treadmill to obtain rolling resistance coefficients of each pair of wheels. Lastly, participants' body mass was determined. All measurements were performed with a rear wheel tire pressure of 5.25 bar.

Fig. 1. a-b. Measurement set-up during the treadmill sessions. The custom-made load pins were integrated in each of the castor wheels (normal castor wheel axle were replaced by the load pins).

The study was approved by the ethical committee of the Technical University of Delft (Nr. 1530). Prior to the measurements, participants were informed about the aim and procedure of the study and provided written informed consent. The data used in this study were collected simultaneously with the data of another study (van Dijk et al., 2023).

2.1.2. Instrumentation

All treadmill measurements took place on a large (3.0×5.0 m) motor-driven treadmill (Bonte, Zwolle, the Netherlands) located at the Vrije Universiteit Amsterdam. A large treadmill was used to make participants feel safe to move forwards, backwards and sideways on the belt. An S-beam load cell (Revere Transducers, Lisse, the Netherlands) was used to measure the horizontal (drag) forces during the drag tests. An RGK Chrome all-courts wheelchair was used for the measurements (see Table 1). Wheelchair setup was equal for all participants. Load pins (Batarow Sensorik, Germany) were integrated in the castor wheel axes of the wheelchair to measure the vertical load on the castor wheels. Three IMUs (NGIMU, X-io Technologies, Colorado Springs, CO, United

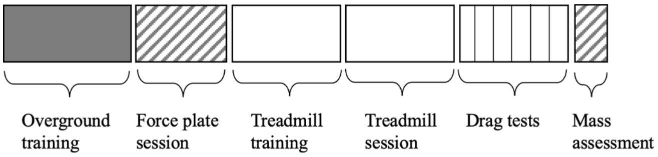


Fig. 2. Schematic overview of the measurement sessions consisting of overground wheelchair training, a force plate (FP) session, treadmill training and three treadmill sessions which were performed at different rear wheel tire pressure. Within each 3.5-minute treadmill session, participants propelled the wheelchair in three conditions: 'no trunk motion', 'moderate trunk motion', and 'full trunk motion'. In addition, drag tests were performed and participants' body mass was assessed.

Table 1
Wheelchair dimensions of the RGK Chrome all-courts wheelchair that was used for all measure-ments. The rear wheels had pneumatic tyres. The front wheels were solid rubber castor wheels.

Mass	13.5 kg
Wheel radius (rear)	0.61 *m*
Wheel radius (front)	0.075 *m*
Camber angle (rear)	13 degrees
Seat position (horizontal distance between backrest and rear wheel axis)	0.08 *m*
Distance front-rear wheels	0.39 *m*

States) were used to collect 3D inertial sensor data with a sample frequency of 100 Hz. In addition, the NGIMU analogue input channels of the frame-mounted sensor were connected to the load pins to act as power source and data logger. Ground reaction forces were measured at 200 Hz using a 1.0×1.0 m custom-made strain gauge force plate as described in the study of Kingma et al. (Kingma et al., 1995). The load cell and force plate were calibrated with known masses at the start of each measurement day. The load pins were calibrated during each force plate session by positioning the castor wheels on the force plate (while rear wheels were positioned at the same height).

2.1.3. Treadmill session

The treadmill sessions consisted of 30 s familiarization, followed by 60 s propelling at a low velocity (1.2 m/s) with no instruction (condition ‘moderate trunk motion’), 60 s propelling at a low velocity with the instruction to keep the trunk vertical (condition ‘no trunk motion’) and 60 s propelling at a high velocity (1.7 m/s) with no instruction again (condition ‘full trunk motion’). Participants were instructed to maintain a constant stroke frequency indicated by a metronome (set at 25 beats/minute during the first 90 s, and 40 beats/minute thereafter). Adherence to the instructions was monitored by observation. Safety was guaranteed by an automatic and a manual security stop.

After each treadmill session, drag tests were performed at 1.7 m/s, while the participants were instructed to sit as still as possible for a period of 30 s in six conditions. The (2x3) conditions consisted of sitting with vertical trunk and sitting bent forward while no mass was added, while 10 kg was added at the footrests and while 10 kg was added on the upper legs. Conditions with varying load distributions were required to be able to solve Eq. (2) numerically, as front wheel load was measured, and rear wheel load could be determined.

