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Development and Testing of an Ergonomic Handle and Wheel Design for Industrial Transport Carts

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Abstract

Background: Transport carts are common supporting tools to move heavy weights at work. Pushing and pulling of carts can induce musculoskeletal disorders if not performed ergonomically. Reasons are dysfunctional body positions due to a given handle position and positions and composition of the transport devices as well as the roller friction and resistance.

Methods and findings: The study reports (1) the development of a new handle design and (2) the effects of the handle design in combination with optimized wheels in different cart maneuvering situations. 28 industrial workers participated in the study. Body positions while cart handling were observed via 3 D-kinemetry. EMG, heart rate monitoring and RPE were used to analyze the body exposure during cart handling in different conditions (cart mass, floor, wheel, handling).

Cart mass and wheel conditions determined the biomechanical strain. The new handle design was used especially by workers with lower body mass to obtain optimal points of force application.

Conclusions: The study reports on the development of a new ergonomic handle design for industrial transport carts based upon a biomechanical analysis of the influences of handle orientation, height and wheel conditions on biomechanical strain, especially for cart maneuvering. The new design induces more ergonomic body positions particularly for lightweight employees.

Keywords: Body exposure; Electromyography; Hand reaction forces; Practical implementation

Introduction

Industrial workspaces have mostly been redesigned to replace the carrying of objects by tasks that require pushing or pulling [1]. A current analysis in the automotive supply sector has shown that about 10% of all working processes involve pushing and pulling on a regular and repetitive basis with a great share (41.2%) requiring the manipulation of objects with total masses between 200 kg and 1000 kg [2].

According to the literature, these tasks increase the risk of musculoskeletal disorders (MSDs), presumably due to high loads and/or frequent task repetitions [3,4]. It has not been specified which parts of the body are negatively affected by pushing and pulling tasks sufficiently yet. A review by Roffrey et al. [5] focusing on low back pain failed to provide a clear answer. According to the authors, there are inconsistent findings if pushing and pulling of heavy loads results in low back pain. Another review by Hoozemans et al. [6] summarizes that overuse and pain can be generally identified in the wrist, forearm, elbow, upper arm and shoulder not everybody region was supported by every study; most consistently overuse and pain were found in the shoulder. The authors conclude that there is evidence for the relation of pushing and pulling tasks and physical problems in the upper extremities. However, this result was based on a limited number of studies. To reduce MSD prevalence, research has focused on how pushing and pulling task intensity is related to internal strain factors at injury-prone body locations such as the knees, the shoulders and the lower back [7]. To assess the biomechanical load, these parameters have to be quantified in terms of intensity, duration and frequency. In addition, a review by Argubi Wollesen et al. [8] suggested the cart mass, the wheels and resulting friction as well as task experience and technique influences biomechanical strain.

Moreover, the handle configuration e.g., height and orientation (horizontally or vertically) affects the efficiency of transmitting forces from the person to the cart by affecting both the capacity to produce force and the resulting postural demand [9]. Following this hypothesis Chow and Dickerson [10] reported differences in shoulder joint pressure comparing 100 cm and 150 cm handle heights with reduced pressure when pushing at 150 cm and increased joint pressure for vertical handle positions.

Consequently, handles can potentially reduce task intensities and internal biomechanical strain. This is shown by a reduction of required hand forces which lead to a decreased muscle activation response between comparable tasks. Previous studies focused on the interactions between task intensity, external parameters (object, environment) and internal strain. Conclusions from task intensity on biomechanical strain are drawn by body segment models that calculate estimates of torques, compressions and shear forces [3,11-15]. Additionally, the shape of the handle can have a significant impact on the amount of force which can be transferred from the user to the object with the hand handle interface acting as the “weak link” in force transmission according to a study by Fothergill et al. [16].

Nevertheless, the reported study results have not been transferred into clear recommendations for favorable handle positions yet. Depending on the nature of the examined strain (local joint stress, general description of physical strain due to hand reaction forces) for straight forward pushing or straight backwards pulling and depending on the examined body region, the recommended handle height varies between individual hip level to shoulder level [10,17,18]. This might have caused the lack of guidelines for workplace or handle design in this context. A review by Garg et al. [19] also failed to address important factors like handle orientation etc. Therefore, the hazards of handling heavy loads manually have not been properly addressed so far [20]. Although Lin et al. [21] reported on normative data for one-handed standing pull strength and effects of handle orientation and between-handle distance regarding bi-manual push strength [22], the studies relied on isometric force or single hand force application only. Accordingly, ‘best practice’ recommendations on how to ergonomically operate carts dynamically in a work related environment and how to create a functional handle design based on related data are still insufficient. Moreover, the previous research did not lead to practical implementations of a sufficient handle design with biomechanical evaluation of different handle designs at the work place extremely scarce.

The systematic literature analysis by Argubi Wollesen et al. [8] leads to the following findings regarding the negative impact of strain:

- The mass of the object to be moved or the magnitude of the exerted force was described as the biggest influencing factor for existing strain [23].
- In addition, only very few studies assessed the impact of cornering, maneuvering and changes of direction [3,12,24]. Therefore, most of the current studies failed to represent the demands of the work environment adequately.
- Moreover, the handle characteristics necessary for an ergonomic movement technique for pushing or pulling have not yet been established.

An ergonomic analysis of carts and a systematic selection and configuration of handles and wheels are still lacking. Therefore, the goal of this study was to address this gap by developing a handle design based on a thorough analysis on the effects of handle height and handle orientation on biomechanical joint load in a first experiment (experiment 1).

