

## Article

# A New Approach to Prevent Injuries Related to Manual Handling of Carts: Correcting Resistive Forces between Floors and Wheels to Evaluate the Maximal Load Capacity

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**Abstract:** Test methods that use pushing forces to evaluate the maximal load capacities of carts in design standards require a flat, smooth and horizontal steel plate and thus do not take into account the real conditions of work. Resistive forces of a single wheel of a cart in a uniform rectilinear motion were measured using a unique test bench with five loads. Forty-four wheels were tested (varying diameters, treads and bearings) with one steel plate and four resilient floor coverings. Based on a linear mixed model, all the following results were significant ( $p < 0.05$ ). Resistive forces were increased linearly with the load and depended on the characteristics of both the wheel and floor. These forces decreased as the diameter increased. They were important for wheels with sleeve bearings but decreased for cone ball bearings and precision ball bearings. Resistive forces depended on the material of the tread and were higher for solid rubber treads. In contrast, the hardness of the tread had little effect. Resistive forces strongly depended on the hardness of the base foam of resilient floor coverings: the softer the base foam, the higher the resistive forces. Test methods in design standards should be reviewed, using corrective forces based on these present results, to prevent musculoskeletal disorders.

**Keywords:** musculoskeletal disorders; resistive forces; pushing forces; manual handling; risk prevention



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## 1. Introduction

Musculoskeletal disorders (MSDs) are known to be one of the main causes of disability in the world [1–5]. Regular pull/push actions exerted on manual handling trolleys, stand aid hoists, mobile hoists, postal roll cages, food trolleys or carts and, more generally, any manually propelled wheeled equipment (two wheels and more) may require large feats of effort, resulting in musculoskeletal disorders for their operators [6–10]. More particularly, these activities are associated with neck, low back, shoulder and forearm pains [6,11–15]. Some design standards for manual handling equipment [16,17] describe test methods for moving forces. The aim of these methods is to evaluate the maximal load of an item of equipment by defining a maximal force not to be exceeded. Nevertheless, these tests tend to be carried out on a flat, smooth and horizontal steel plate, which differs from the real conditions of use. Indeed, floors in secondary industry tend to be made of concrete, and resilient floor coverings tend to be used in tertiary industry (office buildings, hospitals, elderly care homes, hotels, etc.).

When an item of equipment is moving at constant velocity and in a straight line, it submits to a resistive force that opposes motion. This resistive force corresponds to the

minimum force needed to push the equipment. This force is the result of different forces, particularly rolling resistance (also called rolling friction in the literature) and bearing resistance forces [18–21], which depend of the wheels and of the nature (i.e., physical characteristics) of the floor in question. Therefore, it is necessary to evaluate this resistive force and its impact on the function of different types of wheels and of floors found in the settings in which such equipment is used.

A number of studies have evaluated resistive force in the initial and sustained phases of various wheeled items of equipment, such as wheelchairs, hospital beds and airplane meal carts [22–25]. Few studies have measured the force transmitted to the ground (mostly tile and carpet) by a wheel from a wheelchair [26,27] or a manual cart [28]. Those have shown that the types of wheels and floors involved affected the force values. However, these results were only obtained for four-wheel equipment and using a methodology that could not remove the influence of external parameters, such as frame deformation or weight distribution. Other studies have examined the implications of the shear forces between the feet and the floor on acceptable forces during push and pull tasks [29,30]. To date, most of the studies have investigated the biomechanical strain in pushing and pulling tasks. Among these studies, some agreed that pushing/pulling tasks are influenced by workers' experience (the methods used by the experimented workers seem to reduce pushing/pulling forces) [10,31,32]. On the other hand, there is no clear consensus on the issue of gender between the various works found in the literature. Some authors reported that pushing/pulling forces are higher for males than for females [33], while others showed the opposite [34,35]. This result is not surprising because it depends mainly on how the measurement protocols are implemented. The ISO 11228-2:2007 [36] standard gives the maximum acceptable forces for pushing/pulling tasks in the initial and the sustained phases. Two methods are described for evaluating the risk [36]. The first method (Annex A of the ISO 11228-2:2007) permits to evaluate the limits of pushing/pulling forces, taking into account several parameters: gender (maximum acceptable forces are higher for males than for females); frequency; duration and distance of the task (high frequency, long duration and high distance must be avoided). The second method (Annex B of the ISO 11228-2:2007) takes into account the demographic and anthropometric characteristics of the workers (age, gender and stature) to evaluate the limit forces.

Nevertheless, to our knowledge, no study has been carried out that assessed these forces from a mechanical point of view that might enable the designers of a cart to take into account the characteristics of the wheels and floor coverings that reduce both the pushing force and thus the risk of musculoskeletal disorders for the users [37].

The aim of this study was therefore to analyze the resistive force of different types of wheels in contact with different floors, without using a trolley or a cart for removed energy losses, such as frame deformation; influence of weight distribution and specificities induced by the human experimenter (non-zero acceleration, different pushing/pulling strategies for the task's execution, etc.). We studied the influence exerted by the load; the wheel parameters (diameter, tread material and its hardness and bearing) and floor characteristics (materials and hardness). All the manually propelled wheeled equipment using the wheels' characteristics studied can benefit from the results of this study.