2.2. Data analysis

Acceleration, gyroscope and load pin force data were 2nd order low-pass filtered at 6 Hz. The gyroscope data of the wheel sensor were used to obtain wheelchair velocity (van der Slikke et al., 2015). Trunk inclination angle relative to the global vertical (in which 0 degrees was assumed vertical) was obtained using an extended Madgwick filter as described by van Dijk et al. (van Dijk et al., 2021a), with the β-value being 0.0015 (if $|\text{wheelchair acceleration}| < 0.1\ \text{m/s}^2$ for at least 5 consecutive samples) or 0.9635 (otherwise). In addition, vertical trunk acceleration was determined. To this end, the sine of trunk inclination angle was determined to obtain vertical trunk (IMU) displacement, and subsequently differentiated twice.

The drag test-based rolling resistance forces were obtained by averaging the last 10 s of the S-beam force data. Subsequently, the rear (r) and front (f) wheel rolling resistance coefficients, c_r and c_f, were determined by solving Eq. (2) numerically based on the average S-beam force and average load pin force ($F_{N,f}$) of the series of drag tests. Accordingly, c_f and c_r were used to estimate the instantaneous resistance force (F_{IR}) during all treadmill sessions. Power loss was obtained by multiplying the resistance force with wheelchair velocity.

Knowing c_f, c_r and $F_{N,f}$, the only unknown left to determine F_{IR} during the treadmill sessions is the instantaneous vertical acceleration of the system's COM ($a_{COM,z}$, see Eq. (3). Therefore, $a_{COM,z}$ was estimated from vertical trunk acceleration (see above). The relation between $a_{COM,z}$ and vertical trunk acceleration was determined using a force plate session in which participants performed a 2-minute protocol consisting of ‘fake’ wheelchair strokes. Simultaneously, vertical trunk acceleration and the $a_{COM,z}$ (calculated from the instantaneous vertical force on the force plate) were measured. A linear regression analysis was performed to predict $a_{COM,z}$ from vertical trunk acceleration for each participant.

$$F_{IR} = c_f * F_{N,f} + c_r * F_{N,r} \tag{2}$$

$$F_{N,r} = \left(m * g + m * a_{com,z}\right) - F_{N,f} \tag{3}$$

$$F_{IR,a=0} = c_f * F_{N,f} + c_r * (m * g - F_{N,f}) \tag{4}$$

2.2.1. Influence of trunk motion on estimation of power loss

To investigate to what extent trunk motion affects IMU-based power estimates during wheelchair propulsion, the resistance force and resulting power loss were estimated for each condition of trunk motion during the treadmill sessions. F_{drag} was obtained from the drag test with vertical trunk and no added mass, which is essentially the same as an overground deceleration test (Ott & Pearlman, 2021) and was subsequently compared with F_{IR} during wheelchair propulsion. Subsequently, the mean differences and mean absolute differences between F_{drag} and F_{IR}(and corresponding power losses, i.e., P_{drag} and P_{IR}) were determined per condition for each participant. To assess the relation between trunk inclination and the difference between P_{drag} and P_{IR}, trunk inclination range was determined for each participant by determining the maximal difference (i.e., maximum-minimum) in trunk angle per push, which were then averaged over the entire trial.

2.2.2. Relative contribution of changing load distribution and vertical COM accelerations

To determine the mechanism underlying potential deviations between P_{drag} and P_{IR}, the relative contribution of 1) changes in forward-backward load distribution and 2) vertical COM accelerations on the rolling resistance was determined. Therefore, rolling resistance as presented in Eqs. (2) and (3) was compared with the rolling resistance when $a_{com,z}$ was ‘ignored’ by setting it at 0 (see Eq. (4). In this way, $F_{IR,a=0}$ only considers the effect of load distribution (note that both the mass distribution as well as horizontal forces of the wheelchair user on the wheelchair can influence this). Subsequently, the percentage of error due to changes in load distribution (i.e., $\mathrm{F_{IR,a=0} - F_{drag}/F_{IR}*100\ \%}$) and that due to $a_{com,z}$ (i.e., $\mathrm{F_{IR} - F_{IR,a=0}/F_{R}*100\ \%}$) were calculated.