We hypothesized that additionally to the influence of cart weight, the different handle height and handle orientation will lead to different biomechanical loads for pushing, pulling and maneuvering. After proofing the impact of the biomechanical load on the relevant muscle activity of the handle orientation, a handle design was developed concerning previous study results and the results of experiment 1.

Accordingly, the aim of the second experiment (experiment 2) was to examine the effects of this developed handle design on biomechanical loads, body exposure and grip positioning in an industrial environment and additionally, the influence of different surface conditions and wheel characteristics on the afore mentioned parameters.

Materials and Methods

Study design

The observational, descriptive study included two experiments with an embedded grip design step. First [1] assessment of the effects of different handle heights and orientations under laboratory conditions (300 and 500 kg) including maneuvering and cornering. Results of the first experiment lead to the development of an ergonomic handle design followed by [2] the examination of the effects of this handle design under various surface conditions (normal industrial floor and industrial metal grid [30 mm × 30 mm mesh size, 30 mm height]) and wheels (standard wheel: 180 mm diameter, 50 mm width [V182/20R]; lower friction wheel: 200 mm diameter, 50 mm width [POEV 200/20K-SG], both Blickle Raeder+Rollen GmbH u. Co KG, Germany), both on a standardized course and with a standardized cart mass (500 kg). In both experiments and in all conditions the wheels at the handle side could swivel whereas the more distant wheels could not, in order to reflect the standardized conditions of the common industrial transport carts.

Procedure

All participants were instructed to complete a course with typical daily cart maneuvers (**Figure 1**).

The handling of experiment (1) included three different situations with 1 min rest between each situation (**Table 1**).

Straight driving of a track length of 6 m; alternating three times between pulling and pushing, straight on an even ground with a defined braking zone of 1.9 m;

Turns: pushing and pulling 90 degree turns left and right three times each maneuvering a course in which participants are instructed to pull the cart in a right curve first and then left towards the center and subsequently to push the cart turning right and then left back to the starting position, repeating the course three times.

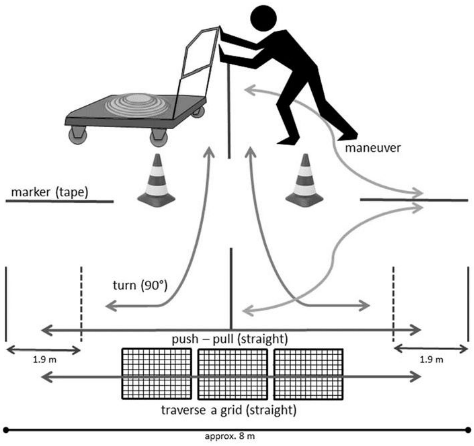


Figure 1 Maneuvering course for stage one and two. For all test conditions, participants were instructed to work in a self-selected, normal work speed. Due to technical limitations (duration, reconstruction of the wheels etc.), a randomization of test conditions was not feasible for both experiments.

Participants

Twenty-eight male industrial employees took part in both stages of the study.

	N	Age [years]	Body height [cm]	Body mass [kg]
Experiment 1	6	19.0 ± 1.8	182.0 ± 0.1	94.5 ± 23.6
Experiment 2	22	19.2 ± 3.4	181.0 ± 0.1	85.8 ± 14.9

Table 1 Description of the participants of Experiment 1 and 2 (N=28; mean ± SD).

Methods of experiment 1

The course was driven on a normal clean floor with a total cart mass (cart and weights) of 300 kg and 500 kg (cart dimensions 1200 mm × 800 mm) as these represent common cart loads in various industrial fields. The handle height was fixed at the individual shoulder and elbow height with the distance between the handles being shoulder width (definition of elbow height: distance between the elbow and the ground with arms held beside the body in a neutral position, handle axis perpendicular to the floor (vertically)=neutral hand position; handle axis parallel to the ground (horizontally)=hand in pronation). Overall, the three task situations of experiment 1 resulted in 24 task conditions with a total of 144 measurement runs (approx. 1-hour duration). This was done within one day by all of the six participants.

Measuring instruments

3D-kinemetry: Three dimensional kinematic data of motion was recorded by 37 retroreflective markers that were tracked by eight infrared cameras (at 200 Hz, measuring accuracy ~ 2 mm; Vicon; Motion 3D Analysis System, Nexus software 1.6.1; Polygon software 3.6.1 Oxford, England).

37 passive markers were fixed on the following body segments onto the bare skin (except for head markers and markers attached to a wristband:

Lower extremities left and right: lateral part of the ankle joint, posterior heel, big toe, lateral condyle of the knee, anterior and posterior iliac spine (bony landmarks) and lateral part of the thigh and lateral part of the lower leg (soft tissue), upper extremities left and right: temple, occiput (head band), seventh neck vertebra, tenth thoracic vertebra, conjunction of the clavicle and the sternum; sternum, scapula, clavicle, lateral epicondyle of the elbow forearm (bony landmarks), upper arms (soft tissue), wrist joint at the thumb side and the little finger (wristband).

The resulting movement trajectories calculated with analysis software (Vicon Polygon) were then combined with the anthropometric data (e.g., body height; leg length) of the participants to create kinematic models based on ISB recommendations [25]. Angle progressions of the humero-thoracic joint (in the following paper referred to as “shoulder”) for abduction and flexion and of the elbow joint (flexion: upper arm relative to forearm) were calculated, and put in relation to existing recommendations of ergonomics according to DIN EN 1005-4-2005 [26].

