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Method Article

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Posted Date: July 13th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10130183/v1>

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Sports Engineering on October 24th, 2026.
See the published version at <https://doi.org/10.1007/s12283-026-00570-7>.

Effect of Applied-Force Misalignments on Rolling Resistance Measurements Using the Force Method

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Abstract

This study investigated the influence of force-application misalignments on measurements of rolling resistance in wheels using the force method. A theoretical model was developed to predict measurement errors caused by angular deviations between the load-cell axis and the normal direction of the rolling surface, as well as by horizontal axle offset during measurements on a cylindrical surface. The model was experimentally evaluated by measuring the rolling resistance coefficient of roller-ski wheels on both a flat treadmill rolling surface and a cylindrical rolling surface.

The results demonstrated that force-based rolling-resistance measurements are highly sensitive to small geometric misalignments. Angular deviations affected measurements on both flat and cylindrical rolling surfaces, whereas horizontal axle offset affected measurements on the cylindrical rolling surface. The experimentally measured rolling-resistance coefficients showed good agreement with the corresponding values predicted by the theoretical model across all tested conditions, indicating that the model adequately captures the dominant effects of applied-force misalignment on measurement errors.

The findings highlight the importance of accurate force-transducer alignment and wheel positioning in rolling-resistance measurements when using the force method. Overall, the proposed theoretical model provides a practical tool for predicting and correcting alignment-induced measurement errors in laboratory-based rolling-resistance testing.

KEYWORDS: rolling friction, rolling drag, drum test, treadmill, cross-country skiing, roller ski, non-pneumatic

1 Introduction

Rolling resistance is an important performance parameter for a wide range of wheeled systems, including bicycle tires, wheelchair wheels, automotive tires, and roller-ski wheels. In simplified terms, the rolling resistance coefficient C_{RR} is defined as the ratio between the rolling resistance force (F_{RR}) and the normal force (F_N).

Rolling resistance primarily arises from viscoelastic hysteresis in the wheel material [1, 2], whereby cyclic deformation leads to energy dissipation in the form of heat. The magnitude of these hysteresis losses depends on the deformation characteristics of the wheel material and the contact conditions between the wheel–surface interface. In addition to hysteresis losses, rolling resistance also includes parasitic losses, such as bearing friction. The hysteresis effect causes the center of pressure of the normal force distribution to be located slightly ahead of the wheel axis in the rolling direction. The moment generated by this normal force about the wheel axis must be countered by the rolling-resistance moment.

While the mechanisms underlying rolling resistance are generally similar across wheeled systems, the accurate quantification of C_{RR} can be particularly important in sports applications, where small differences in resistive forces can influence both athletic performance and experimental outcomes. One such application is roller skiing, used in training and competition to simulate cross-country skiing (XC-skiing) during the snow-free season. They are also commonly used in experiments involving athletes, both in the field [3] and indoors on large treadmills [4].

There are several reasons for quantifying C_{RR} on roller-ski wheels, including achieving values comparable to the friction coefficients of XC-skis on snow, ensuring consistent C_{RR} values among athletes in roller-ski competitions to promote equal conditions, and maintaining high reliability within and between experimental studies involving cross-country skiers. In addition, quantifying rolling resistance is important for distinguishing it from other external forces affecting the skier, such as gravity and aerodynamic drag [5]. However, determining a wheel's C_{RR} is challenging because it is much smaller than F_N , which means that even small absolute measurement errors can lead to substantial relative errors in the C_{RR} estimation.

In previous studies, various methods for measuring the C_{RR} of roller-ski wheels have been proposed and applied. Two common field approaches are the coast-down method, which estimates rolling resistance from the skier's deceleration [3, 6, 7], and the towing method, in which a skier or a weighted sled equipped with roller skis is towed using a string connected to a load cell [8]. These methods have the advantage of assessing rolling resistance under representative environmental conditions, including the combined effects of convective, conductive and radiative heat transfer between the roller ski, the air and the road surface. However, comparisons between studies are challenging because the measurements are sensitive to variations in aerodynamic drag, weather conditions, and surface roughness. The towing method has also been applied in laboratory settings, where either a skier on a treadmill [4, 9, 10], or a weighted sled [11, 12] is towed using a load-cell-equipped string. Another method mounts a single roller ski in a fixture attached to a small treadmill [13]. While this improves control, it is sensitive to alignment and stability of the setup [14]. One portable device

determines rolling resistance from the angular deceleration of a flywheel against which the roller-ski wheel rolls [15]. Another flywheel-based method employs an indirect electrical-power approach, in which the rolling resistance force is estimated using an empirical model [16]. These methods provide stable laboratory conditions for rolling-resistance testing and are not sensitive to misalignment of the applied normal load. However, because rolling resistance is determined indirectly rather than measured directly, the results depend on the validity of the underlying model.