2.3. Statistical analysis

A one-way repeated measures ANOVA was used to assess whether the mean differences between (cycle-average) P_{drag} and (cycle-average) P_{IR} varied significantly between the three conditions of trunk motion. If the Greenhouse-Geisser epsilon ≥ 0.75, the Huynh-Feldt correction was used, otherwise the Greenhouse-Geisser correction was used. Subsequently, the correlation between trunk inclination range and the difference between (cycle-average) P_{drag} and (cycle-average) P_{IR} were analysed using a repeated measures correlation. A QQ-plot and a Shapiro-Wilks test of the residuals were performed to verify the assumption of normality. This assumption was not violated. Statistical analysis was conducted using software R (R Core Team, 2023). The significance level was set at $p < 0.05$.

3. Results

In total, 24 treadmill sessions were analysed. During the sessions, the average trunk inclination was 4 to 14 degrees in the ‘no trunk motion’-condition (trunk inclination range (TIR): 7.1 ± 3), 7 to 61 degrees in the moderate trunk motion condition (TIR: 23.5 ± 12) and 9 to 47 degrees (TIR: 25.0 ± 10) in the full trunk motion-condition. The mean absolute trunk angular velocity was 10 deg/s for no trunk motion, 21 deg/s for moderate and 33 deg/s for full trunk motion. The drag tests revealed rolling resistance coefficients of 0.0147 for the set of castor wheels and 0.0104 and 0.0089 (the tires were replaced after 8 participants) for the rear wheels.

3.1. *Influence of trunk motion on estimation of power loss*

Over time, drag test-based resistance force (F_{drag}) and power loss (P_{drag}) differ from the instantaneous resistance-based force (F_{IR}) and power loss (P_{IR}), see Fig. 3 and 4. On average, P_{drag} is underestimated in both moderate and full trunk motion conditions (see Table 2). A one-way repeated measures ANOVA showed a significant effect for the condition (F(1.6,36.4) = 55.1, $p < .001$) on the difference between P_{drag} and P_{IR}. Post-hoc Bonferroni test for multiple comparisons showed a significant difference between the conditions no and moderate trunk motion ($p < .001$), no and full trunk motion ($p < .001$) and moderate and full trunk motion ($p < .01$).

Moreover, a negative correlation (r(47) = −0.85, $p < .001$) was found between trunk inclination range and the difference between P_{drag} and P_{IR} for all conditions (see Fig. 5).

3.2. *Relative contribution of changing load distribution and vertical COM accelerations*

Substantial differences were observed for the relative contribution of changing load distribution and vertical COM accelerations to the differences between F_{drag} and F_{IR} (see Fig. 6). For full trunk motion, changes in load distribution caused an underestimation of −0.3 to 9.4 % (MD 3.1 %), while vertical COM accelerations caused an underestimation of −0.2 to 0.2 % (MD 0.02 %). From the total difference, 103 % (no), 99 % (moderate) and 99 % (full) is explained by changes in load distribution, compared to negligible effects (-3%, 1 % and 1 %) for vertical COM accelerations. The deviation between F_{drag} and F_{IR} is thus caused by changes in load distribution only.