Hand reaction forces: For detecting and recording the hand reaction forces a piezoelectric 5-component hand force measuring system (Kistler) consisting of two 3D-force-measure-handles was used. The vector sum of the resulting hand reaction forces arises from the longitudinal, lateral and vertical forces and can be measured at a sampling rate of 50 Hz and with a measurement accuracy of < ± 0.5% [2]. The measuring handles were fixed immovably on the transport device and the data-synchronization with the Electromyography EMG and motion analysis data was conducted using a manually placed trigger signal and Vicon-Software.

Electromyography (EMG)

Local muscle activity of the upper extremities (elbow, shoulder) and lumbar spine was recorded wirelessly at 1000 HZ (myon AG, Schwarzenberg, Switzerland) for the following muscles: m. flexor and extensor carpi ulnaris (bilaterally), m. deltoideus pars clavicularis and m. extensor spinae. The EMG-signals were recorded using bipolar surface electrodes (Ambu® Sensor N) with an interelectrode distance of 20 mm. The subjects` skin was shaved, rubbed and cleaned before sensor placement according to the SENIAM Guidelines (seniam.org). Electrodes were placed parallel to the fibers of the recorded muscles. The raw data were collected and later filtered digitally using the software ProEMG (myon AG, Schwarzenberg, Switzerland) with a 20400 Hz 2nd order butter worth bandpass filter. A time period of 100 ms was used to determine the root mean square (RMS). EMG-data was normalized relative to the maximum voluntary contraction (MVC) values. To assess MVC-values, following a standardized warm-up phase, test subjects performed a series of three maximal isometric contractions against resistance in four different poses related to the analyzed muscles (according to Hermens et al. [27]). After the MVC-Assessment, there was a warming up phase for the participants in which they practiced the handling of the carts inside the course.

Statistical Analysis

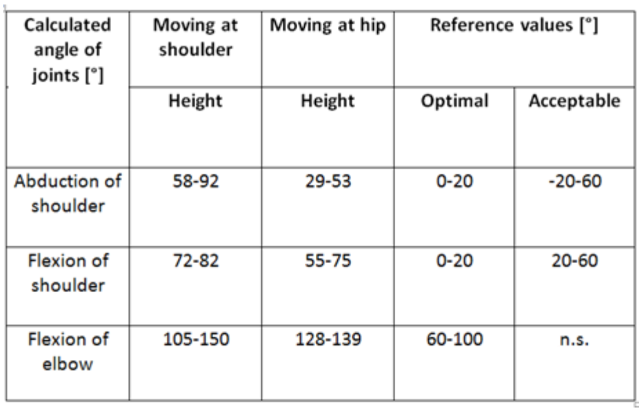
Descriptive statistics as well as a comparison of means in terms of an analysis of variance (ANOVA; 95% confidence interval) were performed. For the main outcomes (hand reaction forces, muscle activity) the analysis on the general linear model and the inner subject factor (grip direction, grip height) was calculated.

Normal distribution and variance homogeneity was previously established using the Kolmogorov-Smirnov and the Levene-test. The partial Eta-square ($_p\eta^2$) functioned as a measure of the effect size (small effect $_p\eta^2 \geq 0.08$, middle effect $_p\eta^2 \geq 0.20$, and $_p\eta^2 \geq 0.32$ high effect, All analyses were done using SPSS (IBM statistics, Chicago, IL, USA) version 22.0.

Results Experiment 1

Kinemetry

While moving carts with handles at elbow height especially in flexion or abduction of the shoulder joint-joint angles were chosen that were considered low in strain according to the following reference values (**Table 2**).

