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ABSTRACT
The gross mechanical efficiency of the manual wheelchair propulsion movement is particularly low compared to other movements. The energy losses in the manual wheelchair propulsion movement are partly due to energy losses associated with the wheelchair, and especially to the rolling resistance of the wheels. The distribution of mass between the front rear wheels and the caster wheels has a significant impact on the rolling resistance. The study of the caster wheels cannot therefore be neglected due to their involvement in rolling resistance. Thus, this study aimed to evaluate the power dissipated due to rolling resistance by different caster wheels, at different speeds and under different loadings on various terrains. Four caster wheels of different shapes, diameters, and materials were tested on two surfaces representative of indoor sports surfaces at four different speeds and under four loadings. The results showed a minimal dissipated power of 0.4 ± 0.2 W for the skate caster, on the parquet, at 0.5 m/s and under a loading of 50 N. The maximal mean power dissipated was 43.3 ± 27.6 W still for the skate caster, but on the Taraflex, at 1.5 m/s and under loading of 200 N. The power dissipated on the parquet was lower than the one on the Taraflex. The Spherical and Omniwheel caster wheels dissipated less power than the two other casters. This study showed that caster wheels cannot be neglected in the assessment of gross mechanical efficiency, particularly in light of the power dissipated by athletes during propulsion.

Abbreviations:
MWC: Manual WheelChair
RR: Rolling Resistance

KEYWORDS
caster; manual wheelchair; power loss; rolling resistance; indoor surface

1. Introduction

Since the advent of wheelchair sports in the 1960s with the first Paralympic Games, the sports performance issues have continued to grow and are now at the heart of several discussions. Indeed, high-level sport imposes more and more demands, whether physiological, technical, or material. It is highly challenging to optimise all these aspects as they depend mainly on the athlete and the discipline. The common denominator of all

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the dynamic wheelchair sports remains the propulsion movement. The gross mechanical efficiency of the manual wheelchair (MWC) propulsion movement is defined as the ratio between power applied to the hand rim and the metabolic energy expenditure associated. The values reported in the literature for wheelchair propulsion are particularly low (between 2.0 and 10.5 % [2–7]) compared to other movements (between 18 and 23 % for cycling [8] and between 20 and 40 % for walking [9,10]). Thus, the MWC propulsion movement constitutes a major issue in sports performance but also in the prevention of the risk of upper limb pain and injury. In wheelchair sports, the material and especially the wheelchair plays a key role in performance [1]. The energy losses during the MWC propulsion movement are partly due to the energy losses associated with the wheelchair. These energy losses are due to the deformation of the MWC chassis, drag forces, energy losses in the bearings, rolling resistance (RR), and swiveling resistance of the wheelchair, i.e. the resistance to wheels rotation along a vertical axis [11]. The energy losses due to the deformation of the MWC chassis are difficult to evaluate and not much studied. In the case of a rigid monobloc wheelchair chassis, which is the case for most sports wheelchairs, the energy losses due to the deformation of the chassis can be considered as negligible compared to the other source of energy losses [11]. For speeds under 5 $m.s^{-1}$ and in a straight line, the energy losses due to the drag forces, and the swiveling resistance are negligible compared to energy losses due to RR. Except in cases of a combination of unfavorable parameters (high axial load, small wheel radius, high load on front wheels), the bearing resistance can often be neglected compared to the rolling resistance [12]. Thus, most of the time, the energy losses associated with the wheelchair during the MWC propulsion are mainly due to rolling resistance (RR) [11]. This rolling resistance force is defined as a force that produces a moment that is opposed to the wheel's driving moment.

Studies have shown that the distribution of mass between the front and the rear wheels had a significant impact on the RR moment. In particular, higher RR was observed with higher mass of the system wheelchair and user supported by the front caster wheels [13–20]. In this context, the study of the wheelchair caster wheels cannot be neglected due to their involvement in RR. Indeed, wheelchair caster wheels are necessary devices responsible for the rotation around the vertical axis especially in dynamic disciplines as para-badminton, rugby, or basket as examples, where rotations, abrupt movements forward and backward, and short sprints are commonly observed. In this case, spherical castors may offer an advantage due to their multidirectional nature, but their effectiveness for translational movements alone remains to be considered.