Roller skis are typically used on asphalt roads or indoor treadmills, making these surfaces particularly relevant for rolling-resistance measurements. However, the use of a rotating cylindrical rolling surface offers several advantages for controlled testing, including compactness, repeatability, and the possibility of maintaining well-defined operating conditions. It is well established in the automotive industry to measure C_{RR} on a cylindrical surface, commonly referred to as drum testing, and similar methodologies may therefore be relevant for roller-ski wheel testing. Widely used standards, such as ISO 28580:2018 [17] and SAE J1269 [18], specify procedures for determining the rolling resistance of pneumatic tires under controlled conditions and are primarily based on drum testing. These standards describe several measurement approaches, including the force method in which the reaction force is measured at the wheel axle, as well as torque-, deceleration-, and power-based methods. To achieve repeatable and comparable results across different test laboratories, accurate alignment is considered critical. ISO 28580:2018 [17] specifies that the camber angle shall be within 2 mrad and the slip angle within 1 mrad. Furthermore, the applied load shall act normal to the test surface and pass through the wheel center within 1 mrad for the force method or 5 mrad for other methods, thereby minimizing measurement errors caused by angular deviations. However, stricter requirements on the order of 0.3 mrad have been suggested as more appropriate [19].

Despite the well-established procedures and alignment requirements in tire testing, equivalent standardization is lacking for roller-ski rolling resistance measurements. Existing methods for roller-ski wheels often provide limited control or documentation of alignment conditions, and the potential influence of force misalignment on the measured C_{RR} has not been systematically quantified. Given the sensitivity of rolling resistance measurements to small force deviations, this represents a potential source of error that may affect experimental validity and comparability across studies. Thus, the aim of this study was to examine the effect of applied-force misalignments in the force method on the measurement error of C_{RR} in roller-ski wheels.

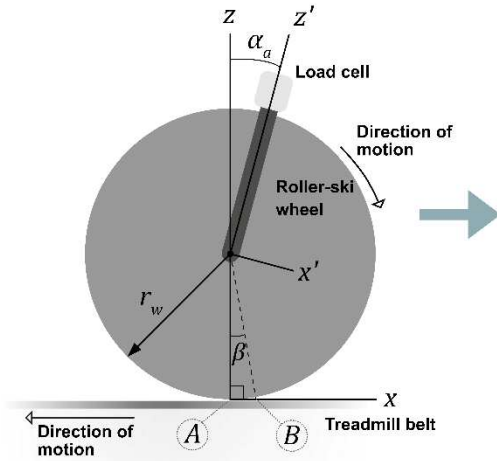
2 Methods

The methods comprised development of a theoretical model, experimental verification measurements, and statistical analysis of the agreement between measured and predicted rolling resistance coefficients.

