Effectiveness of interventions to reduce workload in refuse collectors
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Citation for published version (APA):
Kuijer, P. P. F. M. (2002). Effectiveness of interventions to reduce workload in refuse collectors

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Chapter 4.2

Effect of a redesigned two-wheeled container on mechanical loading of low back and shoulders

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_Ergonomics, conditionally accepted_

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Abstract
The objective of this study was to compare the mechanical and perceived workload between working with a redesigned two-wheeled container and working with a standard two-wheeled container. The three changes of the redesigned container were 1) a displacement of the position of the centre of mass in the direction of the axis of the wheels, 2) a slight increase of the handle position in the vertical and horizontal directions and 3) an increase in diameter of the wheels. The volume of the two-wheeled container remained 0.240 m$^3$. Nine refuse collectors performed the most frequent daily activities with both types of two-wheeled containers in the laboratory. Kinematics and exerted hand forces were assessed as input for detailed 3D biomechanical models of the low back and shoulder to estimate net moments at the low back and shoulders, compressive forces at the low back and contact forces at the glenohumeral joint. Also, the refuse collectors rated the ease of handling the two-wheeled containers on a five point scale.

The use of the redesigned two-wheeled container resulted in a decrease of the exerted hand forces, a decrease of net moments at the low back and shoulders, and a decrease of the contact forces at the glenohumeral joint compared to the standard two-wheeled container. However, pulling an empty redesigned container on the pavement resulted in an increase of the shoulder moment. No differences between both two-wheeled container were found for the compressive forces at the low back. Pushing and pulling the redesigned two-wheeled container was rated as more easy than pushing and pulling the standard two-wheeled container. No differences in subjective ratings were found for rotating the two-wheeled container and for pulling an empty two-wheeled container on the pavement.

It is concluded that, provided that empty two-wheeled containers are placed back on the pavement as little as possible, the introduction of the redesigned two-wheeled container could result in a reduction of the low back and shoulder load.
4.2.1 Introduction

Working as a refuse collector is a physically demanding job. Several studies showed that the physical workload of refuse collectors can be classified as high \(^{42,69,121}\). In most parts of The Netherlands, refuse bags have been replaced by two-wheeled containers to reduce the workload and the risk of musculoskeletal complaints \(^{43}\). The replacement of lifting by pushing and pulling resulted in a marked reduction of compressive forces at the low back \(^{28,125}\). However, pushing and pulling tasks are also suggested to be a risk factor for developing pain or stiffness in the neck and shoulder region \(^{61,64,142}\). A further reduction of the mechanical load of low back and shoulders might be achieved by ergonomically optimising the design of the two-wheeled container.

A previously performed study suggested that two aspects of the two-wheeled container seem of importance: the position of the centre of mass (COM) and the position of the handle (HP) \(^{74}\). Kingma et al. \(^{74}\) investigated the effect of the COM and the HP for steady, symmetric, two-handed pushing and pulling on exerted forces and joint loading. A displacement of the COM towards the axis of the wheels resulted in a slight reduction in joint loading and in an increased stability of the container. This increased stability probably reduces the risk of unexpected disturbances in the mechanical equilibrium due to irregular surfaces, thereby requiring smaller and less frequent force adaptations. Furthermore, any handling of a two-wheeled container starts with tilting. The displacement of the COM towards the wheel axis roughly halved the required horizontal tilting force. The effect of the HP on exerted forces and joint loading was less pronounced. An increase of the handle height of about 0.1 m in vertical and horizontal direction towards the refuse collector resulted in a small reduction of the vertical force and of the loading of the elbow and shoulder, without adverse effects on low back loading. A more than 0.1 m increase in HP caused refuse collectors with a relatively short body height to tilt the container quite far. This relatively large tilt angle resulted in an increased joint loading.