Literature reported two other major points. First, the RR was inversely proportional to the diameter of the caster [14,16,21]. Second, the deformation of the surface was a factor in increasing of the RR [22].

Thus, the aim of the study was to compare the power dissipated due to RR by different caster wheels, at different speeds and under different loads on various terrain, focusing on the translation phase. Especially, the aim of this study was to verify whether spherical wheels present lower rolling resistance during translational movements compared to other types of caster wheels. Indeed, beyond their main advantage of being multidirectional, spherical wheels do not necessitate any spin rotation during any changes of direction.

The novelty of this study lied in the type of surface and wheels tested but also in the isolated study of the wheelchair caster wheels.

It was expected that the lowest power would be dissipated on the less deformable floor, regardless of the caster, the loading, or the speed.

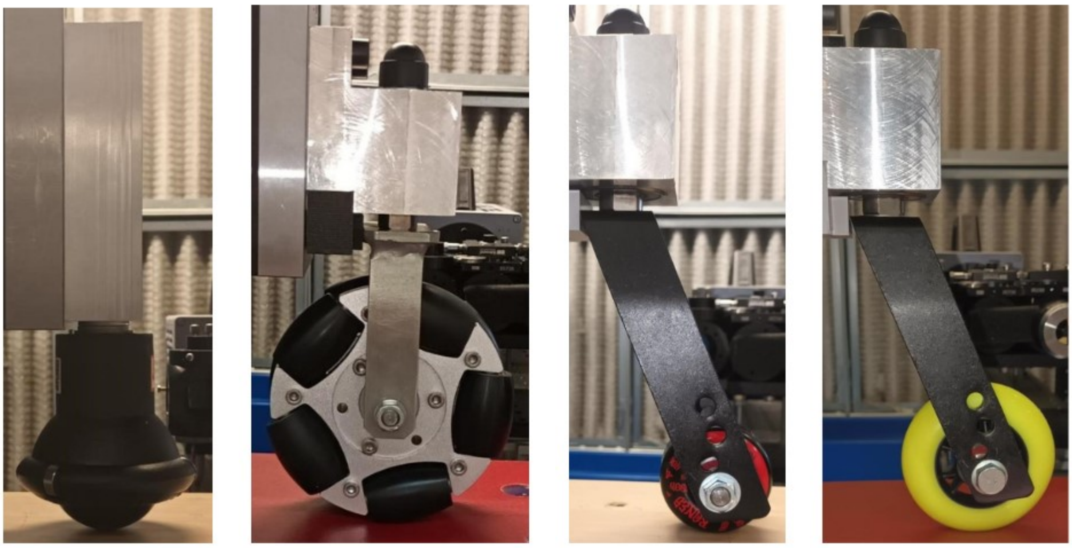
2. Methods

2.1. Experimentation

Four casters with different geometries and materials (Table 1, Figure 1) were tested on two surfaces representative of indoor sports surfaces: a parquet floor and a Taraflex®-type PVC floor.

Table 1. Characteristics of the casters tested in the study.

Name	Diameter [mm]	Roller material	Manufacturer
Spherical	50.8	Phenolic resin	Omnitrack
Omniwheel	127	Nylon	Nexus Robotics
Skate	52	Hard resin	Bones
Roller	80	Polyurethane	Matter



(a) Spherical. (b) Omniwheel. (c) Skate. (d) Roller.

Figure 1. Caption. Casters tested in the study. The beige surface corresponds to the parquet and the red one to the Taraflex floor.

Figure 1. Alt Text. (a) Spherical caster wheel mounted on its specific fork and placed on a parquet surface. (b) Omniwheel caster wheel mounted on its specific fork and placed on a Taraflex surface. (c) Skate caster wheel mounted on its specific fork and placed on a parquet surface. (d) Roller caster wheel mounted on the same fork as the skate caster wheel and placed on a Taraflex surface.