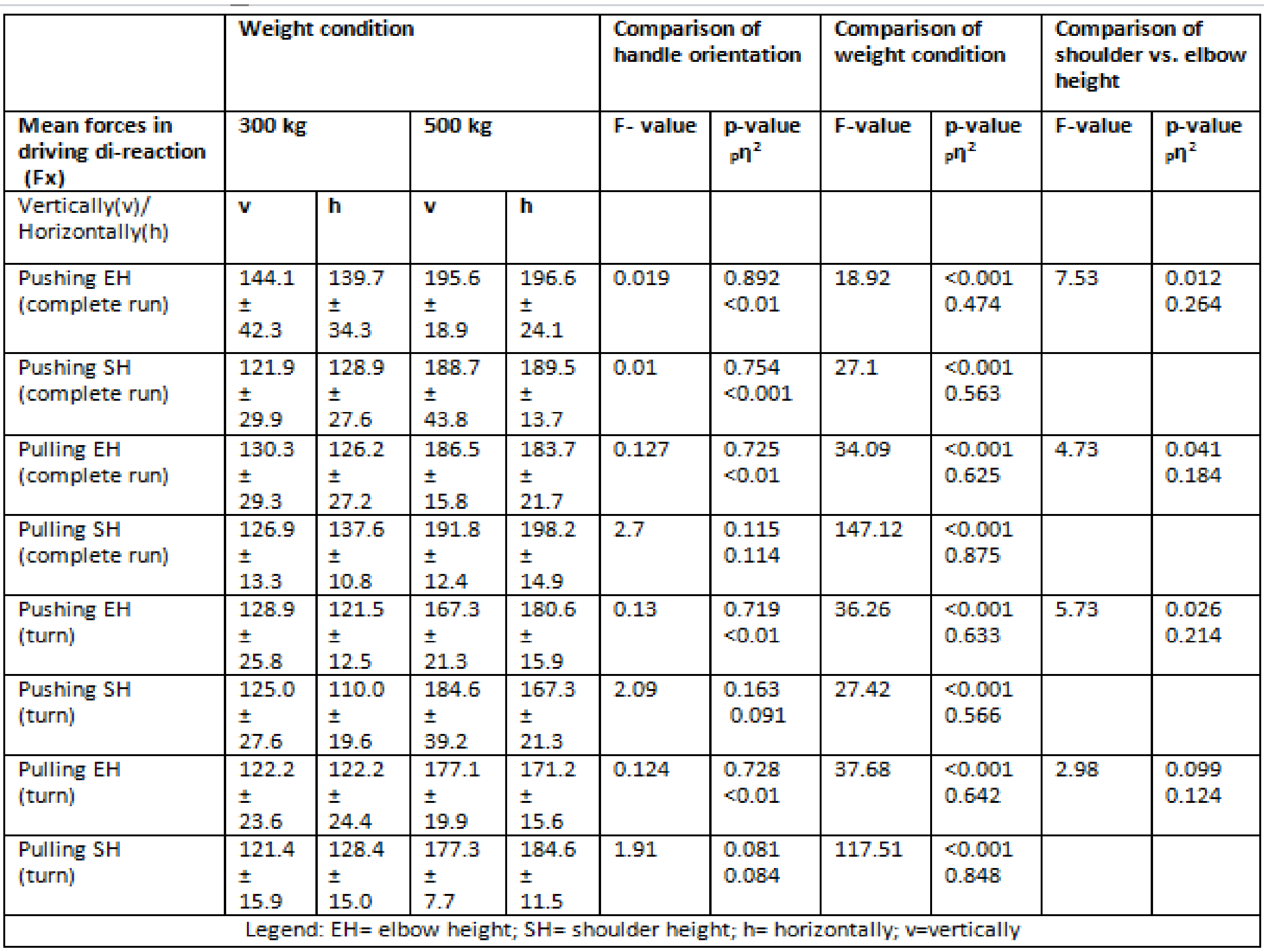


Calculated angle of joints [°]	Moving at shoulder	Moving at hip	Reference values [°]	
	Height	Height	Optimal	Acceptable
Abduction of shoulder	58-92	29-53	0-20	-20-60
Flexion of shoulder	72-82	55-75	0-20	20-60
Flexion of elbow	105-150	128-139	60-100	n.s.

Table 2 shows that the angle alteration of participants substantially exceeded reference values especially at shoulder height. **Table 2** Angle progression while moving the cart (comparison of grip heights; n=6; minimum and maximum range). Legend: reference values were taken from the DIN EN 1005-4-2005 ISO [26]. n.s=not specified.

Hand reaction forces: The mass of the cart during pulling had an influence on the hand reactions force independently of the handle orientation (horizontally vs vertically). Hand reaction forces showed significant differences between grip heights for both pushing (F=7.53; p=0.012; $_p\eta^2$=0.264) and pulling (F=4.73; p=0.041; $_p\eta^2$=0.184) for the complete run. Especially for pulling the relation between vertical and horizontal reaction forces became more economical with a grip change from elbow to shoulder height, with less force applied to a vertical direction.

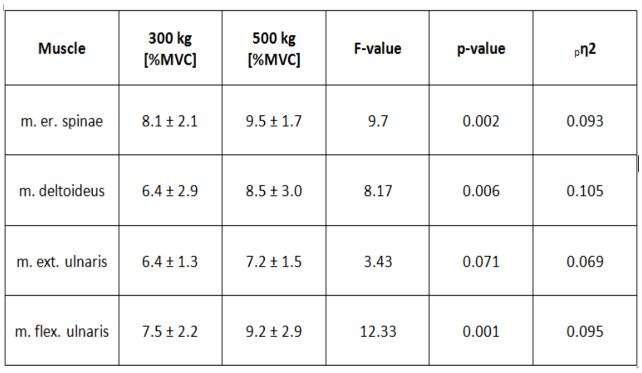
The difference between elbow and shoulder height for pulling whilst turning failed to be significant (F=2.98; p=0.099; $_p\eta^2$=0.124). For pushing in turns there were differences in hand reaction forces for the grip heights (F=5.73; p=0.026; $_p\eta^2$=0.214). The total force while pushing and pulling was higher than values deduced from the literature (1/min according to Backhaus [3] and 1/8 h according to Haslam [28]). A higher amount of the mean force (F_{tot}) was reached during pushing and pulling tasks in the driving direction (F_x) with a lower height of the handle (**Table 3**).