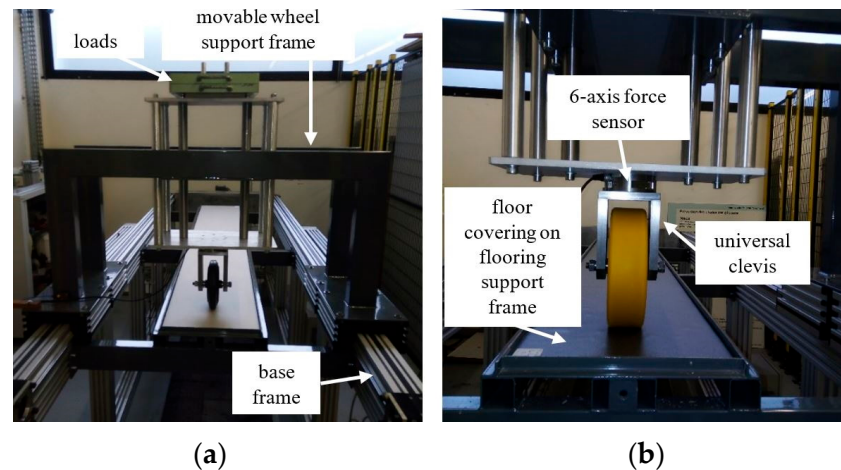
## 2. Materials and Methods

To characterize the resistive force of different types of wheels and floors, an original test bench was developed. This bench was designed to maintain a single wheel's contact with a floor and to prevent that wheel from swiveling. The wheel's motion was motorized, and measurements were made at a constant velocity for zero inertial force (uniform rectilinear motion).

### 2.1. Description of the Test Bench

The test bench was constructed with an aluminum base frame (Figure 1). The longitudinal horizontal sections serve as rails for linear guides. These guides had a programmable

alternating rectilinear motion and were driven by an electric motor by means of belts. Two independent mechanically welded frames were attached to the base frame. One, motionless, supported the floors (flooring support frame), while the other, movable, supported a unique wheel and the loads (wheel support frame). The wheel support frame was attached to the movable linear guides of the base frame. This wheel support frame also included vertical guide pins for changing the unique wheel and adapting the height according to the diameter of the wheel. These axes were terminated at each end by a platform. Wheel loads were placed on the top platform.



**Figure 1.** Bench: (a) overview of the different parts of the test bench; (b) focus on the universal clevis.

Although a single-axis force gauge can accurately measure resistive forces [38], a six-axis force sensor FTS-Delta SI-660-60 (SCHUNK, Neckar, Germany) was used to acquire the vertical and horizontal components of resistive force. This sensor was fixed to the lower part of the bottom platform. A universal steel wheel clevis was fixed to the lower part of the force sensor. This clevis was very stiff in order to avoid its deformation. Moreover, an accelerometer (Piezotronics 3711D1FA3G PCB, Depew, NY, USA) was fixed onto the wheel support frame to acquire the acceleration signal in the direction of the translational motion of the wheel. All experimental signals (acceleration and forces) were acquired using a DEWE-43A data acquisition system (DewesoftX Version 2022.4) with a sample rate of 100 Hz. Once the wheel was fixed on the universal clevis, it was placed in contact with the floor. The floors were glued to a steel plate (measuring  $2000 \times 300$  mm) with acrylic adhesive in accordance with the manufacturer's recommendations. This plate was installed in the flooring support frame. A computer program was used to define and control the motion velocity and the number of round trips of the wheel. To perform these round trips, the base frame comprised telemechanic limit switches at its longitudinal ends.

For a wheel moving on the flooring and for each load, the trial consisted of carrying out three roundtrips. Useful signals were obtained along the longitudinal direction during the steady state, where this signal was constant. The average of this signal was calculated using Stata software version 18 for each outward and each return. The resistive force  $F$  was then expressed by Relation (1):

$$F = (1/3) \sum_{i=1}^3 [|\text{average}(\text{outward}_i)| + |\text{average}(\text{return}_i)|] / 2 \pm 2\sigma / \sqrt{3}, \quad (1)$$

where  $\sigma$  was the repeatability standard deviation.

## 2.2. Velocity at the Steady State

The constant velocity to be reached at the steady state, where acceleration was zero, was set via the Human–Machine Interface. At first, the steady state was reached in 0.5 s. Following this, on a roundtrip, it was reached in under 1 s. Analysis of the literature

showed different speed values when the wheeled equipment was manually propelled. The informative Annex D of the standard ISO 11228-2:2007/Amd.1:2022 [36,39] requires a velocity of 0.33 m/s for measuring initial and sustained forces when a cart or a trolley is pushed by an operator. Nevertheless, some studies reported that operators push with different velocities in the range 0.25–1.5 m/s [40]. Resnick and Chaffin [41] reported that stronger operators push a cart in the range of 0.8–1.1 m/s, whereas weaker operators push it in the range of 0.4–0.5 m/s, for loads comprising between 45 kg and 225 kg. By comparison, an average walking speed of 1.34 m/s is estimated [42]. A speed faster than 1 m/s when pushing a loaded manually propelled wheeled item of equipment can be reached by very few operators. Moreover, a recent study using a drum-based testing machine suggested that velocity (for speeds between 0.5 m/s and 1 m/s) does not significantly influence the rolling resistance force for wheelchair wheels [21]. As a result, all trials were performed at 0.69 m/s (2.5 km/h), which can be an average speed of wheeled equipment manually propelled at a steady state.