A specific and innovative [21] test bench adapted from a rectilinear cutting bench (Figure 2) was used. The novelty of this test bench lied in its ability to isolate the caster wheels for measuring rolling resistance on various surfaces, under controlled speeds and loadings. It was composed of a horizontal plane and a 6-axis force sensor (3-D dynamometer type 9257B, Kistler). Each caster was mounted on a specific fork fixed to the dynamometer, mounted itself to the frame of the test bench. The test bench permitted to impose a rectilinear back-and-forth movement between the caster wheel and the plane, and to reach speeds up to 2 m/s.

The force sensor measured the efforts applied by the surface to the caster at different tested speeds (0.5 m/s, 1.1 m/s, 1.5 m/s, 2 m/s). The fork did not allow the caster to swivel along its vertical axis, so that between each round-trip, the caster did not change orientation. The speeds were chosen to correspond to daily low (0.5 m/s) and

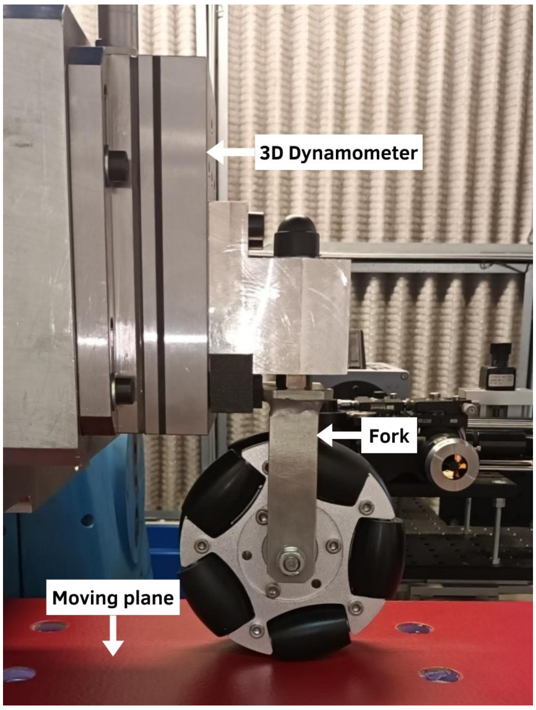


Figure 2. Caption. Test bench used for the study.
Figure 2. Alt Text. Photograph of the test bench with the Omniwheel caster mounted on its specific fork, mounted on the 3D dynamometer, and placed on the moving plane.

normal (1.1 m/s) displacement speeds [14,22], and to higher speeds (1.5 m/s and 2 m/s) up to the speed limit of the test bench and corresponding to the displacement speed in para-badminton. Tests were conducted under four constant compressive loads (50 N, 100 N, 150 N, 200 N). These loading conditions were based on the literature with a total mass system (subject and wheelchair) of 100 kg with a loading on each single caster corresponding to 5 %, 10 %, 15 %, and 20 % of this total mass [22]. The choice of the loading conditions was also based on the fact that the global RR coming from all the wheels increased when more than 30 % of the total mass of the system is supported by the front casters [14]. Kinematics data were acquired at 200 Hz from a speed sensor integrated into the test bench and force data at 1000Hz from the 3D-dynamometer. Each caster was tested once under the surface, load and speed conditions described above, for a total of 128 tests.

2.2. Data processing

During the experiments, the fork was blocked in rotation, preventing the caster from changing direction. The transition phase between the forward and backward phases was excluded from the data so only the phases in straight line were studied. The distance covered in each phase (forward or backward phase) was 35cm and two whole round-trips were studied for each trial, so four paths of the caster on the surface.

Force data were resampled at 200 Hz and filtered with a 2nd order Butterworth low-pass filter with a cut-off frequency of 4 Hz. Force data were synchronized with the kinematics data from constraints defined from the recognizable pattern on both velocity and force signals (transition between the forward and the backward phase).