	Weight condition				Comparison of handle orientation		Comparison of weight condition		Comparison of shoulder vs. elbow height	
Mean forces in driving di-reaction (Fx)	300 kg		500 kg		F- value	p-value $p\eta^2$	F-value	p-value $p\eta^2$	F-value	p-value $p\eta^2$
Vertically(v)/ Horizontally(h)	v	h	v	h						
Pushing EH (complete run)	144.1 ± 42.3	139.7 ± 34.3	195.6 ± 18.9	196.6 ± 24.1	0.019	0.892 <0.01	18.92	<0.001 0.474	7.53	0.012 0.264
Pushing SH (complete run)	121.9 ± 29.9	128.9 ± 27.6	188.7 ± 43.8	189.5 ± 13.7	0.01	0.754 <0.001	27.1	<0.001 0.563		
Pulling EH (complete run)	130.3 ± 29.3	126.2 ± 27.2	186.5 ± 15.8	183.7 ± 21.7	0.127	0.725 <0.01	34.09	<0.001 0.625	4.73	0.041 0.184
Pulling SH (complete run)	126.9 ± 13.3	137.6 ± 10.8	191.8 ± 12.4	198.2 ± 14.9	2.7	0.115 0.114	147.12	<0.001 0.875		
Pushing EH (turn)	128.9 ± 25.8	121.5 ± 12.5	167.3 ± 21.3	180.6 ± 15.9	0.13	0.719 <0.01	36.26	<0.001 0.633	5.73	0.026 0.214
Pushing SH (turn)	125.0 ± 27.6	110.0 ± 19.6	184.6 ± 39.2	167.3 ± 21.3	2.09	0.163 0.091	27.42	<0.001 0.566		
Pulling EH (turn)	122.2 ± 23.6	122.2 ± 24.4	177.1 ± 19.9	171.2 ± 15.6	0.124	0.728 <0.01	37.68	<0.001 0.642	2.98	0.099 0.124
Pulling SH (turn)	121.4 ± 15.9	128.4 ± 15.0	177.3 ± 7.7	184.6 ± 11.5	1.91	0.081 0.084	117.51	<0.001 0.848		
Legend: EH= elbow height; SH= shoulder height; h= horizontally; v=vertically										

Table 3 Comparison of hand reaction forces for pushing and pulling with horizontal and vertical handle orientation for the cart masses 300 kg and 500 kg (mean ± SD). Legend: EH=elbow height; SH=Shoulder Height; h=horizontally; v=vertically.

Electrical activity of muscles: Similar to the results for the hand forces, the relation between the electrical muscle activity and the cart's mass was the most evident. The percentage changes (mean ± sd) of medium and maximal muscle activity are summarized in **Table 4**.



Muscle	300 kg [%MVC]	500 kg [%MVC]	F-value	p-value	$p\eta 2$
m. er. spinae	8.1 ± 2.1	9.5 ± 1.7	9.7	0.002	0.093
m. deltoideus	6.4 ± 2.9	8.5 ± 3.0	8.17	0.006	0.105
m. ext. ulnaris	6.4 ± 1.3	7.2 ± 1.5	3.43	0.071	0.069
m. flex. ulnaris	7.5 ± 2.2	9.2 ± 2.9	12.33	0.001	0.095

Table 4 Change of medium electrical muscle activity with the cart's mass (mean ± SD).

All muscle groups (m. er. spinae, m. deltoideus and m. flex. ulnaris) showed highly significant changes of medium activity with increased cart mass. Analogue to medium electrical activity, maximal muscle activity increased significantly with increasing cart mass for the observed muscle groups (m. er. spinae, m. detoideus and m. flex. ulnaris).

Handle height resulted in significant differences in 25% of the task conditions. The medium electrical muscle activity of the anterior deltoids and the flexor muscle in the forearm was respectively lower at a lower grip height. These differences were only shown for the heavier cart mass (500 kg).

Following the DIN CEN ISO TR 7250-2 and ergonomic advices of Scheuer, Müller-Arnecke, Windel and Bleyer. [29] the handle design e.g., for a bow-shaped handle should consider the elbow height (minimum 90 cm, maximum 120 cm, median 105 cm), the European norm for the shoulder length (bideltoid) with a range of 39.5-48.5 cm and minimum hand dimensions of 13 cm width and 8 cm depth. These dimensions were included in the handle design.

Resulting handle design of experiment 1

Figure 2 Resulting handle design for industrial transport carts.

Results Experiment 2

The second experiment included the same maneuvers as stage one with a total cart mass of 500 kg (cart and load) in a real working area (normal floor of the industrial hall). Additionally, there was a grid which had to be crossed (see **Figure 1**) and two different wheel types were used (standard wheel vs. optimized wheel with lower frictional resistance). Each participant had to complete 60 maneuvers in total (same 24 as in Experiment 1 plus 3 times pushing and pulling in a straight line over the grid for both wheel conditions (approx. 2 hours duration)). The measurements were done within one week during working hours.

Measuring instruments

Experiment two included the detection of hand reaction forces on the handles and the EMG measurements of experiment 1. Instead of kinemetry the heart rate was monitored and the perceived exertion was acquired. Moreover, the change of the grip position during the cart maneuvering was analyzed.

Heart rate monitoring and Borg Scale

The heart rate was monitored with the system and team software of Acentas GmbH (Hörgertsha, Germany) with 0.5 Hz. After every condition the participants estimated their rate of perceived exertion (RPE) with the 15-point Borg RPE scale [30].

Changes of grip position

The changes of the grip position were analyzed via video recordings of all participants. For each participant the changes in grip direction and grip height were counted and summarized by two independent researchers. The median of the body mass of all participants (83.7 kg) was chosen to evaluate the effect of the body composition on the individual need to change the grip position. Analyses were done for the two subgroups (body mass above and below 83.7 kg).

Statistical Analysis

Descriptive statistics as well as a comparison of means in terms of analysis of variance with a 95% confidence interval were performed. For the main outcomes (hand reaction forces, muscle activity or heart rate) an analysis of variance on the general linear model and the inner subject factor (grip direction, grip height, floor or wheel) was calculated.