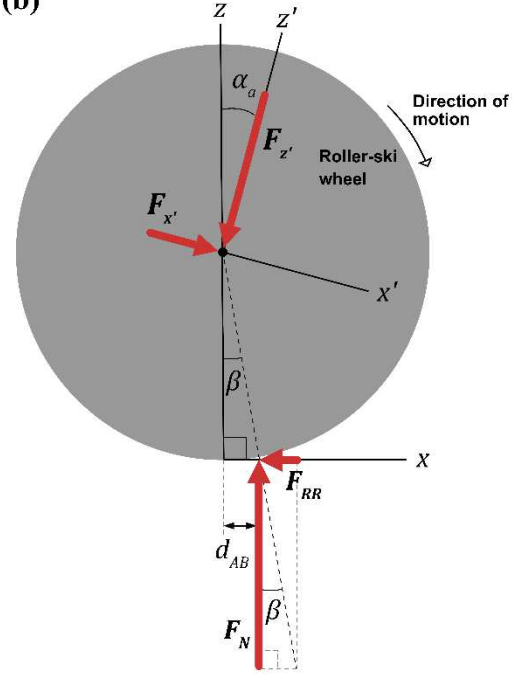
2.1 Theoretical Model

A theoretical model was developed to predict the effect of applied-force misalignments on the rolling resistance coefficient. The model included two misalignment angles, the angular deviation between the load cell's z' -axis and the direction normal to the rolling surface (α_a); the inclination angle (α_c) caused by a horizontal axle offset between the wheel and the cylinder (d_{Fz}). In addition, the model included the distance between the center of pressure of the normal force between the static contact point and the center of pressure during rolling (d_{AB}), resulting from the hysteresis of rolling resistance. When the wheel rolls on a flat surface (Figure 1a and 1b), such as a treadmill, only angular misalignment α_a contributes to measurement error. In contrast, when the wheel rolls on a cylindrical surface (Figure 1c and 1d) measurement error may arise from both α_a and the inclination angle α_c induced by d_{Fz} and d_{AB} .

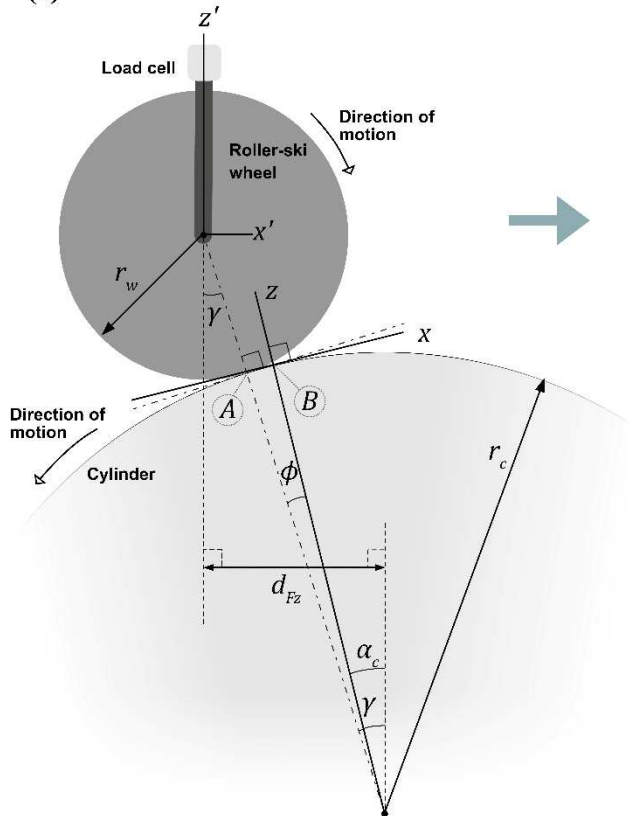
(a)



(b)



(c)



(d)