### 2.3. Loads

The tests were carried out, for each wheel and flooring, under five different loads: 13, 24, 37, 49 and 62 kg. These loads were in good agreement with the static and dynamic load capacities of the different wheels.

### 2.4. Floors Tested

We studied a flat, smooth and horizontal steel plate and four resilient indoor floor coverings. The resilient floor coverings were composed of three PVC multilayer floor coverings (PVC.Fl.1, PVC.Fl.2 and PVC.Fl.3) and one monolayer rubber floor covering (Rub.Fl.). PVC multilayer floor coverings are constituted, from top to bottom, by a usage layer, a very thin intermediate layer and a base foam. The aim of this base foam is to reduce impact sounds. Moreover, according to the French UPEC classification of flooring (UPEC defines four types of stress: U for resistance of pedestrian wear, P for resistance of punching caused by fixed or mobile equipment, E for water resistance and C for chemical resistance) [43], which summarizes the technical features for normal use, the three PVC multilayer floor coverings have the same classification (U3 P3 E2/3 C2). The monolayer rubber floor covering is classified as U4 P3 E1/2 C1/2. The same classification P (for Puncturing) suggests that the four floor coverings exhibit identical behavior when mechanical stress is induced by the rolling motion of the handling equipment. In addition to this classification, Shore-A hardness studies were used to distinguish these four floor coverings, which are made with elastomeric materials. We studied the hardness of the floorings using the determination method described in the standard EN ISO 868 [44]. Hardness tests were performed, especially in the case of multilayer floor coverings, in one part, on complete floor covering and, in the other part, on each mechanically separated layer (except for PVC.Fl.2.): the usage layer (with the very thin intermediate layer) and the base foam. Hardness was conveniently measured vertically by means of a Shore-A durometer coupled with a Bareiss BS 61 II test stand at a temperature of 25 °C. The test stand permitted us to correctly position the durometer's indenter at vertical positions of the specimen and to apply the correct test load. The hardness value A/15 was read within 15 s after the specimen's indentation. Mean values were then calculated with five different indentations of the specimen.

### 2.5. Wheels Tested

Forty-four different wheels were tested. A wheel is characterized by its diameter, tread and wheel bearing. The wheel diameters tested were 80, 100, 160 and 200 mm. The treads were solid rubber (hardness of A80 and A85); elastic-tire (A64, A67 and A68); thermoplastic rubber (A87 and A88); synthetic rubber (A87 and A88); injected polyurethane (A91, A92 and A95); casted polyurethane (A92) and polyamide (D75). The wheel bearings were sleeve bearing (S.B.), wheel with cone ball bearing (C.B.B.) and wheel with precision ball bearing

(P.B.B.). Finally, this study included 44 wheels and 25 observations for each wheel (i.e., a total number of 1100 observations).

## 2.6. Statistical Analysis

To verify the linearity between load and force, linear regression models were used. The origin was fixed to zero. The performance of the linear regression models between the resistive force and the load was evaluated using the adjusted coefficient of determination  $R^2$  and the normalized root mean square error (NRMSE).

A linear mixed model was used to analyze the main effects of different factors on the resistive force and wheels' characteristics, as well as their interaction effects. These models are designed to analyze variables from different levels without making a priori assumptions on their respective importance and using a statistical model that properly includes the various dependencies [45]. It included the load; the floor covering (steel, PVC.Fl.1, PVC.Fl.2, PVC.Fl.3 and Rub.Fl); the wheel's tread (solid rubber, elastic-tire, thermoplastic rubber, synthetic rubber, injected polyurethane, casted polyurethane and polyamide); the wheel bearing (S.B., C.B.B. and P.B.B.) and the wheel's diameter (80, 100, 160 and 200 mm) as explanatory variables. Interactions with mechanical significance were tested. In the case of a non-significant interaction, this was removed from the model. Significant effects were then analyzed using Bonferroni's post hoc comparison tests. The significance threshold was set at 5% ( $p < 0.05$ ). The residual normality of the models was verified. The effect size was evaluated by means of Cohen's  $d$  values for post hoc comparisons. The effect size was considered small ( $0.2 \leq d < 0.5$ ), medium ( $0.5 \leq d < 0.8$ ) or large ( $d \geq 0.8$ ), according to Cohen [46]. In the case of statistical significance ( $p < 0.05$ ), only results with a small, medium or large effect size ( $d > 0.20$ ) were presented. The main effects, which were significant, are illustrated in figures. Visually, when confidence intervals overlap, this means that there is no significant difference between the values being compared.

Statistical analysis was performed using Stata software version 18.

## 3. Results

Details of the linear mixed model (coefficients, standard errors,  $p$ -values and 95% confidence intervals) can be found in Appendix A.