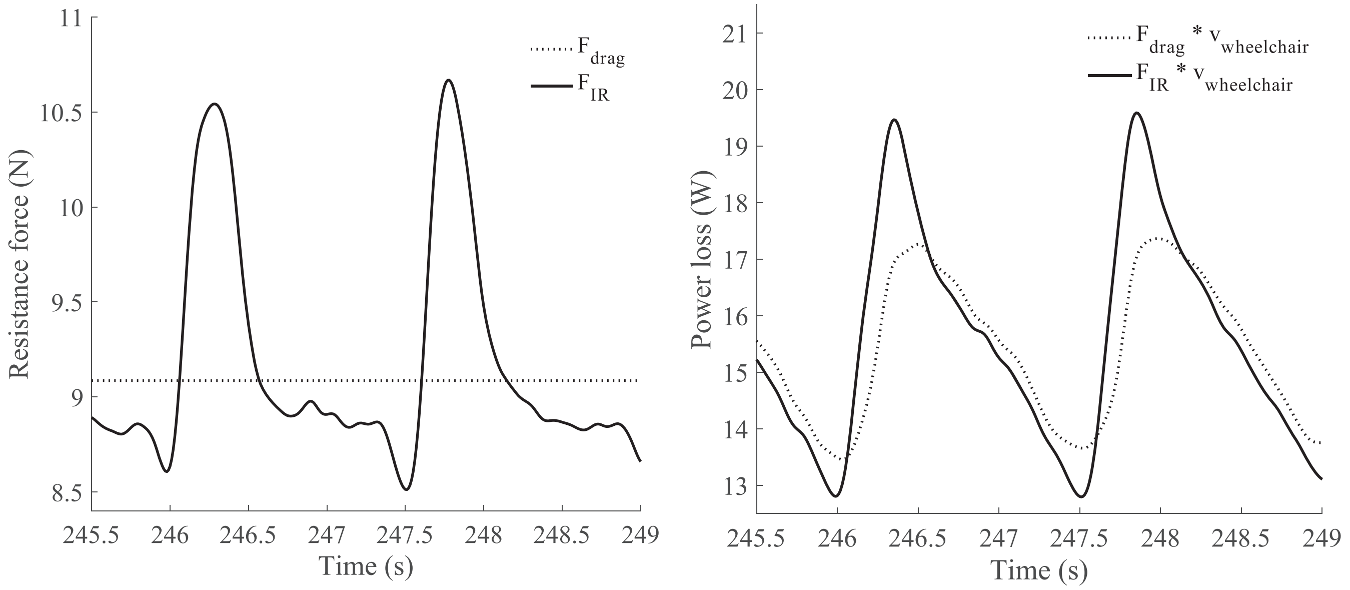
4. Discussion

Table 2
Mean (SD) drag test-based and instantaneous resistance-based power (P) and resistance force (F) values for each condition. The mean difference (MD) and the mean absolute difference (MAD) is presented. In addition, the average trunk inclination range is given for each condition.

Condition	Variable	Drag	IR	MD (%)	MAD (%)	Range of trunk inclination (°)
No	F	8.4 (1.3)	8.4 (1.3)	0.6 (1.6)	1.4 (1.0)	7 (3)
	P	10.0 (1.6)	10.0 (1.6)	0.6 (1.6)	1.4 (1.0)	
Moderate	F	8.4 (1.3)	8.6 (1.3)	−2.3 (2.0)	2.5 (1.8)	24 (12)
	P	10.0 (1.6)	10.3 (1.6)	−2.4 (2.0)	2.6 (1.9)	
Full	F	8.4 (1.3)	8.7 (1.3)	−3.2 (2.3)	3.2 (2.3)	25 (10)
	P	14.3 (2.3)	14.8 (2.3)	−3.3 (2.3)	3.3 (2.3)	

The first aim of this study was to investigate the relation between trunk motion and the difference between power calculated from instantaneous rolling resistance, i.e., P_{IR}, and drag test-based power loss, i.e., P_{drag}, during wheelchair propulsion. Comparisons between P_{IR} and P_{drag} showed almost no difference for wheelchair propulsion without moving the trunk (mean difference [MD] 0.6 ± 1.6 %), and a small underestimation of P_{drag} for wheelchair propulsion with moderate (MD −2.4 ± 2.0 %) and full (MD −3.3 ± 2.3 %) trunk motion. A significant negative correlation was found between the trunk inclination range and the difference between P_{drag} and P_{IR}, indicating a larger underestimation when trunk motion increases. In addition, the results show that the difference between P_{drag} and P_{IR} (when trunk motion is present) is for 99 % caused by changes in forward-backward load distribution, whereas the effects of vertical COM accelerations were negligible.

Compared to previous studies, the rolling resistance coefficients, drag forces and power values as found in the present study were similar to the values reported previously during treadmill and overground wheelchair propulsion (Mason et al., 2014; Rietveld et al., 2021). In addition, the larger relative influence of forward-backward load distribution (compared to vertical COM acceleration, or, total wheel load)



Figs. 3 and 4. Typical example of resistance force (left figure) and corresponding power loss (right figure) derived from the drag test-based resistance force, i.e., F_{drag} (dotted line), and the instantaneous resistance force, i.e., F_{IR} (solid line). These data are obtained from the condition with full trunk motion for two pushing cycles.