Power (P) dissipated by the caster was calculated as the dot product of the horizontal force (F_h) applied by the place on the caster and the linear speed (v) of the plane:

$$P = F_h \times v$$

The mean and standard deviation (SD) of the power dissipated on each of these four paths was calculated for each trial, only on the straight-line phase (data from the reverse direction phase, resulting in a transient phase, were excluded) to ensure that power was calculated at constant speed. Thus, a trial corresponded to a test on one surface, for one caster wheel, at one speed, under one loading and for two round-trips of the caster on the surface. To evaluate the impact on the power dissipated of the different parameters (loading, surface, speed and caster type), the mean value of the mean powers was calculated for the trials implying the parameter. The mean power over all the trials was also calculated as a reference.

2.3. Statistics

The one-sample Kolmogorov-Smirnov test showed that the data were not normally distributed. Thus, the statistical analyses were performed with non-parametric tests. A Kruskal-Wallis test was performed to find if there were significant differences between the mean values of the power among the different levels of each parameter. This was the case for all the parameters so a Wilcoxon post-hoc test was performed to compare the means of all the groups. A Bonferroni adjustment was made for the caster, speed and loading parameters. The level of statistical significance was set at $p < 0.05$.

3. Results

The impact of the different parameters (surface, caster, loading and speed) on the dissipated power for all trials is presented in Figure 3. In assessing the impact of the parameters on the dissipated power, some SD values were higher than the mean values, leading to the negative values shown in Figure 3. These values do not represent negative calculated values of dissipated power. The values presented for each level of each parameter must be interpreted in relation to the dissipated power values of the other levels of the concerned parameter.

On the parquet, the powers dissipated were between 0.4 ± 0.2 W (for the skate caster, under a loading of 50 N and at 0.5 m/s) and 2.7 ± 1.8 W (for the skate caster, under a loading of 200 N and at 1.5 m/s) (Table 2). The power dissipated on the Taraflex was significantly superior to the one dissipated on the parquet. The power dissipated on the Taraflex was more than six times higher than on the parquet (Figure 3).

Significant differences were observed regarding the mean power dissipated by the different front caster wheels. The spherical and the Omniwheel casters dissipated an equivalent power, more than twice as lower than the average power of all conditions. The power dissipated by the skate caster was roughly five times higher than the one dissipated by the spherical and Omniwheel casters and almost twice as higher than the power dissipated by the roller caster. The power dissipated by the skate caster was twice as higher than the average power over all the trials (Figure 3).

At loadings of 50 N and 100 N, the power dissipated was equivalent and lower than the average power over all trials. From 100 N, the power dissipated varied linearly

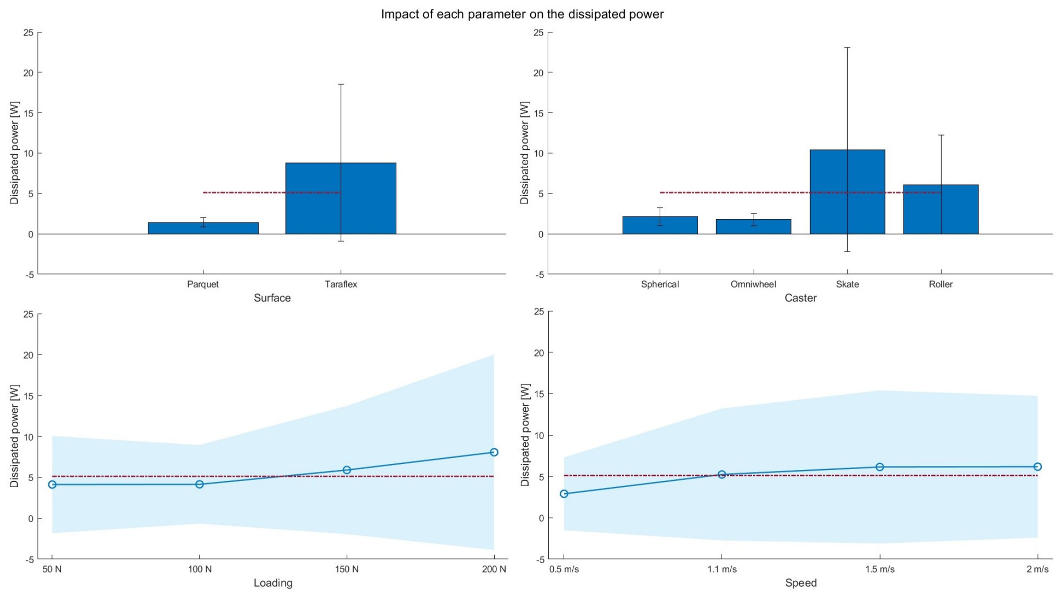


Figure 3. Impact of the parameters on the dissipated power for all the trials. The power values for each level of the parameter correspond to the average value of the power dissipated over all tests involving the level of the parameter concerned. The black error bars on the upper graphs and the colored areas on the lower graphs represent the standard deviation. The red line represents the mean value of the power dissipated over all the trials.