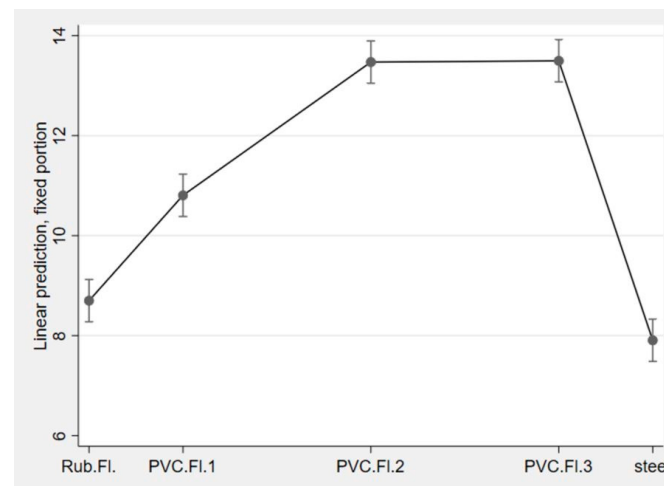
### 3.1. Load's Effect

The main effect on the resistive force of the load, considering all the floors and all the wheels, was significant ( $p < 0.001$ ). The resistive force increased linearly as the load carried by the wheel increased. Strong adjusted coefficients of determination  $R^2$  were obtained for all wheels on the steel plate and on all floors, meaning that the regression model fit the observed data (adjusted  $R^2$  were greater than 0.92, except for one wheel, for which the value was 0.80 on Rub.Fl. floor covering). Moreover, the linear regression models accurately predicted the dataset. Indeed, a very high goodness of fit with 95% of the data with a NRMSE lower than 5% and, more precisely, lower than 1% for 58% of the data was obtained. In addition, for 5% of the data, the NRMSE were between 5% and 10%.

### 3.2. Floor's Effect and Hardness of Floor Coverings

#### 3.2.1. Floor's Effect

The main effect on the resistive force of the different floors, considering all the floors and all the wheels, was significant ( $p < 0.001$ ). In all cases, the force was lower for the steel plate (0.4 N at 13 kg for a 200 mm casted polyurethane wheel with P.B.B.). The highest force was recorded for PVC.Fl.3 (49 N for an 80 mm solid rubber wheel with S.B.), followed by PVC.Fl.2 (48 N for an 80 mm solid rubber wheel with S.B.). Figure 2 presents the predictive margins of the resistive force for each floor with 95% confidence intervals.



**Figure 2.** Predictive margins of floors on the resistive force (95% confidence intervals).

### 3.2.2. Hardness of Floor Coverings

As the results obtained for the different floor coverings differed, the UPEC classification could not be used to distinguish them with regard to resistive forces. We therefore studied the hardness of floor coverings. The mean hardness values (in Shore-A/15) of separated layers of the floor coverings and of complete floor coverings are reported in Table 1. The greater the hardness, the more the material in question was able to resist deformation. Thus, with a Shore-A hardness of 95, monolayer rubber floor covering Rub.Fl. is hard. Moreover, the hardness values of usage layers were lower when measured on the complete floor covering rather than on mechanically separated layers, because the base foam was compressed by the indentation. However, in all cases, the usage layers were harder than the base foams. The usage layers of the three PVC multilayer floor coverings were hard materials but less hard than Rub.Fl.'s usage layer. Moreover PVC.Fl.1's usage layer was harder than PVC.Fl.2's and PVC.Fl.3's usage layers. In contrast, the hardness of the base foam was equal on the complete floor and on the mechanically separated layer. PVC.Fl.1's base foam hardness was greater than the hardness of PVC.Fl.2's and PVC.Fl.3's base foams, which were at the mid-range of the Shore-A scale. PVC.Fl.1's base foam had a medium hardness, whereas PVC.Fl.2's and PVC.Fl.3's base foams had a medium softness, although PVC.Fl.2's base foam was slightly harder than PVC.Fl.3's base foam. Therefore, PVC.Fl.2's and PVC.Fl.3's base foams provided the best impact absorption, but, unfortunately, they also deformed more than a harder material.

**Table 1.** Hardness values (in Shore-A/15) of the four floor coverings tested.

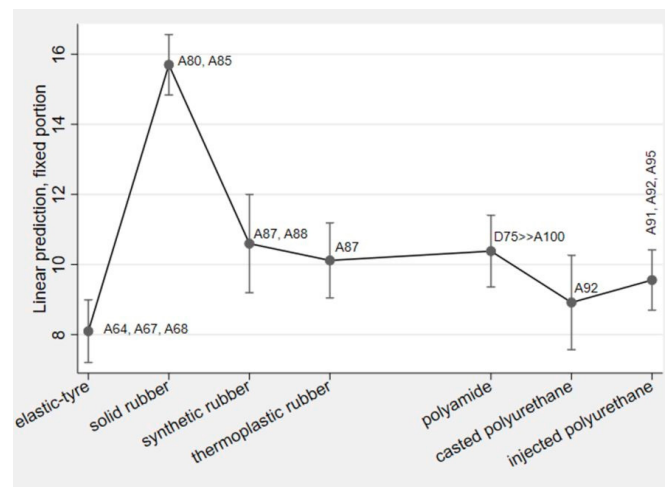
|                                 |             | Rub.Fl. | PVC.Fl.1 | PVC.Fl.2 | PVC.Fl.3 |
|---------------------------------|-------------|---------|----------|----------|----------|
| On mechanically separated layer | Usage layer | /       | /        | A/15:91  | A/15:86  |
|                                 | Base foam   | /       | /        | A/15:49  | A/15:47  |
| On complete floor covering      | Usage layer | A/15:95 | A/15:88  | A/15:77  | A/15:74  |
|                                 | Base foam   | A/15:95 | A/15:73  | A/15:52  | A/15:49  |