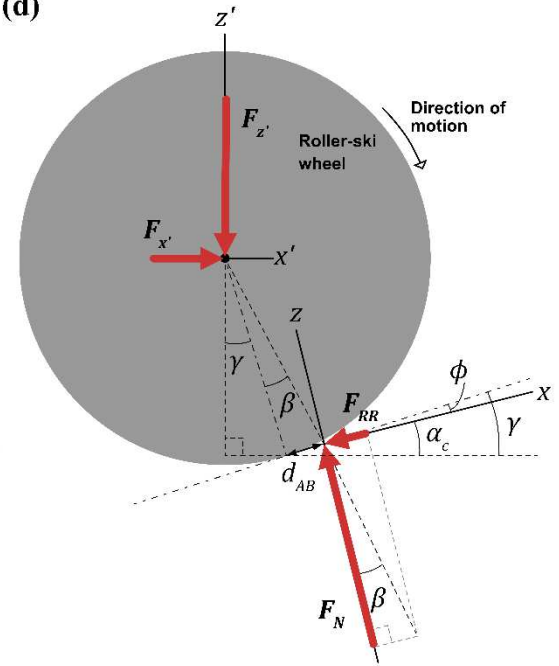


Fig.1 Two-dimensional representations and corresponding free-body diagrams of a roller-ski wheel of radius r_w , rolling on a flat treadmill rolling surface (a-b) and a cylindrical surface of radius r_c (c-d). d_{AB} is the distance between the center of pressure of the normal force between a loaded stationary wheel (A) and a rolling wheel (B). The angular deviation, α_a and α_c , can occur between the load-cell axes (x' - z') and the contact force axes (x - z), where α_c results from both d_{AB} and a horizontal axle offset d_{FZ} . The free-body diagram includes the load-cell components $F_{x'}$ and $F_{z'}$ and the contact forces at center of pressure B; the rolling resistance force F_{RR} and normal force F_N . The geometric model assumes an elastic roller-ski wheel rolling on a rigid (non-elastic) surface.

The C_{RR} is defined as the ratio between the F_{RR} and F_N . In practice, however, when the force method is used, the rolling resistance coefficient measured by the load cell ($C_{RR,lc}$) is determined from the ratio of the load cell force components F_x' and F_z' . Consequently, $C_{RR,lc}$ is equal to the true C_{RR} only when the measurement equipment is perfectly aligned. The relationship between $C_{RR,lc}$ and C_{RR} can be expressed according to Equation (1). For small α , Equation (1) can be approximated according to Equation (2).

$$C_{RR,lc} = \frac{F_x'}{F_z'} = \frac{F_{RR} \cos(\alpha) + F_N \sin(\alpha)}{F_N \cos(\alpha) - F_{RR} \sin(\alpha)} = \frac{C_{RR} \cdot F_N \cos(\alpha) + F_N \sin(\alpha)}{F_N \cos(\alpha) - C_{RR} \cdot F_N \sin(\alpha)} = \frac{C_{RR} \cos(\alpha) + \sin(\alpha)}{\cos(\alpha) - C_{RR} \sin(\alpha)} \quad (1)$$

$$C_{RR,lc} \approx C_{RR} + \tan(\alpha) \quad (2)$$

where C_{RR} is the true value of the rolling resistance coefficient of the roller-ski wheel and $\alpha = \alpha_a + \alpha_c$ (Figure 1), where: α_a is the clockwise angle from the normal direction of the rolling surface to the load cell's z' -axis, and α_c is the inclination angle caused by a horizontal axle offset (d_{Fz}) and a peripheral contact-pressure center displacement (d_{AB}) on a cylindrical surface. α_c can be expressed as a function of d_{Fz} and d_{AB} , according to

$$\alpha_c = \gamma - \phi = \sin^{-1} \left(\frac{d_{Fz}}{r_w + r_c} \right) - \tan^{-1} \left(\frac{d_{AB}}{r_c} \right) \quad (3)$$

where γ and ϕ are geometric angles defined in Figure 1, r_w and r_c are the wheel radius and cylinder radius, respectively, and d_{AB} is expressed as

$$d_{AB} = r_w \tan \beta = r_w \cdot C_{RR} = r_w \frac{F_{RR}}{F_N} \approx r_w \frac{F_x'}{F_z'} \quad (4)$$

The approximation on the right-hand side of Equation (4) assumes that $C_{RR} \approx C_{RR,lc}$ that is reasonable considering that the resulting angle $\phi = \tan^{-1} \left(\frac{d_{AB}}{r_c} \right)$ is indeed small.

Considering the opposite problem, where the equipment misalignments are known, and the true C_{RR} is to be calculated, the following equation can be used along with Equation (3–4):

$$C_{RR} = \frac{F_{RR}}{F_N} = \frac{F_x' \cos(\alpha) - F_z' \sin(\alpha)}{F_x' \sin(\alpha) + F_z' \cos(\alpha)} \approx C_{RR,lc} - \tan(\alpha) \quad (5)$$

Forces perpendicular to the x - z -plane, such as F_y , were not included in the model, as the experimental equipment can be adjusted so that F_y approaches zero. F_y typically arises when the wheel is subjected to a slip or toe angle; conditions known to substantially increase the rolling resistance [20].

2.2 Verification Measurements

Verification measurements were conducted using two experimental setups; a motor-driven aluminum cylinder ($r_c = 300$ mm) with a cylindrical and smooth rolling surface (Side

System, Oviken, Sweden); and a small treadmill [13] with a flat rubber mat rolling surface (Rodby Innovation AB, Vänge, Sweden).