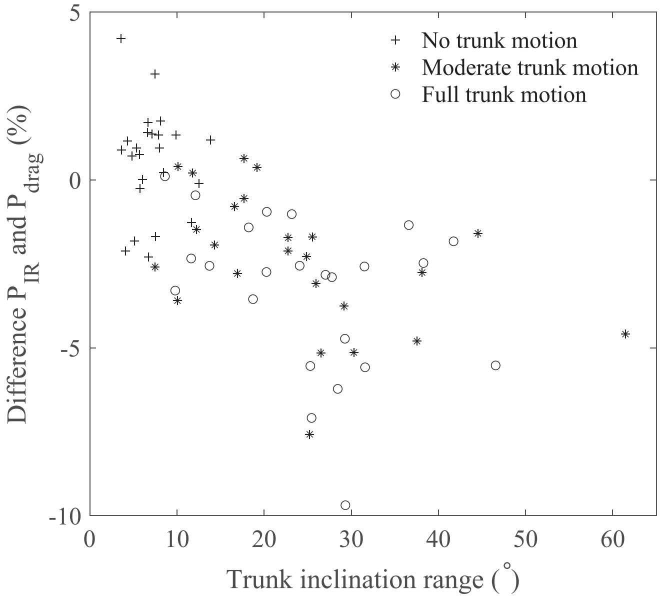


Fig. 5. Difference between P_{drag} and P_{IR} against the trunk inclination range (i.e., the maximal difference (i.e., maximum-minimum) in trunk angle per push averaged over the entire trial) for all participants and all conditions. The condition with no trunk motion is indicated by '+', the condition with moderate trunk motion is indicated by '*', and the condition with full trunk motion is indicated by 'o'. The difference is determined by $(P_{drag} - P_{IR})/P_{IR}$.

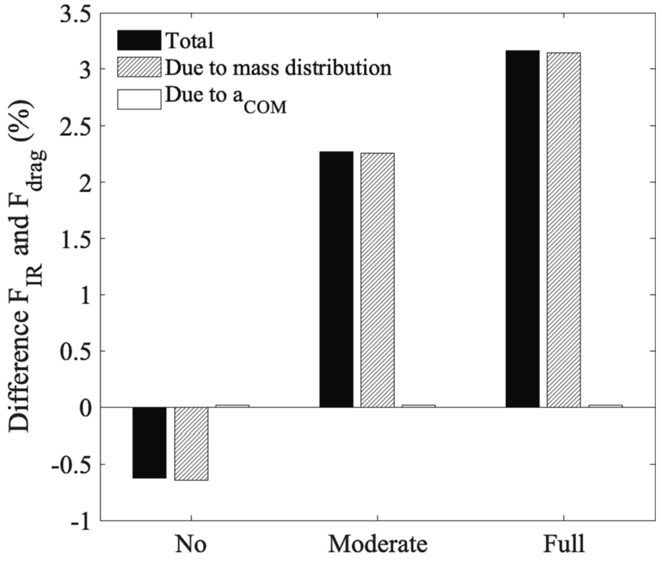


Fig. 6. The mean difference between F_{drag} and F_{IR}, compared with the mean differences due to (changes in) mass distribution and COM accelerations only. The difference is determined by $(F_{drag} - F_{IR})/F_{IR}$.

was reported by a previous study of de Saint Rémy et al. (2003). However, their results were based on deceleration tests with different (static) masses and mass distributions, and the findings were not related to a measured trunk or upper body motion. The present study is, as far as we know, the first to quantify the relation (and its underlying mechanisms) between trunk motion and the difference between drag test-based rolling resistance and actual rolling resistance during wheelchair propulsion.

The present study found an underestimation of 1 to 6 % for the drag test-based power loss when no instructions on trunk motion were given, and a larger underestimation when more trunk motion was measured. This underestimation can be explained by the differences between the small castor wheels (high rolling resistance coefficient, i.e., 0.0147) and large rear wheels (low rolling resistance coefficient, i.e., 0.0104 and 0.0089) in combination with a changing load distribution. Whereas, in the present study, the rear wheel coefficients were 30–40 % smaller than the front wheel coefficients, the relative differences between rolling resistance coefficients differ over wheelchairs. In this regard, the underestimation will be smaller when rolling resistance coefficients become more similar, for instance, due to a lower rear wheel tyre pressure (see Appendix A). When interpreting rolling resistance or power (loss) based on drag tests, both trunk motion and the relative difference between rolling resistance coefficients of the rear and castor wheels should thus be considered.