### 3.3. Effect of Wheels' Characteristics

#### 3.3.1. Effect of Wheels' Treads

The main effect on the resistive force of the wheel's tread was significant ( $p < 0.001$ ). The hardness of the wheel's tread was not included in the linear mixed model, because it did not exhibit a significant effect ( $p = 0.092$ ). Indeed, resistive forces were higher for wheels with a solid rubber tread that had high hardness values (A80 and A85), and wheels with elastic-tire tread (with lower hardness values A64, A67 and A68) had the weakest

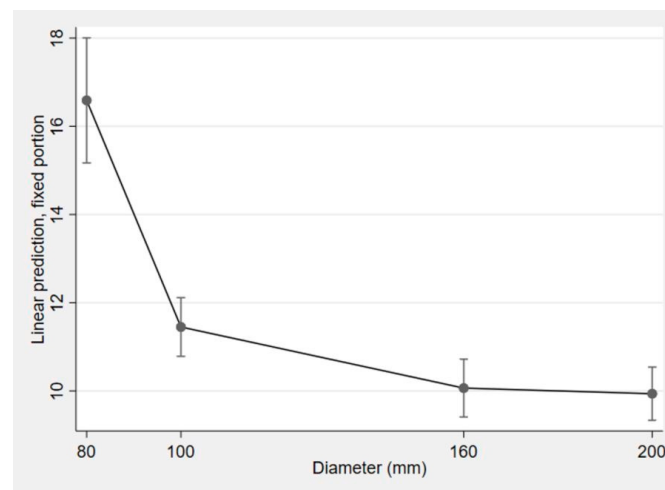
resistive forces. Figure 3 depicts the predictive margins, with 95% confidence intervals, of the wheels' treads on the resistive force.



**Figure 3.** Predictive margins of the wheels' treads on the resistive force (95% confidence intervals).

### 3.3.2. Effect of Wheels' Diameter

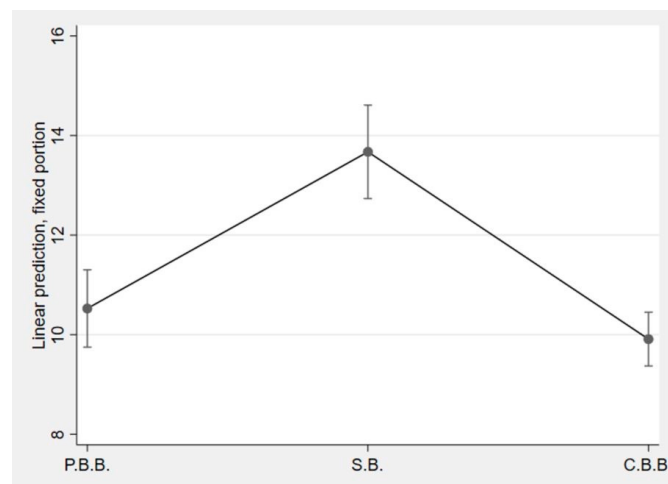
The main effect on the resistive force of the wheels' diameter was significant ( $p < 0.001$ ). The resistive force decreased when the wheels' diameter increased (Figure 4). The resistive force was the highest for a wheel diameter of 80 mm. A high difference was recorded between 80 mm and 100 mm. Nevertheless, beyond 100 mm, the resistive force slowly decreased. The resistive forces were similar for wheel diameters of 160 mm and 200 mm.



**Figure 4.** Predictive margins of the wheels' diameter on the resistive force (95% confidence intervals).

### 3.3.3. Effect of the Wheel Bearing Types

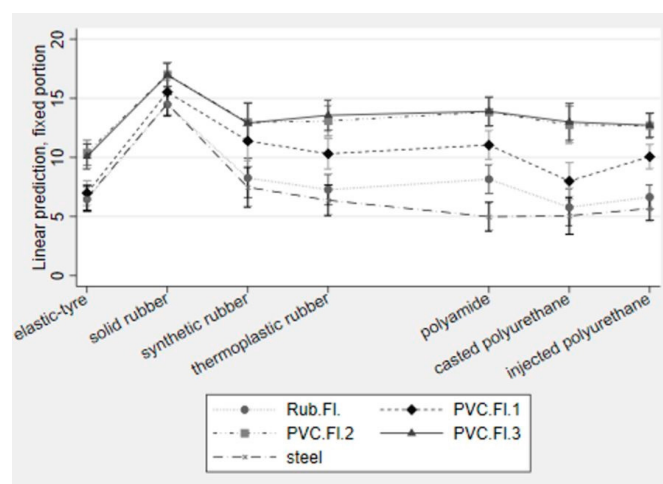
The main effect on the resistive force of the bearing type of the wheel was significant ( $p < 0.001$ ). Compared to high-quality bearings like C.B.B. and P.B.B., S.B. increased the resistive force. Indeed, S.B., which was the simplest type of bearing, increased the friction, because the axis was directly in contact with the plain bearing. Moreover, the resistive forces were not significantly different for C.B.B. and P.B.B. bearings (Figure 5).