Figure 3. Alt Text. Four graphs illustrating the mean and standard deviation of dissipated power for all trials at each level of each parameter. The two upper graphs display the results as histograms with error bars. The left histogram shows the results for the surface parameter while the right histogram shows the results for the caster wheel parameter. The two lower graphs present the results as lines with shaded error bands. The left line graph shows the results for the loading parameter and the right line graph shows the results for the speed parameter.

positively with the loading. The power dissipated under a loading of 200 N significantly increased by 98% compared to a loading of 50 N (Figure 3).

The power dissipated at 0.5 m/s was a little more than two times lower than the average power. The powers dissipated at 1.5 m/s and 2 m/s were equivalent (Figure 3).

The minimal mean power dissipated was 0.4 ± 0.2 W for the skate caster, on the parquet, at 0.5 m/s and under a loading of 50 N. The maximal mean power dissipated was 43.3 ± 27.6 W still for the skate caster, but on the Taraflex, at 1.5 m/s and under a loading of 200 N (Table 2). The mean power over all the trials was 5.1 ± 3.0 W.

The Kruskal-Wallis test showed at least one significant difference between groups for each parameters ($p < 0.05$). The results of the Wilcoxon test showed that the differences between the different levels of each parameter were significant for all the combinations, except for seven combinations of levels of parameters (Table 3).

4. Discussion

This study was the first one presenting dissipated power due to rolling resistance. However, the power dissipated can easily be estimated from the values presented in the literature and then compared to the present study, even if the casters and the surfaces tested in this study were innovative.

High standard deviations were observed on the Taraflex, at high loading and for the skate and roller casters, even at low velocities. The deformation of the Taraflex during the trial, causing irregularities on the surface could explain the high stan-

Table 2. Mean and standard deviations of the power dissipated [W] during the trials.

		Spherical		Omniwheel		Skate		Roller	
		Parquet	**Taraflex**	**Parquet**	**Taraflex**	**Parquet**	**Taraflex**	**Parquet**	**Taraflex**
50 N	**0,5 m/s**	0,6±0,1	1,0±0,5	0,6±0,1	0,7±0,3	0,4±0,2	5,8±3,8	0,6±0,2	2,0±0,8
	1,1 m/s	1,3±0,4	1,9±1,0	1,3±0,4	1,5±1,0	1,4±0,7	5,0±3,0	0,6±0,3	4,4±2,5
	1,5 m/s	1,7±0,7	2,3±1,4	1,6±0,7	1,9±1,2	0,8±0,5	7,0±4,1	1,7±0,9	5,4±3,2
	2 m/s	1,8±0,9	2,4±1,5	1,8±1,0	2,1±1,5	1,6±1,2	6,6±4,2	0,9±0,8	6,3±3,9
100 N	**0,5 m/s**	0,7±0,1	1,5±0,6	0,7±0,1	1,0±0,5	0,7±0,3	8,1±3,3	0,5±0,3	4,9±1,9
	1,1 m/s	1,5±0,5	2,7±1,5	1,4±0,4	2,1±1,1	1,1±0,6	14,0±8,4	0,9±0,7	9,2±5,3
	1,5 m/s	1,8±0,7	3,1±2,2	1,4±0,5	2,2±1,4	1,6±0,9	17,5±11,0	1,7±1,4	11,3±7,1
	2 m/s	2,0±1,0	3,8±3,1	2,0±1,0	2,6±1,8	1,3±1,0	15,9±10,1	2,4±1,4	11,0±7,0
150 N	**0,5 m/s**	0,7±0,1	1,7±0,7	0,7±0,1	1,4±0,6	0,8±0,3	12,8±5,1	0,7±0,5	7,1±2,8
	1,1 m/s	1,5±0,5	3,0±1,6	1,4±0,4	2,6±1,4	1,5±1,2	24,2±13,8	1,5±1,1	14,8±8,5
	1,5 m/s	1,8±0,8	3,7±2,1	1,5±0,6	2,7±1,6	1,3±0,9	27,2±17,2	1,6±1,3	14,6±8,8
	2 m/s	2,0±1,0	4,3±3,5	1,8±1,0	3,3±2,0	2,4±1,5	26,4±17,0	2,0±1,3	15,3±9,4
200 N	**0,5 m/s**	0,7±0,2	1,9±0,8	0,6±0,1	1,5±0,6	1,1±0,8	20,2±8,2	1,0±0,4	9,8±3,7
	1,1 m/s	1,3±0,6	3,4±1,8	1,3±0,4	2,8±1,5	2,1±1,1	36,3±21,1	1,7±1,1	17,8±10,3
	1,5 m/s	1,8±0,8	4,3±2,5	1,7±0,7	3,2±1,8	2,7±1,8	43,3±27,6	2,1±1,7	20±11,7
	2 m/s	2,0±1,0	4,6±3,2	1,9±0,9	3,6±2,3	2,6±1,8	40,2±26,5	2,5±1,9	18,2±11,5