Normal distribution and variance homogeneity was previously established using the Kolmogorov-Smirnov and the Levene test. The partial Etasquare ($_p\eta2$) functioned as a measure of the effect size (small effect $_p\eta2 \geq 0.08$, middle effect $_p\eta2 \geq 0.20$, and $_p\eta2 \geq 0.32$ high effect [31], All analyses were done using SPSS (IBM statistics, Chicago, IL, USA) version 22.0. Comparison of different grip positions.

For both situations (wheel and floor condition) the variable use of grip positions by the test subjects was chosen independently of the wheel and floor condition. The orientation of grips (horizontally vs. vertically) was changed more frequently than the grip height. The changing frequency was determined by the body mass of the participants. Employees with a lower body mass (<83.7 kg) changed their grip orientation four times and grip height three times more often than participants with a higher body mass (**Table 5**).

	Mean	Standard wheel	Optimized wheel	Body mass <83.7 kg	
				S	O
Number of changes in grip direction (horizontal / vertical)	170	84	86	74	66
Number of changes in grip height	92	44	48	36	34

Table 5 Frequency of grip positions for curve and maneuvering (n=22). Legend: S=standard wheel, O=optimized wheel.

Comparison of the standardized versus the optimized wheels

Lower forces [N] were required with the optimized wheel in comparison to the standardized wheel (standard wheel grid: 212.5 N ± 14.9 N, no grid: 191.3 N ± 12.7 N; optimized wheel grid: 119.8 N ± 17.6 N, no grid: 119.0 N ± 24.8 N; comparison of the floor condition: F=23.8; p=<0.001 $_{p}\eta$2=0.391; comparison of the floor x wheel condition: F=20.54; p=<0.001 $_{p}\eta$2=0.357).

Maneuvering on a grid showed decreased forces in comparison to the normal floor condition for the standard wheel but not for the optimized wheel.

Floor condition		Standard wheel		Optimized wheel		Comparison of the wheel condition		Comparison of the floor × wheel condition	
	Muscle	Grid	No grid	Grid	No grid	F-value	p-value ($_p\eta^2$)	F-value	p-value ($_p\eta^2$)
Mean diff. [MVC]	m. flexulnaris	7.9 ± 3.4	9.2 ± 6.5	6.7 ± 2.5	6.7 ± 4.8	14.95	0.001 (0.468)	1.66	0.215 (0.089)
	m. deltoideus	8.1 ± 2.7	6.9 ± 3.3	5.7 ± 2.2	5.2 ± 3.0	14.71	0.003 (0.572)	0.42	0.530 (0.037)
	m. trapezius	9.5 ± 2.2	8.6 ± 2.5	5.2 ± 2.4	4.8 ± 2.1	48.85	<0.001 (0.742)	0.1	0.758 (0.006)
	m. er. spinae	9.4 ± 3.7	9.3 ± 3.3	6.4 ± 2.7	7.1 ± 2.8	27.2	<0.001 (0.630)	0.55	0.468 (0.033)
Max diff. [MVC]	m. flexulnaris	50.4 ± 21.4	57.4 ± 23.7	42.9 ± 16.1	45.2 ± 22.6	3.39	0.083 (0.166)	0.19	0.670 (0.011)
	m. deltoideus	77.5 ± 14.3	64.8 ± 25.1	60.4 ± 19.5	62.5 ± 29.2	4.85	0.050 (0.306)	2.89	0.12 (0.205)
	m. trapezius	56.4 ± 17.0	62.5 ± 12.8	45.2 ± 9.3	34.5 ± 11.6	21.62	<0.001 (0.560)	4.01	0.061 (0.191)
	m. er. spinae	54.3 ± 17.3	51.9 ± 17.7	40.7 ± 13.0	42.3 ± 19.2	11.96	0.003 (0.428)	0.36	0.559 (0.022)

Table 6 Comparison of muscle activation (differences in % MVC mean and maximum ± SD) using the standard or optimized wheel depending on floor condition and handling maneuvers.