**Figure 5.** Predictive margins of the wheels' bearings on the resistive force (95% confidence intervals).

### 3.4. Interactions

Only the interaction between the treads and the floors was significant ( $p < 0.001$ , Figure 6). Elastic-tire tread exhibited the weakest resistive force on the soft floor covering (PVC.Fl.2 and PVC.Fl.3) and on the medium hard floor covering (PVC.Fl.1). For hard floors (steel and Rub.Fl.), the resistive forces were of the same order of magnitude for all the wheel treads, except for solid rubber tread, which exhibited a high resistive force for all floors ( $d > 0.8$ ). For all treads, the resistive forces were higher for multilayer floor coverings (PVC.Fl.1, PVC.Fl.2 and PVC.Fl.3) than for the steel plate, mostly with a large effect size ( $d > 0.8$ ). Only elastic-tire tread and solid rubber tread exhibited no significant difference between PVC.Fl.1 and the steel plate ( $p > 0.05$ ). Likewise, there was no significant difference between the two soft multilayer floor coverings PVC.Fl.2 and PVC.Fl.3. Finally, there was no significant difference between the monolayer rubber floor covering Rub.Fl. and the steel plate for all treads, except for polyamide tread, which displayed a higher resistive force for Rub.Fl. than for the steel plate ( $0.5 > d > 0.8$ ).



**Figure 6.** Interaction effect of the wheel tread and floor (95% confidence intervals).

## 4. Discussions and Perspectives

In this study, the resistive force was measured for 44 different wheels of varying characteristics moving on one steel plate and on four resilient floor coverings. While the pushing force has tended to be measured using a cart on several identical wheels, these results were obtained by analyzing a single wheel on these floors.

#### 4.1. Load

The linear increase of the resistive force with loads for all wheels and floors has been established with a high adjusted coefficient of determination ( $R^2 > 0.92$ ) and a NRMSE lower than 5% for 95% of the data. This linear relationship was in accordance with a previous work that measured pushing forces using a cart [28].

#### 4.2. Floor

The resistive forces were strongly dependent of the floor coverings. Therefore, the UPEC classification was not effective in distinguishing and classifying these floor coverings in view of their resistive forces. Conversely, comparisons of the resistive force measurements and Shore-A hardness studies gave interesting results. The resistive force of Rub.Fl., which had a high Shore-A hardness value, was close to that of steel. In contrast, the resistive force was the highest for soft floor coverings like PVC.Fl.2 and PVC.Fl.3. Previous studies found that, the harder the floor, the weaker the pushing force required to move the cart [28,47,48]. While true, this statement was simplistic, because, for multilayer resilient floor coverings like those studied in the present paper, the hardness depended on the different layers of the floor (each one having its own hardness). Undeniably, base foams (except for Rub.Fl., which is a monolayer floor covering) that were harder had lower resistive forces, whereas the hardness of the usage layers was similar. Base foam deformation led to greater energy dissipation and, thus, higher resistive forces. As a result, the Shore-A hardness of a floor covering's base foam could be used as an effective means for monitoring the resistive force.

#### 4.3. Wheel's Tread

The resistive force depended on the type of tread of the wheel and, contrary to White's [49] findings, not by the hardness of the wheel's tread. Indeed, solid rubber treads, with a hardness of A80 and A85, had greater resistive force compared to other treads that exhibited inferior and superior hardness values. For example, elastic-tire treads (with hardness values of A64, A67 and A68) and polyurethane treads (with hardness values of A91, A92 and A95) had lower resistive forces than solid rubber treads. As a result, harder treads did not reduce the pushing force required [50].

#### 4.4. Wheel's Diameter

The resistive force decreased when the wheel's diameter increased. These results agreed with the findings of previous studies [18,28]. Nevertheless, the more the diameter increased, the more the resistive force slowly decreased (Figure 4).

#### 4.5. Wheel's Bearing Type

The type of wheel's bearing affected the resistive force. S.B., using a sliding motion between the bore of the wheel and the axle shaft, increased the resistive force compared to C.B.B. and P.B.B., because it had a higher rotational friction. S.B. was a basic type of bearing. On the opposite end of the spectrum, C.B.B. and P.B.B. facilitated motion due to reducing the rotational friction between the bore of the wheel and the bearing.

#### 4.6. Interaction between Treads and Floors

Regardless of the floor covering, solid rubber treads must be prohibited in order to reduce the resistive force and thus the pushing–pulling force required to move a cart. For soft floor coverings, preference should be given to elastic-tire treads. A polyamide tread seemed more appropriate for very hard flooring and must therefore be used on concrete floors deployed in the industrial field. Moreover, the use of a flat, smooth and horizontal steel plate, as recommended by design standards of manual handling equipment [16,17], was inappropriate for evaluating the maximum weight capacity of a cart. Indeed, it was overestimated in relation to the real conditions of use. This overestimation may increase musculoskeletal disorders. The test methods described in the design standards might

therefore need to be modified to take into account the floor coverings on which the cart will be driven. However, there are so many different floor coverings that it was impossible to be exhaustive. Since the resistive force depended on the hardness of the base foam used for a particular floor covering, it is possible to use the Shore-A hardness scale to classify these floors. We recommend that corrective forces are defined in order to correct the results obtained with the steel plate (as a reference floor) and in order to take into account the influence of the floor coverings. These corrective forces would be determined from the resistive force results obtained in the present study. They would consider the various influencing factors identified (base foam hardness, wheel's tread, wheel's diameter and wheel's bearing). By combining these corrective forces with the mechanical model of a cart, it would then be possible to define the maximum weight capacity of the cart on the resilient floor coverings. This new approach would, in turn, prevent some injuries that occur during manual handling. Our work on this new approach will be presented in another article.