As drag tests are used to determine rolling resistance in many wheelchair measurements based on IMUs, ergometers or treadmills, the results of the present study may impact previously reported results on drag-test based rolling resistance or power loss. For example, Rietveld et al. (2021) reported differences in rolling resistance for different tennis court surfaces, like grass and hardcourt. However, as most wheelchair tennis players propel with considerable trunk movements (Ju et al., 2021), the actual values for rolling resistance during wheelchair propulsion would be higher than reported by Rietveld et al. (2021). Moreover, as a larger rolling resistance is associated with increasing trunk motion (Chow et al., 2000), actual differences between 'resistive' surfaces and 'less resistive' surfaces may also be larger than the ones reported by Rietveld et al. (2021). In addition, results of studies that compared the effect of tyre pressure on rolling resistance based on standard drag tests may not be valid as well (de Groot et al., 2013). As the accuracy of rolling resistance depend on 1) relative differences between rolling resistance coefficients and 2) amount of trunk motion, which are both intentionally or unintentionally altered when rear wheel tyre pressure is changed, making comparisons regarding actual rolling resistance based on drag tests is not valid. Overall, previously reported results regarding rolling resistance or power that were based on drag-test based rolling resistance should be handled with caution.

In wheelchair field sports, the results of the present study may have implications as well. In disciplines like wheelchair basketball or wheelchair rugby, differences are seen in the amount of trunk motion between athletes from different classifications and between accelerating from standstill versus steady-state wheelchair propulsion (Altmann et al., 2016; van Dijk et al., 2021b). Ignoring the effects of trunk motion may thus lead to an underestimation in power for athletes with high classifications compared to athletes with lower classifications. In addition, within a short sprint starting from stand-still, the power during the first pushes will be underestimated more than the power in the later pushes. When monitoring power in wheelchair sports practice, and mainly when comparisons between or within athletes are made, trunk motion should be determined and ideally be corrected for.

For future measurements one may, depending on the extent of trunk motion, correct for this to obtain accurate rolling resistance (and power) estimates. As the load pins used in this study are not convenient to use in daily practice, an additional IMU on the chest – in combination with a proper prediction model – may be used to estimate changing (upper body) mass (and thus load) distribution. This was already done in one of our previous studies by determining rolling resistance based on three different drag tests each having a different (known) trunk angle and, subsequently, determining the relation between trunk angle and drag test-based rolling resistance (van Dijk et al., 2021b). However, no gold standard was determined such that the accuracy of this method could not be determined. All in all, the underestimated rolling resistance may be corrected by adding (IMU-based) information on trunk motion.

For the present study, some limitations should be noted. First, all experiments were executed on a treadmill. However, as several precautions were taken to stimulate natural wheelchair propulsion (such as using a large treadmill and a respectable familiarization period), we believe that the relations and conclusions found in this study translate

Table A1
Mean (S.D.) drag force and mean difference (MD) for the three conditions and for different tyre pressures of the rear wheels are presented. The corresponding rolling resistance coefficients (i.e., *c*) of the rear and castor (or front) wheels is given. Due to a tyre change after the 9th participant, the first value for c_{rear} corresponds to the participant 1–9, the second value to participant 10–25.

	c_{front}	c_{rear}	F_{drag} (N)	MD (%)	MD (%)	MD (%)
Trunk motion				No	Moderate	Full
Normal	0.0147	0.0104 – 0.0089	8.4 (1.3)	0.6 (1.6)	−2.3 (2.0)	−3.2 (2.3)
Tire pressure −33 %	0.0147	0.0112 – 0.0100	9.0 (1.4)	0.5 (1.1)	−0.9 (4.7)	−2.2 (2.4)
Tire pressure −76 %	0.0147	0.0139 – 0.0123	10.6 (1.6)	0.3 (0.4)	−0.6 (0.6)	−0.9 (0.8)

well to the field. Second, in this study, drag tests were used to determine F_{drag}, while, in the field, deceleration tests are more convenient. As drag tests and deceleration tests are both indirect methods to determine F_{drag}, they should result in the same value when circumstances are equal (Ott & Pearlman, 2021). Lastly, this study focused on four-wheeled wheelchairs, whereas in wheelchair racing, another type of wheelchair is used. Because the rolling resistance coefficients of wheelchair racing wheels are more similar, arm movements may have more influence on the resistance force, and velocities are higher, our results are not expected to translate well to wheelchair racing.