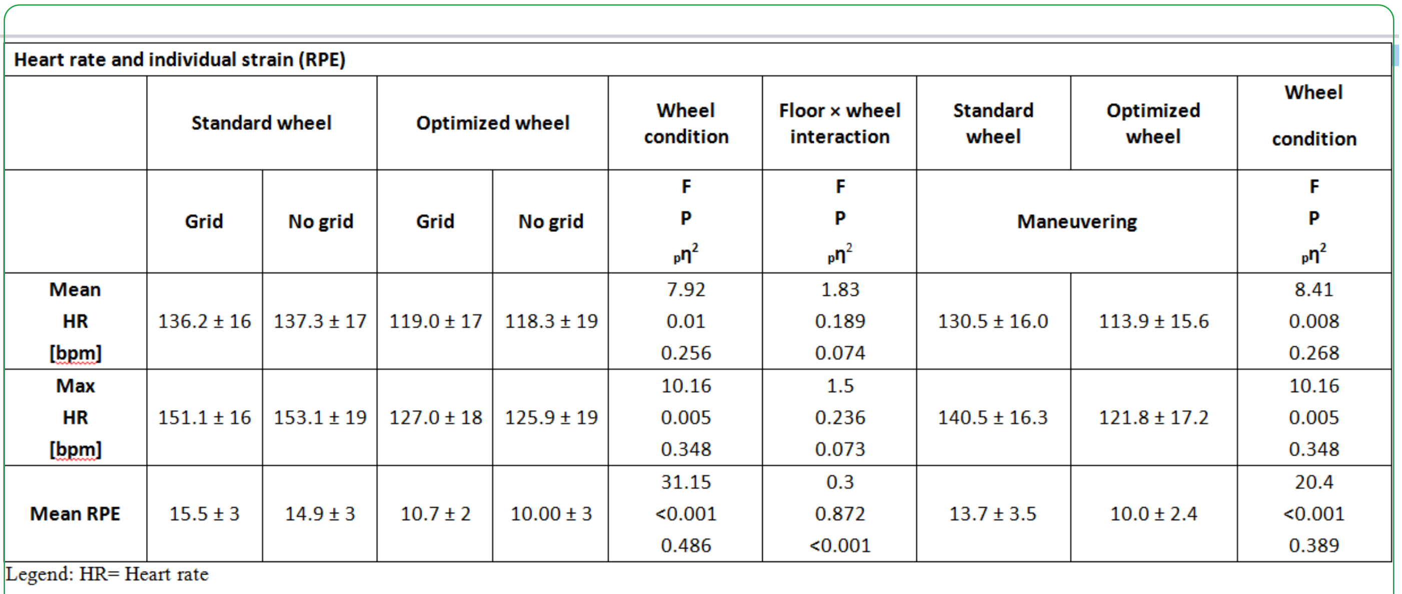
Electromyography (EMG)

Table 6 summarizes all observed differences in muscle activity for the different working conditions for the right side of the body.

Maneuvering with the standard wheel showed increased muscle activity for all conditions (about 20.6%; cf. **Table 6**). Pushing the cart required more mean muscle activity of the m. flex. ulnaris, m. deltoideus and m. trapezius. Pulling increased the muscle activity for the m.er. spinae. The mean muscle activity was reduced by the use of the optimized wheel. The maximum muscle activity increased significantly for pulling with the optimized wheel in comparison to the standard wheel. Comparable results were observed for the left side of the body.

Heart rate and RPE

The observed exposure differed between the wheel and the maneuvering condition. The heart rate was significantly determined by the wheel condition but not by the maneuvering conditions. Cart handling with the optimized wheel was rated with reduced Borg Scores (**Table 7**).



Heart rate and individual strain (RPE)

	Standard wheel		Optimized wheel		Wheel condition	Floor × wheel interaction	Standard wheel	Optimized wheel	Wheel condition
	Grid	No grid	Grid	No grid	F P $_p\eta^2$	F P $_p\eta^2$	Maneuvering		F P $_p\eta^2$
Mean HR [bpm]	136.2 ± 16	137.3 ± 17	119.0 ± 17	118.3 ± 19	7.92 0.01 0.256	1.83 0.189 0.074	130.5 ± 16.0	113.9 ± 15.6	8.41 0.008 0.268
Max HR [bpm]	151.1 ± 16	153.1 ± 19	127.0 ± 18	125.9 ± 19	10.16 0.005 0.348	1.5 0.236 0.073	140.5 ± 16.3	121.8 ± 17.2	10.16 0.005 0.348
Mean RPE	15.5 ± 3	14.9 ± 3	10.7 ± 2	10.00 ± 3	31.15 <0.001 0.486	0.3 0.872 <0.001	13.7 ± 3.5	10.0 ± 2.4	20.4 <0.001 0.389

Legend: HR= Heart rate

Table 7 Mean and peak values for the heart rate and RPE for the different wheel and maneuvering conditions (mean ± SD). Legend: HR=Heart rate.

Discussion

The goal of this study was to develop and verify a handle design, which reduces muscle activity for pushing and pulling tasks and accompanying physical load.

Experiment 1

The literature review and results of the first experiment illustrate that a single optimal handle position (handle height and handle orientation) could not be identified due to the large number of relevant strain factors. Different anthropometric preconditions of co-workers handling the same cart are further influential factors.

According to the findings of Bennett et al. [32] one might consider that the muscle activation of the upper body is lower during pushing compared to pulling. On the other hand Lett et al. [14] showed that the compression forces impacting on the lower back decrease for pushing at shoulder height and for pulling at hip height. Reduced torques can be achieved by maneuvering at shoulder height and reducing cart mass [33].

With regard to the different strain factors and strain localizations, previous findings suggest a usage of different handle heights to minimize strain (e.g., [23]). For instance, joint torques are minimized if the vector of the resulting hand reaction force runs through the joints or close by. An example for this can be seen when the reactive hand force points towards the shoulder when pushing [34]. These conditions cannot be realized simultaneously for the shoulder joint and the lumbar spine with only one handle bar in a fixed height and orientation as seen on many industrial transport carts. It therefore seems reasonable to supply handles at the shoulder height as well as elbow height to prevent one sided strain. Both of these positions show advantages for specific workload conditions. An example for the latter is the observation of an efficient physical effort with a simultaneous lower muscle activity in both arms during pushing at elbow height. The compression forces and torques in the shoulder joint however were lower when handles were at shoulder height [33]. Therefore our suggestion of a variable handle design as presented in **Figure 2** was confirmed by the results of this study.

In addition, one has to consider the practical implication, that all straining factors were primarily dependent on the mass of the carts regardless of the handle positions. Reference data for hand reaction forces are already reached when the exposure frequency to strain corresponds to 1/min and the mass of the cart exceeds 200 kg [3]. If the exposure frequency remains low (once in 8 h) initial forces measured at the hands of 420-446 N are acceptable [28]. In this study, this reflects the occurring strain in laboratory measurements with cart's masses of 500 kg.