Before implementing such an expensive work improvement, it is imperative to establish its effect on the workload of the refuse collectors. Therefore, an efficacy study was performed with both two-wheeled containers in which the most frequent daily activities were studied in terms of mechanical workload of the low back and shoulder. Because most activities with a two-wheeled container are not performed symmetrically \(^{88}\), detailed 3D biomechanical models were used to evaluate the effects. In order to get more insight in the ease of use, the refuse collectors also rated the handling of both types of containers. In summary, the aim of this study was to compare the mechanical and perceived workload between working with a redesigned two-wheeled container and working with a standard two-wheeled container.
4.2.2 Methods

4.2.2.1 Participants

Nine healthy male refuse collectors participated in the experiments. They were employed by different refuse companies in The Netherlands and had at least one year of experience with collecting refuse using two-wheeled containers. Body height is likely to have a large influence on posture and joint loading, while working with two-wheeled containers. Therefore, refuse collectors with a large range in body height were selected. The mean and standard deviation of age (years), body height (cm) and body weight (kg) were 33 (6), 178 (11) and 82 (19), respectively. All participants gave informed consent prior to the experiments and reported no musculoskeletal problems at that moment.

4.2.2.2 Design of two-wheeled containers

Two two-wheeled containers were used in the experiments: 1) a standard two-wheeled container (Otto, 0.240 m$^3$) and 2) a redesigned two-wheeled container with the same volume. The redesign is based on the results of the aforementioned study on the effect of HP and COM on mechanical loading $^{74}$. The handle was displaced 0.1 m in horizontal direction towards the refuse collector and 0.1 m upwards in vertical direction (figure 1). The diameter of the wheels was increased from 0.2 m to 0.3 m. Although the laws of rolling resistance are not yet definitely established, a widely acceptable relationship is that the horizontal push force of a cart, is equal to the coefficient of friction times the total weight of the cart divided by the wheel radius $^{1}$. Therefore, an increase in diameter of the wheels of about 50% might result in a reduction of the horizontal force of about 30%. However, in this study not only the wheel size differed but also the width of the wheel was larger and another type material for the wheels was used.

Changes in width, depth and position of wheel axis were performed in such a way that, assuming a homogeneous filling, it resulted in a displacement of the COM about halfway towards the axis of the wheels (figure 1). The increase in width resulted in an increase in length of the wheel-axis from 0.55 m (standard two-wheeled container) to 0.69 m (redesigned two-wheeled container). The COM positions in the standard and redesigned containers were created by using blocks of foam and lead. On average, a loaded two-wheeled container weighs about 40 kg and an extremely heavy two-wheeled container more than 60 kg. In the Netherlands, two types of refuse are collected using two-wheeled containers so called green ('organic fraction') and grey ('non-organic fraction') refuse. Therefore, the actual position of the COM was calculated for three different container filling conditions (figure 1) with masses of about 40 kg, 45 kg and 74 kg (including weight of the container). Information on the density of refuse was received from the National Institute of Public Health and Environment.
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Figure 1. A schematic presentation of the standard (- - -) and redesigned two-wheeled container (—) and the position of the three centres of mass (COM) in both containers (40 kg, 45 kg and 74 kg).

4.2.2.3 Experimental set up

A brick-paved road and a pavement of tiles were built in our laboratory. The road was 6 m long and 2.5 m wide. The area of the pavement was 1.5 m x 1.5 m. The pavement was about 0.13 m higher than the surface of the road. The most frequent daily activities with a two-wheeled container were performed, i.e. 1) tilting the two-wheeled container and pulling it with one hand, 2) tilting the two-wheeled container and pushing it with two hands, 3) rotating the two-wheeled container, and 4) pulling the empty two-wheeled container up the pavement.
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For the last two activities the refuse collectors were free to do it with one or two hands. The only restriction was that they had to do it with the same number of hands with the other type of two-wheeled container. The first three activities were performed with the three different container fillings. In accordance with the real working situation, the last activity was only performed with an empty two-wheeled container. The empty standard two-wheeled container weighed 20 kg and the empty redesigned container 21.2 kg. Four refuse collectors started with the standard two-wheeled container and the other five started with the redesigned two-wheeled container. The order of the three container fillings was selected at random. With each filling, the activities 1 to 3 were performed in ascending order. When these three activities had been performed with all three fillings, activity 4 was performed with the empty container. Then the activities were performed with the other two-wheeled container. Again, the same procedure was followed. Before each trial, the refuse collectors practised with the two-wheeled container.