In both setups, the forces acting on the roller-ski wheel were measured using a six-axis load cell (NET Force/Torque sensor Mini58, ATI Industrial Automation, Apex, USA). Prior to testing, the load cell was verified using known dead weights that applied a horizontal force through a lightweight line attached to the load cell and routed over a low-friction bearing. The load cell was mounted to a screw jack (ZIMM GSZ-2-SL, Lustenau, Austria) supported by an aluminum block. The screw jack was used to apply the force F_z' . To prevent unintended motion in the direction of the rolling-resistance force, the load-application axis was mechanically constrained in the rolling direction using ball bearings (Figure 2), thereby minimizing angular deviations and horizontal axle offset. The load cell was mounted below these bearings such that the load-cell force components were unaffected by the constraint.

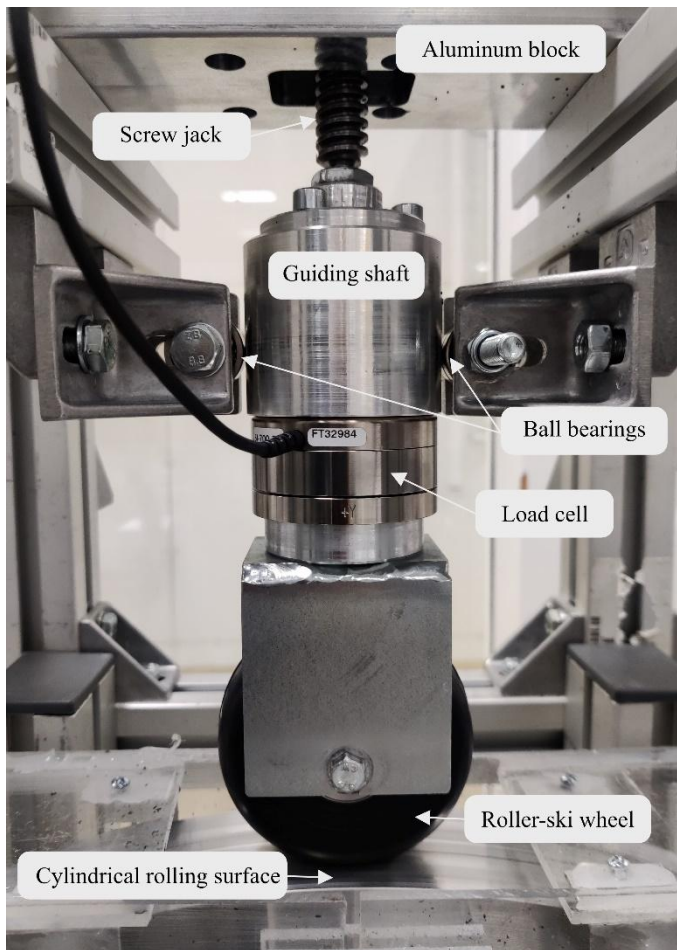


Fig.2 Close-up of the verification measurement setup used on the cylindrical rolling surface. Ball bearings guided the load-cell and screw-jack assembly in the rolling direction while allowing free motion along the loading axis, thereby minimizing angular deviations and horizontal axle offset.

The load-cell components $F_{x'}$ and $F_{z'}$ were recorded at 1000 Hz using a MATLAB script, and the signals were averaged over an approximately 20 s interval for each measurement. $F_{y'}$ was adjusted to be as close to zero as possible to avoid the measurement errors caused by slip angle. Between each measurement, the wheel was unloaded and the load cell was calibrated.

Four roller-ski wheels (Swenor, Sarpsborg, Norway) were tested: two classical wheels with diameters 69 mm and 76 mm and two skate wheels with diameters of approximately 100 mm. For each skiing style, one race-purpose wheel (PU78A) and one standard wheel (STD2) were tested. Prior to testing, the wheels were preheated to 40°C in an oven and then further conditioned by rolling until steady-state conditions in C_{RR} were reached [11]. The ambient temperature was kept at $23 \pm 1^\circ\text{C}$ during the measurements. Both the warm-up and measurements were performed at a rolling speed of 20 ± 2 km/h with an applied normal load of 300 ± 2 N.