dard deviations observed on this surface. This phenomenon is accentuated under high loadings and is very probably due to the phenomenon of large deformations and the viscoelastic behavior of Taraflex. Regarding the skate and roller casters, a slight mechanical clearance could have modified the linearity of the trajectory of the casters on the surface. This phenomenon could have induced higher rolling resistance when the perpendicularity of the caster's axis was not perfect with the velocity direction [24–26].

The highest powers dissipated were on the Taraflex floor with a maximum value of 43.3 ± 27.6 W (Table 2). Chan et al. [22] showed that the deformation of the surface was a factor of increase of the RR. The Taraflex is a surface more deformable than the parquet, so it was not surprising to find that the power dissipated on the Taraflex was higher than the one dissipated on the parquet, regardless of the values of the other parameters.

The impact of the loading highlighted in this study was in agreement with the literature. Ott et al. [21] indicated that beyond a mass supported by the front caster wheels corresponding to 30 % of the total system mass, the RR was higher. It was the case in this study because the RR was higher from 150 N supported by one caster, that corresponded to 30 % of a total of 1000 N supported by the both front casters.

Several authors showed that the RR increased according to a positive linear relation with the loading, regardless the other parameters [23,24]. It was the case for this study, even if the power dissipated was equivalent under loadings of 50 N and 100 N. However, from 100 N, the differences between the loadings were not statistically significant. This may be mainly due to the high standard deviation found at these loads. It was also possible that the deformation of the rigid casters would not be sufficient to have a significant effect on the power dissipated due to RR.

Large differences were observed between the power dissipated by the four casters tested because of their disparate geometries and materials. This made it difficult to compare, but some trends could be identified. First of all, the casters with a more rigid material in contact with the surface (spherical and Omniwheel casters) dissipated less power than the casters with a more deformable material under a similar loading. However, it is important to note that a slight misalignment with the movement direction may have occurred for the skate and roller casters, which could have increased the

Table 3. Results of the Wilcoxon test (p-value). Values with a * represent the combinations for which the differences were not significant.