#### 4.7. Perspectives

Future works could use the same test bench to study the resistive force required to move these wheels on other floor coverings, like natural fiber flooring (coconut, wool, sisal, seagrass, etc.) or synthetic fibers (polyamide, polypropylene, polyester, etc.). It could also study the additional effort generated by the threshold bars when the cart moves. Furthermore, this study could also be extended to measure the swiveling force on the wheel's and floor's characteristics and the swivel offset. It is established that a long offset makes swiveling easier, while a short offset makes doing so more difficult. Frank and Abel [18] experimented on the turning resistance of 11 wheelchairs on three floors and observed that bigger wheels with soft treads gave higher resistance. Fallot et al. [51] studied seven wheels turning on three floors, showing that the swiveling resistance was more important for carpets than for tiles but that this effort was mainly influenced by the type of wheel. However, none of these studies took into account the offset, and they studied the effects of only a few different wheels.

#### 5. Conclusions

An original test bench allowed us to evaluate the resistive force required to overcome the resistive force that opposes the linear motion of a wheel. It permitted independent parameters, including those related to using a human experimenter, frame deformation and weight distribution. The resistive force increased linearly with the load. The resistive force depended on both the wheel's characteristics (diameter, type of tread and type of bearing) and the type of floor. This force decreased with the wheel diameter. Nevertheless, once the wheel diameter exceeded 100 mm, the influence of the diameter was less significant. In addition, this force also decreased for wheels with C.B.B. and P.B.B. compared to wheels with S.B. Although the resistive force depended on the type of tread, it did not depend on the hardness of the tread. Indeed, it was higher for wheels with solid rubber tread. Therefore, manually propelled wheeled equipment could be equipped with high-diameter wheels in order to reduce pushing forces. For a straight line motion, wheels with solid rubber tread must be excluded. Wheels with elastic-tire tread or polyurethane tread (casted or injected) are the best choice. S.B. bearing must be also excluded to the benefit of C.B.B. or P.B.B. bearings.

Moreover, our study highlighted that the hardness of the base foam for resilient floor coverings can be used to classify these floors: the softer the base foam (low Shore-A hardness), the higher the resistive force. Consequently, to reduce the pushing forces for moving a manually propelled wheeled equipment, it suits to install a hard monolayer floor covering (>A75) or a multilayer floor covering with a hard base foam (>A75).

Furthermore, the methods for testing the pushing forces described in design standards that are used for evaluating the load capacity of carts were not appropriate and should be reviewed to bring them in line with the real conditions in which such devices are used. Our results provide the correction forces required, which, when combined with the thrust

force measurements on the steel plate, enable us to estimate the maximum load capacity for each floor covering without making any additional measurements. The calculation of correction forces will be valorized in a next article to elaborate abacuses, which will enable the modeling of pushing forces (mechanical model). Theoretically, this predictive model could be used by manufacturers or customers to design carts with pushing forces as low as possible. Then, the efforts necessary to move the carts will be limited for users, and the equipment will be adapted to the working conditions. Using this new approach would also prevent a number of musculoskeletal injuries associated with manual handling. Of course, there are other approaches that can be investigated to prevent these disorders. One of the parameters that influences the resistive forces is the hardness of the floor base foam. By modifying the nature of this material, it can be possible to limit the effort necessary to move the carts. The nature of the materials used to design the wheels is also very important, since it is at the origin of the shear and friction forces on the floor coverings. The development of new materials such as composites can be interesting, because it enables us to control and adjust the surface energy of the material used for the wheels. If this last is very far from the surface energy of the floor coverings, it leads to a strong reduction in the interactions and, thus, in the shear and friction forces.

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## Appendix A

**Table A1.** Linear mixed model.

| Mixed-effects ML regression<br>Group variable: wheel |             |           |       |        |           | Number of obs = 1100<br>Number of groups = 44<br>Obs per group:         |                                    |
|------------------------------------------------------|-------------|-----------|-------|--------|-----------|-------------------------------------------------------------------------|------------------------------------|
| Log likelihood = −2637.8917                          |             |           |       |        |           | Wald chi2(40) = 5964.25<br>Prob > chi2 = 0.0000<br>[95% conf. interval] |                                    |
| Res. Force                                           | Coefficient | Std. err. | Z     | p >  z |           |                                                                         | min. = 25<br>avg = 25<br>max. = 25 |
| Diameter                                             |             |           |       |        |           |                                                                         |                                    |
| 100                                                  | −5.137178   | 0.8044351 | −6.39 | 0.000  | −6.713842 | 3.560514                                                                |                                    |
| 160                                                  | −6.522323   | 0.8054865 | −8.10 | 0.000  | −8.101048 | −4.943599                                                               |                                    |
| 200                                                  | −6.649512   | 0.7894358 | −8.42 | 0.000  | −8.196778 | −5.102246                                                               |                                    |
| Bearing                                              |             |           |       |        |           |                                                                         |                                    |
| S.B.                                                 | 3.145798    | 0.7006577 | 4.49  | 0.000  | 1.772534  | 4.519062                                                                |                                    |
| C.B.B.                                               | −0.615206   | 0.5154209 | −1.19 | 0.233  | −1.625412 | 0.3950004                                                               |                                    |

Table A1. Cont.