On the cylindrical rig, the horizontal axle offset (d_{Fz}) was adjusted from -2 mm to $+2$ mm in 1 mm increments while the angular deviation between the load cell's z' -axis and the direction of the surface normal (α_a) was kept constant. On the treadmill, α_a was adjusted from -10 mrad to $+10$ mrad in 5 mrad increments, where 10 mrad is equal to 1% incline. Horizontal axle offset and angular alignment were adjusted using precision steel shims placed between the aluminum block and a counterpoint. At each position, 10 measurements were carried out for each wheel. To verify correct alignment (zero position), the rolling surface was driven in both forward and reverse directions. Proper alignment was confirmed when the load cell measured identical $C_{RR,lc}$ in both directions while maintaining the same wheel position.

2.3 Statistics

The statistical analyses were done in IBM SPSS for Windows statistical software release 29.0 (SPSS Inc., Chicago, IL. USA). The measured mean value of the rolling resistance coefficient ($C_{RR,lc,meas}$) for each individual position was compared with the corresponding predicted value from the theoretical model ($C_{RR,lc,pred}$) for each wheel using a one-sample t-test. Nominal $C_{RR,lc,pred}$ value was obtained from the intercept of a linear regression fitted to the measured data. Mauchly's test indicated that the assumption of sphericity was not violated for any wheel type ($p > 0.05$), and therefore sphericity-assumed results were used. Thus, a repeated-measures analysis of variance (ANOVA) was performed to analyze whether the angular deviation between the load cell's z' -axis and the direction normal to the rolling surface (α_a) and horizontal axle offset (d_{Fz}), significantly affected $C_{RR,lc,meas}$. Bonferroni post hoc tests were used following the ANOVA to identify significant differences while controlling for multiple comparisons ($p < 0.05$). Partial eta squared (η_p^2) was used as a measure of effect size.

3 Results

To illustrate the effect of applied-force misalignment on rolling resistance measurements using the force method, Figure 3a and 3b show the theoretically predicted ($C_{RR,lc,pred}$) and experimentally measured mean values ($C_{RR,lc,meas}$) when varying the angular deviation between the load cell's z' -axis and the direction normal to the rolling surface (α_a), and the horizontal axle offset (d_{Fz}), respectively.

The analysis showed statistically significant differences between all misalignment levels for α_a , d_{Fz} , and all wheel types ($p < 0.001$) with large effect sizes (partial $\eta^2 \approx 1.0$).