	Caster					
	Spherical vs Omniwheel	**Spherical vs Skate**	**Spherical vs Roller**	**Omniwheel vs Skate**	**Omniwheel vs Roller**	**Skate vs Roller**
p	0.09	< 0.001	< 0.001	< 0.001	< 0.001	0.11*
	Speed					
	0.5 m/s vs 1.1 m/s	**0.5 m/s vs 1.5 m/s**	**0.5 m/s vs 2 m/s**	**1.1 m/s vs 1.5 m/s**	**1.1 m/s vs 2 m/s**	**1.5 m/s vs 2 m/s**
p	< 0.001	< 0.001	< 0.001	2.3e-2	1.5e-3	0.20*
	Loading [N]					
	50 N vs 100 N	**50 N vs 150 N**	**50 N vs 200 N**	**100 N vs 150 N**	**100 N vs 200 N**	**150 N vs 200 N**
p	2.11e-2*	< 0.001	< 0.001	0.14*	0.02*	0.28*
	Surface					
	Parquet vs Taraflex					
p	< 0.001					

power dissipated by these casters. Then, most of the authors agreed that the lower the diameter of the caster, the higher the RR [14,16,21,22]. However, Ott et al. [24] and Sprigle et al. [23] observed that commercial casters with a larger diameter exhibited higher RR than others with a smaller diameter. The results of this study are difficult to connect to those of the literature regarding this point because several diameters of casters were tested, but with different geometries and materials. According to Chan et al. [22], the width of the caster, so the width of the contact area with the ground, would result in an increase of the RR. The results of this study are in accordance with this observation. Indeed, the skate caster, which was the caster with the larger contact surface area, due to its width and its deformable material, was also the caster that dissipated the most power. On the contrary, the spherical and the Omniwheel casters resulted in less friction on the ground and therefore less power dissipation than the other casters. Indeed, they were made from more rigid materials, so the contact surface with the floor was reduced. Especially, in the case of a rigid floor, their contact can be seen as a punctual contact. Once again, it is important to note that the slight misalignment with the movement direction that may have occurred with the skate caster could also be the origin of these differences.

The impact of the speed on the power dissipated was minimal from 1.5 m/s because the power dissipated was roughly equivalent for the speeds 1.5 m/s and 2 m/s. However, for speeds 0.5m/s, 1.1m/s and 1.5m/s, the power augmented with the speed, which suggests that the RR remains constant with the speed. This result is in accordance with the conclusions of Ott et al. [24] who showed that the influence of the speed on the RR was minimal.

Thus, with regard to the results of the impact of the different parameters on the power dissipated, the optimal combination to obtain the lowest possible power dissipation: a parquet surface, a 100 N or less loading, a speed of 0.5 m/s, and a spherical or an Omniwheel caster. In the case of sports involving high speeds, this study showed that, regardless of the surface roughness, the choice of a spherical or an Omniwheel caster would be advantageous due to the low mean power dissipated under various surface, loading, and speed conditions, even when moving in a straight line. Moreover, their multidirectional nature makes them particularly interesting candidates for sports involving rotations and abrupt forward and backward movements.

Power losses by the caster wheels cannot be neglected in light of the power developed by the athletes during propulsion. Indeed, Van der Woude et al. [27] reported mean power outputs for athletes and sedentary subjects between 22 and 106 W against mean dissipated power by the casters in this study of 5 W per caster, so 10 W as a total. Thus, the choice of the caster wheels is crucial for performance as they largely influence the gross mechanical efficiency of the manual wheelchair propulsion movement.

5. Conclusion

This study was the first one evaluating the power dissipated due to RR in front casters during wheelchair propulsion. However, the trends observed in this study in terms of influence of each parameter studied on power dissipated due to rolling resistance are close to those found in the literature.

This study was also the first one investigating the effect of a floor representative of wheelchair sports applications as a Taraflex-type PVC floor and investing the effect of a spherical caster. This study has shown that the Taraflex floor considerably increased the dissipated power, regardless of the other parameters. Then, it would not be recommended to use this type of floor for wheelchair sports performance and injury prevention purposes and lower musculoskeletal constraints with equivalent performance.

This study also revealed that spherical and Omniwheel casters seemed to be interesting candidates for use on wheelchairs, especially in a deformable floor such as a Taraflex floor because of their contact surface area close to a punctual contact.

In future work, it would be interesting to study the effect of the diameter for a same type of caster and also the effect of a fork free to rotate on power dissipation.

In the field, tests could also validate the present results by mounting the casters on the wheelchairs and evaluating their performances in straight-line movements, rotations, and abrupt changes of direction.

6. Disclosure statement

No potential conflict of interest was reported by the author(s).

7. Acknowledgements

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