|              |                  |            |           |       |       |            |           |
|--------------|------------------|------------|-----------|-------|-------|------------|-----------|
| Tread        |                  |            |           |       |       |            |           |
|              | Sol.rub          | 7.961803   | 0.8483109 | 9.39  | 0.000 | 6.299144   | 9.624462  |
|              | Syn.rub          | 0.8955412  | 1.107486  | 0.81  | 0.419 | −1.275091  | 3.066173  |
|              | The.rub          | −0.2099413 | 0.9299813 | −0.23 | 0.821 | −2.032671  | 1.612788  |
|              | Polya            | −1.597063  | 0.9122858 | −1.75 | 0.080 | −3.38511   | 0.1909844 |
|              | Cas.pol          | −1.526128  | 0.9787755 | −1.56 | 0.119 | −3.444493  | 0.3922363 |
|              | Inj.pol          | −0.89026   | 0.8022754 | −1.11 | 0.267 | −2.462691  | 0.6821708 |
| Floor        |                  |            |           |       |       |            |           |
|              | Rub.Fl.          | −0.1201949 | 0.5759169 | −0.21 | 0.835 | −1.248971  | 1.008582  |
|              | PVC.Fl.1         | 0.4010548  | 0.5759169 | 0.70  | 0.486 | −0.7277216 | 1.529831  |
|              | PVC.Fl.3         | 3.500329   | 0.5759169 | 6.08  | 0.000 | 2.371553   | 4.629106  |
|              | PVC.Fl.2         | 3.813249   | 0.5759169 | 6.62  | 0.000 | 2.684473   | 4.942026  |
| Floor #tread |                  |            |           |       |       |            |           |
|              | Rub.Fl.#Sol.rub  | 0.0587853  | 0.7726736 | 0.08  | 0.939 | −1.455627  | 1.573198  |
|              | Rub.Fl.#Syn.rub  | 0.9073139  | 1.102797  | 0.82  | 0.411 | −1.254128  | 3.068756  |
|              | Rub.Fl.#The.rub  | 1.021173   | 0.9286381 | 1.10  | 0.271 | −0.7989244 | 2.84127   |
|              | Rub.Fl.#Polya    | 3.291485   | 0.8797276 | 3.74  | 0.000 | 1.567251   | 5.01572   |
|              | Rub.Fl.#Cas.pol  | 0.8501504  | 0.9975174 | 0.85  | 0.394 | −1.104948  | 2.805248  |
|              | Rub.Fl.# Inj.pol | 1.075153   | 0.8144695 | 1.32  | 0.187 | −0.5211774 | 2.671484  |
|              | PVC.Fl.1#Sol.rub | 0.5811482  | 0.7726736 | 0.75  | 0.452 | −0.9332643 | 2.095561  |
|              | PVC.Fl.1#Syn.rub | 3.519972   | 1.102797  | 3.19  | 0.001 | 1.35853    | 5.681414  |
|              | PVC.Fl.1#The.rub | 3.53343    | 0.9286381 | 3.80  | 0.000 | 1.713333   | 5.353528  |
|              | PVC.Fl.1#Polya   | 5.66196    | 0.8797276 | 6.44  | 0.000 | 3.937726   | 7.386195  |
|              | PVC.Fl.1#Cas.pol | 2.539317   | 0.9975174 | 2.55  | 0.011 | 0.5842191  | 4.494415  |
|              | PVC.Fl.1#Inj.pol | 3.969078   | 0.8144695 | 4.87  | 0.000 | 2.372747   | 5.565409  |
|              | PVC.Fl.3#Sol.rub | −1.073436  | 0.7726736 | −1.39 | 0.165 | −2.587849  | 0.440976  |
|              | PVC.Fl.3#Syn.rub | 1.925582   | 1.102797  | 1.75  | 0.081 | −0.2358599 | 4.087025  |
|              | PVC.Fl.3#The.rub | 3.689882   | 0.9286381 | 3.97  | 0.000 | 1.869784   | 5.509979  |
|              | PVC.Fl.3#Polya   | 5.409364   | 0.8797276 | 6.15  | 0.000 | 3.68513    | 7.133599  |
|              | PVC.Fl.3#Cas.pol | 4.440795   | 0.9975174 | 4.45  | 0.000 | 2.485697   | 6.395893  |
|              | PVC.Fl.3#Inj.pol | 3.525469   | 0.8144695 | 4.33  | 0.000 | 1.929138   | 5.1218    |
|              | PVC.Fl.2#Sol.rub | −1.367995  | 0.7726736 | −1.77 | 0.077 | −2.882407  | 0.1464179 |
|              | PVC.Fl.2#Syn.rub | 1.663072   | 1.102797  | 1.51  | 0.132 | −0.4983702 | 3.824514  |
|              | PVC.Fl.2#The.rub | 2.899438   | 0.9286381 | 3.12  | 0.002 | 0.079341   | 4.719535  |
|              | PVC.Fl.2#Polya   | 5.043116   | 0.8797276 | 5.73  | 0.000 | 3.318881   | 6.76735   |
|              | PVC.Fl.2#Cas.pol | 3.890569   | 0.997517  | 3.90  | 0.000 | 1.935471   | 5.845667  |
|              | PVC.Fl.2#Inj.pol | 3.176885   | 0.8144695 | 3.90  | 0.000 | 1.580554   | 4.773216  |
|              | WeightC          | 0.293873   | 0.0044627 | 65.85 | 0.000 | 0.285126   | 0.3026196 |
|              | Cons.            | 11.94014   | 0.9700958 | 12.31 | 0.000 | 10.03879   | 13.84149  |

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