4.2.2.4 Exerted hand forces and kinematics

Two 3D force transducers (SRMC3A series, Advanced Mechanical Technology, Inc., USA) were attached to the two-wheeled container to assess the exerted hand forces. LED markers were attached to the left and right side of the body at the level of the L5-S1 joint. Furthermore, markers were attached at the shoulders, the right side of the thorax, the elbows, the right wrist, and the container. The 3D marker positions were recorded using an optoelectronic system (Optotrak, Northern Digital Inc., Canada). Exerted forces and marker positions were sampled at 50 Hz.

4.2.2.5 Biomechanical model of the low back

Kinematics and anthropometrical data were used as input for an upper body quasi-dynamic 3D linked segment model \(^\text{73}\). The linked segment model consisted of five segments: left and right forearms plus hands, left and right upper arms, and trunk plus head. Net moments at the L5-S1 level were calculated using standard linked segment mechanics.

During the experimental pushing and pulling activities surface-EMG recordings were made of eight bilateral muscle pairs of the trunk according to Van Dieën and Kingma \(^\text{155}\) using bipolar disposable Ag-AgCl electrodes. Signals were amplified 20 times, band-pass pre-filtered (10-400 Hz) and A-D converted (22 bits at 1600 Hz). All signals were high-pass filtered at 30 Hz to reduce cardio-electric interference \(^\text{112}\), and subsequently low-pass filtered (Butterworth) at 2.5 Hz after full-wave rectification. Filtered data were normalised to the maximum value found in maximum voluntary contraction tests derived from McGill \(^\text{93}\).

An EMG driven distribution model was used to estimate compressive forces at the L5-S1 level. The model has for the most part been described previously \(^\text{152,155}\). Muscle forces were
estimated as the product of maximum muscle stress, normalised EMG amplitude, and correction factors for instantaneous muscle length and contraction velocity plus the passive force developed by the muscle’s connective tissue. Maximum muscle stress was iteratively adjusted to obtain maximum agreement between the time series of muscle moments and net external moments \(^94\). The anthropometry of the model was scaled to the anthropometry of the participants. Compressive forces were determined by the sum of the forces of the muscle slips as defined by the model, the gravitational forces resulting from the mass of the upper body, and the reaction forces at the hands.

4.2.2.6 Biomechanical model of the shoulder
The mechanical loading of the shoulder was estimated using a dynamic 3D shoulder-elbow model \(^{146,149}\). The model is based on the finite element theory \(^{147}\) and has been validated in several studies \(^{25,52,146}\). Standardised postures of the participants were assessed prior to the experiments to record the position of LED markers on bony landmarks in relation to LED marker positions on cuffs on the trunk, and on the right lower and upper arm \(^{148}\). During the experiments the LED marker positions on the cuffs and on the acromioclavicular joint were used to predict the position of the scapula and the clavicle. The glenohumeral joint rotation centre was predicted on the basis of the orientation of the scapula \(^96\). The anthropometry of the participants was scaled to the anthropometry of the model \(^{165,166}\). The kinematics of the right arm and the exerted forces at the right hand were used to calculate net moment and force components around three axes through the right glenohumeral joint.

4.2.2.7 Subjective rating
After each trial the refuse collectors were asked to rate whether handling the container was more or less easy than handling a ‘normal two-wheeled container’. A five point scale was used, ranging from 1 (‘more easy’) to 5 (‘less easy’). When the handling felt as comparable as handling a normal two-wheeled container, this was rated as a 3 on the scale.

4.2.2.8 Data analyses
The exerted force and net moment components were used to calculate resultant exerted forces and resultant net moments at the low back and shoulder joint. The peak exerted force, peak net moment at the low back and shoulder, and peak compressive force at the low back were determined for each trial. Peak values were defined as the 90th percentile value found during the whole trial. This definition was used to reduce the risk of analysing measurement errors. Due to a frequent loss of some LED markers, it appeared not to be possible to estimate contact forces at the glenohumeral joint for all trials and also not for the complete trial. Therefore, the maximum contact force at the glenohumeral joint was only determined for the
tilting phase in pulling and pushing. Sustained values were determined for the resultant exerted force, the resultant net moment at the low back and shoulder and the compressive forces at the low back. The sustained value was defined as the average value calculated over the time period of 1.5 seconds during which the velocity of the container was higher than the mean velocity of the container, while at the same time the period contained the lowest mean acceleration of all 1.5 second periods that fit within the time that the velocity was higher than the mean velocity. The sustained values were calculated for pulling with one hand and pushing with two hands. The other two activities were very dynamic and of short duration. Therefore, it was not meaningful to calculate a mean value.