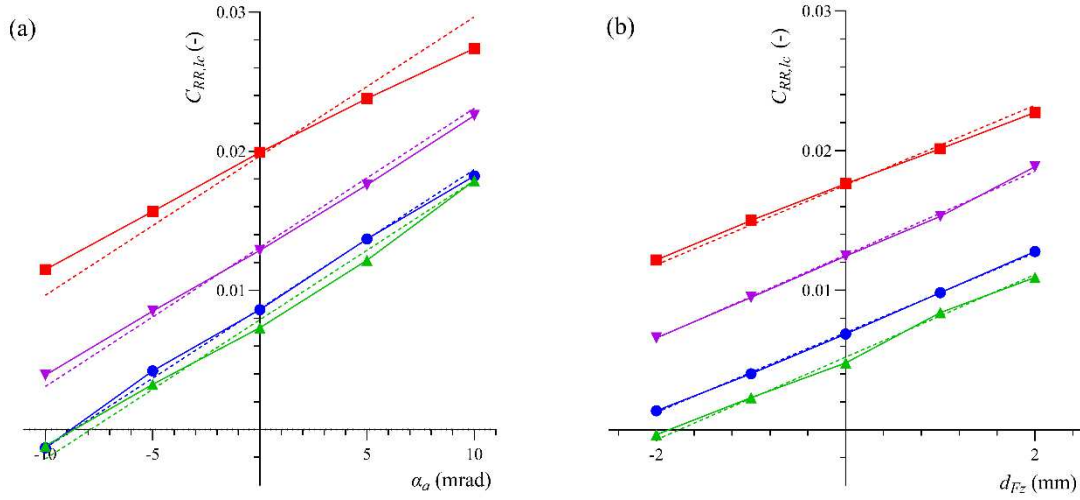


Fig.3 The mean values ($n = 10$) of the measured rolling resistance coefficient ($C_{RR,lc,meas}$) for Swenor roller-ski wheels: (■) Skate STD2, (▼) Classic STD2, (●) Skate PU78A and (▲) Classic PU78A, when varying (a) the angular deviation between the load cell's z' -axis and the direction normal to the rolling surface (α_a) on a flat rubber-mat treadmill; and (b) horizontal axle offset (d_{Fz}) on cylindrical surface with a radius of 300 mm. Error bars (SD) are hidden behind the markers. The dashed line represents the corresponding theoretical predicted rolling resistance coefficient ($C_{RR,lc,pred}$).

The theoretical model predicted that the rolling resistance coefficient ($C_{RR,lc,pred}$) of roller-ski wheels increases by approximately 0.001 per mrad of angular deviation between the load cell's z' -axis and the direction normal to the rolling surface (α_a). For horizontal axle offset (d_{Fz}) on a cylindrical rolling surface with a 300 mm radius, the predicted increase is approximately 0.0029 per mm offset for classical wheels and 0.0030 per mm for skate wheels.

Moreover, for most test conditions, statistically significant differences were observed between $C_{RR,lc,meas}$ and $C_{RR,lc,pred}$ ($p < 0.05$), see Table 1. However, the magnitude of the residuals was very small, suggesting that the observed differences were primarily a consequence of the low variability and high reliability of the measurements rather than a practically relevant deviation.

Table 1: Mean residuals in the rolling resistance coefficient between the measured and the predicted values ($C_{RR,lc,meas} - C_{RR,lc,pred}$) when varying the angular deviation between the load cell's z'-axis and the direction normal to the rolling surface (α_a) on a flat treadmill surface, and horizontal axle offset (d_{Fz}) on a cylindrical surface. SD denotes the standard deviation within each set of measurements. The statistical significance level was set at $p < 0.05$.

Type of Swenor roller- ski wheel	n	Angle Deviation on Treadmill				Horizontal axle offset on Cylinder			
		α_a [mrad]	Mean residuals	SD	p-value	d_{Fz} [mm]	Mean residuals	SD	p-value
Skate PU78A	10	10	-0.00045	0.00004	<0.001	2	0.00009	0.00013	0.053
	10	5	0.00001	0.00007	0.657	1	0.00001	0.00004	0.720
	10	0	-0.00008	0.00004	<0.001	0	-0.00010	0.00006	<0.001
	10	-5	0.00052	0.00006	<0.001	-1	-0.00010	0.00004	<0.001
	10	-10	0.00000	0.00009	0.935	-2	0.00011	0.00016	0.055
Skate STD2	10	10	-0.00226	0.00007	<0.001	2	-0.00051	0.00006	<0.001
	10	5	-0.00087	0.00032	<0.001	1	-0.00025	0.00007	<0.001
	10	0	0.00026	0.00015	<0.001	0	0.00010	0.00010	<0.05
	10	-5	0.00102	0.00012	<0.001	-1	0.00032	0.00007	<0.001
	10	-10	0.00184	0.00021	<0.001	-2	0.00034	0.00011	<0.001
Classic PU78A	10	10	0.00001	0.00008	0.780	2	-0.00022	0.00007	<0.001
	10	5	-0.00072	0.00010	<0.001	1	0.00022	0.00007	<0.001
	10	0	-0.00057	0.00007	<0.001	0	-0.00042	0.00011	<0.001
	10	-5	0.00036	0.00011	<0.001	-1	0.00006	0.00005	<0.01
	10	-10	0.00092	0.00011	<0.001	-2	0.00035	0.00007	<0.001
Classic STD2	10	10	-0.00052	0.00015	<0.001	2	0.00034	0.00014	<0.001
	10	5	-0.00051	0.00013	<0.001	1	-0.00022	0.00008	<0.001
	10	0	-0.00021	0.00007	<0.001	0	-0.00009	0.00013	<0.05
	10	-5	0.00042	0.00005	<0.001	-1	-0.00007	0.00009	<0.05
	10	-10	0.00082	0.00007	<0.001	-2	0.00004	0.00007	0.138

4 Discussion

Although the theoretical model accurately predicted the effect of applied-force misalignment, the small differences observed between predicted and measured results are likely explained by experimental uncertainties associated with instrument alignment, operating handling, and inherent limitations in measurement accuracy. Overall, the close agreement supports the validity of both the measurement approach and the underlying theoretical model.