5. Conclusion

During wheelchair propulsion with active trunk movement, ignoring the effects of trunk motion leads to an underestimated mechanical power of 1 to 6 % when this is based on drag test values. In addition, more trunk motion was related to a larger underestimation of power. Therefore, depending on the required accuracy of power output and the amount of trunk motion in the target group, the influence of trunk motion should be considered. As the power difference was caused by (trunk motion-induced) changes in load distribution between the front wheels and rear wheels during wheelchair propulsion, future studies should assess changes in forward-backward load distribution to obtain accurate rolling resistance and power values.

To conclude, including trunk motion in the mechanical power estimation improves the accuracy of power output estimations during handrim wheelchair propulsion and is crucial to ensure fair comparisons between and within athletes.

CRediT authorship contribution statement

Marit P. van Dijk: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Marco J.M. Hoozemans:** Writing – review & editing, Supervision, Resources. **Monique A. M. Berger:** Writing – review & editing, Supervision. **DirkJan H.E.J. Veeger:** Writing – review & editing, Supervision.

Declaration of competing interest

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Appendix A

To assess to what extent the differences between F_{drag} and F_{IR} depend on the relative difference between front- and rear-wheel rolling resistance coefficients, the treadmill session and drag tests were repeated two more times with different tire pressures (immediately after the first set of drag tests). Based on these data, differences between F_{drag} and F_{IR} were determined for the two additional situations in which the tyre pressure of the rear wheel tyres was lowered with 33 % (to 3.5 bar) and 76 % (to 1.75 bar), respectively. Table A1 shows that when the relative difference between front- and rear-wheel rolling resistance coefficients becomes smaller, F_{drag} and F_{IR} become more similar.

References

Altmann, V.C., Groen, B.E., Groenen, K.H., Vanlandewijck, Y.C., Van Limbeek, J., Keijsers, N.L., 2016. Construct Validity of the Trunk Impairment Classification System in Relation to Objective Measures of Trunk Impairment. Archives of Physical Medicine and Rehabilitation 97 (3), 437–444. https://doi.org/10.1016/j.apmr.2015.10.096.

Chow, J.W., Millikan, T.A., Carlton, L.G., Chae, W., Morse, M.I., 2000. Effect of resistance load on biomechanical characteristics of racing wheelchair propulsion over a roller system. Journal of Biomechanics.

de Groot, S., Vegter, R.J.K., Van Der Woude, L.H.V., 2013. Effect of wheelchair mass, tire type and tire pressure on physical strain and wheelchair propulsion technique. Medical Engineering & Physics 35 (10), 1476–1482. https://doi.org/10.1016/j.medengphy.2013.03.019.

de Klerk, R., Vegter, R.J.K., Veeger, H.E.J., Van Der Woude, L.H.V., 2020. Technical Note: A Novel Servo-Driven Dual-Roller Handrim Wheelchair Ergometer. IEEE Transactions on Neural Systems and Rehabilitation Engineering 28 (4), 953–960. https://doi.org/10.1109/TNSRE.2020.2965281.

de Saint Rémy, N. de S., Vaslin, P., Dabonneville, M., Martel, L., Gavand, A., 2003. Dynamique de la locomotion en fauteuil roulant manuel: Influences de la masse totale et de sa répartition antéropostérieure sur la résultante des forces de freinage. Science & Sports 18 (3), 141–149. https://doi.org/10.1016/S0765-1597(03)00076-5.

de Vette, V.G., Veeger, D. (H.E.J.), van Dijk, M.P., 2022. Using Wearable Sensors to Estimate Mechanical Power Output in Cyclical Sports Other than Cycling—A Review. Sensors 23 (1), 50. https://doi.org/10.3390/s23010050.