Overall, on the basis of our study results, a handle pattern has been created which provides the option to choose between grip positions either at shoulder or at elbow height. This choice can be made independently of the body height and with both the vertical or horizontal handle axis. Furthermore the possibility to adjust gripping to an individual distance exists. Therefore, the new handle design tackles most of the aforementioned concerns regarding the overbearing biomechanical load in pushing and pulling tasks of heavy carts in the modern workplace.

Experiment 2

The developed handle design was tested in a real working situation. The opportunity to change the grip position was mostly adopted by workers with a lower body mass and resulted in reduced peak forces and accompanying muscle activity for the whole group. The heart rate and RPE also decreased. Overall these findings can be interpreted as an acceptance of the handle design by the industrial workers. In addition, mainly the workers with lower body mass and resulting less muscle strength benefited from the new design. As these are the ones who have to move more weight in relation to their body mass, the benefits of the new design for handling heavy carts become ever more apparent.

Moreover, lower strains even under difficult floor conditions (grid versus normal floor) were reached by using an optimized wheel. These findings are in line with recent recommendations suggesting hard rolling wheels and large wheel diameters [19]. The larger the wheel diameter and the harder the rolling wheels, the lower forces required to push or pull the cart [11,35,36]. With optimized wheels, shear forces can be reduced [37]. However, one must consider, that pulling over the grid led to smaller forces compared to pulling on normal floor. This might be a result of lower forces required to stop the cart with optimized wheels on the grid.

The findings of the different conditions for peak and mean forces were accompanied with according changes of trunk muscle activity. The highest muscle activity was recorded with the standard wheel on the grid.

The observed values mostly did not exceed the recommendations of Steinberg et al. ([38]; 5-10% of MVC). However, due to the different handling conditions, a local activity of up to 16.3% of the MVC (shoulder muscles while pushing) was recorded. Even so, one has to bear in mind that existing limits for the maximum forces apply to static activity. Nevertheless, if the pushing activity has to be executed for a long period of time this might be defined as static because the upper part of the body is fixed and only the legs are moving, which is the arms, the shoulder girdle and the trunk have no relative movement to one another, therefore comparable physiological and biomechanical characteristics apply as for static activity, at least for the upper body.

Cart handling with the standard wheel led to a mean increase of muscle activity. The highest differences were observed for maneuvering and especially for handling the cart around corners. This leads to the suggestion that the upper body muscles are strained by local fatigue. Therefore, one might conclude that the optimized wheel is the best recommendation to decrease upper body strain, when cart handling demands many maneuvering actions.

Cart handling on the grid increased trunk muscle activity. However, the influence of the grid did not reach the same activity levels as the standard wheel. Only the peak forces of the m. trapezius are significantly increased on the grid. However, using the optimized wheel led to increased activity while stopping the cart.

Despite a careful selection of wheels and suitable handle positions the handling of carts with high masses remains a straining task.

It is difficult to submit definite recommendations of threshold limit values that indicate the need of motorized driving assistance. Precise indications of boundary conditions on which the strain limits are applicable are often lacking in the literature. One of the most important influencing factors is the performance frequency of a certain task during the day [3,28]. Furthermore, it is not often clear whether stated limit values are based on a group of persons with a particular physical aptitude. Moreover work experience and a skilled motor motion technique increase physical resilience [14]. Assuming a population of healthy adults without preexisting conditions, limit values of acceptable strain are expected to decrease with increasing age and possible injuries. The avoidance of high cart mass (>500 kg) and the provision of suitable driving assistance shows a high potential in reducing the incidence of musculoskeletal disorders. Nevertheless based upon the biomechanical analysis, a suitable handle design was created which allows the workers to change the grip position for the maneuvering processes, thereby reducing the biomechanical strain on their bodies induced by the heavy load. The developed handle design was well used and accepted by the workers especially if they had a lower body mass. This results in the need of optimized points of force application while cart handling. Moreover, physical strain can be reduced by the use of an optimized wheel. A combination of the handle design, reduced cart masses and an optimized wheel can significantly reduce the work exposure. The findings of the different conditions for peak and mean forces were accompanied with according changes of trunk muscle activity. The highest muscle activity was recorded with the standard wheel on the grid.

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Limitations

As both studies were carried out in close coordination with companies, a few known limitations of research in the field occurred. Foremost to mention is the lack of female test subjects. This was due to the limited availability of female employees in the respected field. As certain experience of maneuvering heavy carts was mandatory in order to assess real world kinematic data, there was no substitution with women out of other professional fields. Hence, the outcomes of this study could potentially differ regarding influences by gender. However, based on the influence of body mass on the variable use of grip positions, with lower body mass resulting in a higher frequency of grip change, we assume similar effects for female workers. Another limitation is the lack of diversity regarding age. Test subjects were relatively young which was also due to restricted availability of older test subjects. Nevertheless, all test subjects had at least one year or more experience in maneuvering heavy carts daily at the work place. Older test subjects might have shown different movement behavior due to even more experience. On the other hand, given that our test subjects were not inexperienced, we expected that major differences would be mostly provoked by existing musculoskeletal issues, a confounding factor which would have been resulted in the exclusion of said test subjects. Regardless, the possibility of different findings cannot be ruled out.

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