The theoretical model may be applied to correct rolling resistance measurements in cases where misalignment is known but cannot be removed through adjustment of the test setup. Under these conditions, the model offers a practical means of compensating for alignment-induced errors.

Although the test setup was initially adjusted using laser measurement tools and spirit levels, additional fine-tuning was required to achieve proper alignment. Operating the rolling surface in both forward and reverse directions proved to be an effective verification method. Alignment was verified when consistent C_{RR} values were obtained in both directions, indicating that residual misalignment effects had been minimized.

According to automotive industry standards for measuring the rolling resistance of pneumatic tires, ISO 28580:2018 [17], the applied load in the force method shall act

perpendicular to the test surface and pass through the wheel center within 1 mrad. Based on the theoretical model developed in the present study, a 1 mrad angular deviation would result in an increase or decrease in the measured rolling resistance coefficient of approximately 0.001. Such a deviation may therefore produce a relatively large measurement error at low rolling resistance coefficients, whereas the relative effect becomes less pronounced at higher rolling resistance coefficients.

The model presented in this study does not fully account for the systematic differences observed between measurements performed on a cylindrical rolling surface and those conducted on a flat treadmill surface. This indicates that geometric force misalignment alone is insufficient to explain the observed discrepancies. Rolling resistance in roller-ski wheels is primarily governed by hysteresis losses arising from cyclic viscoelastic deformation of the wheel material. Due to the higher strain attained when an elastic cylinder deforms to a rigid cylindrical surface, the corresponding hysteresis should be stronger than on a flat surface. The framework by Clark and Dodge [21] distinguishes between a measurement effect and a stress effect. The former corresponds to the mechanism captured by the present model, while the latter is not explicitly represented. If the stress-effect formulation proposed by Clark and Dodge is incorporated in addition to the measurement effect, the rolling resistance measured for a typical roller-ski wheel on a cylindrical surface with a radius of 300 mm would need to be reduced by approximately 5.6–8% to determine the wheel's C_{RR} on a flat surface.

Another factor that may contribute to the observed differences between cylindrical and treadmill measurements is the difference in rolling-surface material. The cylindrical rig employed a smooth metallic surface, whereas the treadmill used a rubber mat. Since rolling resistance is influenced by contact mechanics, differences in surface stiffness can affect the measured C_{RR} .

Factors other than those discussed in the present study may also influence the rolling resistance coefficient, both during laboratory measurements and under real-world roller-skiing conditions. Such factors include surface roughness [19] and thermal conditions, such as ambient air and surface temperatures [15]. In addition, airflow, whether generated by a wind tunnel during laboratory testing or by natural wind under outdoor conditions, may influence rolling resistance through its effect on convective heat transfer and wheel temperature. Moreover, in the present experiments, a constant normal load was applied to the wheel. In practice, however, the load acting on a roller-ski wheel varies continuously throughout the skiing cycle, which may affect the C_{RR} . The influence of dynamic loading on roller-ski rolling resistance therefore warrants further investigation.

5 Conclusion

The results showed that force-based measurements of C_{RR} are sensitive to small misalignments, including angular deviations between the load cell's z' -axis and the normal direction of the rolling surface (α_a) on both treadmill and cylindrical surfaces, as well as horizontal axle offset (d_{Fz}) on cylindrical surfaces. The measured rolling resistance coefficients ($C_{RR,lc,meas}$) were in good agreement with the corresponding values predicted by the theoretical

model ($C_{RR,lc,pred}$) across all tested conditions. This agreement indicates that the theoretical model adequately predicts the effects of force misalignment on rolling resistance measurements. Overall, the study contributes to improved validity and comparability of roller-ski rolling resistance measurements in both laboratory testing and sports engineering research.

Acknowledgments

The author would like to thank Magnus Ahnesjö for valuable assistance with the experimental setup and development of the MATLAB scripts used for the measurements.

Declarations

This study was partly funded by the European Union Regional Development Fund.



**Funded by
the European Union**

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