Goosey, V.L., Campbell, I.G., Fowler, N.E., 2000. Effect of push frequency on the economy of wheelchair racers. Medicine & Science in Sports & Exercise 174. https://doi.org/10.1097/00005768-200001000-00026.

Ju, Y.-Y., Chu, W.-T., Shieh, W.-Y., Cheng, H.-Y.-K., 2021. Sensors for Wheelchair Tennis: Measuring Trunk and Shoulder Biomechanics and Upper Extremity Vibration during Backhand Stroke. Sensors 21 (19), 6576. https://doi.org/10.3390/s21196576.

Kingma, I., Toussaint, H.M., Commissaris, D.A.C.M., Hoozemans, M.J.M., Ober, M.J., 1995. Optimizing the determination of the body center of mass. Journal of Biomechanics 28 (9), 1137–1142. https://doi.org/10.1016/0021-9290(94)00164-Y.

Mason, B., Lenton, J., Leicht, C., Goosey-Tolfrey, V., 2014. A physiological and biomechanical comparison of over-ground, treadmill and ergometer wheelchair propulsion. Journal of Sports Sciences 32 (1), 78–91. https://doi.org/10.1080/02640414.2013.807350.

Ott, J., Pearlman, J., 2021. Scoping review of the rolling resistance testing methods and factors that impact manual wheelchairs, 205566832098030 Journal of Rehabilitation and Assistive Technologies Engineering 8. https://doi.org/10.1177/2055668320980300.

R Core Team. (2023). R: A Language and Environment for Statistical Computing. *R Foundation for Statistical Computing, 2023*. https://www.R-project.org/.

Rietveld, T., Mason, B.S., Goosey-Tolfrey, V.L., van der Woude, L.H.V., de Groot, S., Vegter, R.J.K., 2021. Inertial measurement units to estimate drag forces and power output during standardised wheelchair tennis coast-down and sprint tests. Sports Biomechanics 1–19. https://doi.org/10.1080/14763141.2021.1902555.

Sauret, C., Vaslin, P., Lavaste, F., de Saint Remy, N., Cid, M., 2013. Effects of user's actions on rolling resistance and wheelchair stability during handrim wheelchair propulsion in the field. Medical Engineering and Physics 35 (3), 289–297. https://doi.org/10.1016/j.medengphy.2012.05.001.

van der Slikke, R.M.A., Berger, M.A.M., Bregman, D.J.J., Lagerberg, A.H., Veeger, H.E.J., 2015. Opportunities for measuring wheelchair kinematics in match settings; reliability of a three inertial sensor configuration. Journal of Biomechanics 48 (12), 3398–3405. https://doi.org/10.1016/j.jbiomech.2015.06.001.

van der Woude, L.H.V., Groot, G.D., Hollander, A.P., Schenau, G.J.V.I., Rozendal, R.H., 1986. Wheelchair ergonomics and physiological testing of prototypes. Ergonomics 29 (12), 1561–1573. https://doi.org/10.1080/00140138608967269.

van Dijk, M. P., van der Slikke, R.M.A., Berger, M.A.M., Hoozemans, M.J.M., & Veeger, H. E. J. (2021). Look mummy, no hands! The effect of trunk motion on forward wheelchair propulsion. *39th ISBS Conference*, 4.

van Dijk, M.P., Kok, M., Berger, M.A.M., Hoozemans, M.J.M., Veeger, D.H.E.J., 2021a. Machine Learning to Improve Orientation Estimation in Sports Situations Challenging for Inertial Sensor Use. Frontiers in Sports and Active Living 3, 670263. https://doi.org/10.3389/fspor.2021.670263.

van Dijk, M.P., Hoozemans, M.J.M., Berger, M.A.M., Veeger, D.H.E.J., 2023. From Theory to Practice: Monitoring Mechanical Power Output During Wheelchair Field and Court Sports Using Inertial Measurement Units [Preprint]. Journal of Biomechanics. https://doi.org/10.2139/ssrn.4414741.

van Ingen-Schenau, G.J., Cavanagh, P.R., 1990. Power equations in endurance sports. Journal of Biomechanics 23 (9), 865–881.

Veeger, H.E.J., van der Woude, L.H.V., 1989. The effect of rear wheel camber in manual wheelchair. The Journal of Rehabilitation Research and Development 26 (2), 37–46.