For each of the four activities, the effect of the type of two-wheeled container and the total weight of the two-wheeled container on all measures of the exerted forces, net moments, and compressive and contact forces were tested using generalised estimating equations (GEE)\(^84\). The analysis considers the measurements within participants as a repeated measurement and account for this dependency. In the GEE analysis the factors of interest were coded according to equation (1).

\[
X = C + B_1 \cdot \left( \text{standard container} = 0, \text{redesigned container} = 1 \right) + B_2 \cdot \text{weight (kg)} + B_3 \cdot \left( \text{standard container} = 0, \text{redesigned container} = 1 \right) \cdot \text{weight (kg)} \quad (1)
\]

where B1-B3 are regression coefficients and the constant (C) comprises the hypothetical value of the outcome measure (X) when moving a standard two-wheeled container with a weight of 0 kg. A difference between both two-wheeled containers was marked as significant when regression coefficient B1 or B3 was statistically significant (p-value < 0.05).

A difference between the subjective ratings of the two types of two-wheeled containers was tested with a Wilcoxon signed rank test for matched pairs. The mean values of the subjective ratings for each of the four activities are displayed in the results. Again, a significance level of 5% was used.
4.2.3. Results

4.2.3.1 Exerted hand forces

The use of the redesigned two-wheeled container resulted in lower peak and sustained exerted hand forces compared to the standard two-wheeled container for the activities pulling, pushing and rotating (figure 2). The peak force for pulling an empty two-wheeled container on the pavement did not differ between the two types of containers.

![Graph showing exerted hand forces](image)

*Figure 2. Mean and standard deviation of exerted force (sustained and peak) for pulling, pushing and rotating the standard and the redesigned container with the three different weights (40 kg, 45 kg and 74 kg) and for pulling the empty (21 kg) standard and the empty redesigned container on the pavement (★ significant difference).*

4.2.3.2 Moment at the low back and the shoulder

The peak moment at the low back for pushing the redesigned container was lower than for pushing the standard container (figure 3). The same effect was found for the peak moment at the low back for rotating. The peak moment at the low back for pulling a loaded container and for pulling an empty container on the pavement did not differ between the two types of containers. The sustained moments during pulling and pushing did also not differ between both types of containers.

The use of the redesigned container resulted in a lower sustained and peak moment around the shoulder for pushing (figure 4). For pulling, a reduction was found for the peak moment only. The peak moment for rotating did not differ between both types of containers. Remarkably, the use of the redesigned two-wheeled container resulted in a higher peak moment while pulling an empty container on the pavement.
Figure 3. Mean and standard deviation of moment at the low back (L5/S1) (sustained and peak) for pulling, pushing and rotating the standard and the redesigned container with the three different weights (40 kg, 45 kg and 74 kg) and for pulling the empty (21 kg) standard and the empty redesigned container on the pavement (*significant difference).

Figure 4. Mean and standard deviation of moment at the glenohumeral joint (GH) (sustained and peak) for pulling, pushing and rotating the standard and the redesigned container with the three different weights (40 kg, 45 kg and 74 kg) and for pulling the empty (21 kg) standard and the empty redesigned container on the pavement (*significant difference).

4.2.3.3 Compression force at the low back and contact force at the shoulder joint
The type of two-wheeled container did not affect the compression force at the low back (figure 5). However, the type of container did affect the contact force at the shoulder joint (figure 6). The contact force was lower for tilting the redesigned container than for tilting the standard container.
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Figure 5. Mean and standard deviation of compression force at the low back (L5/S1) (sustained and peak) for pulling, pushing and rotating the standard and the redesigned container with the three different weights (40 kg, 45 kg and 74 kg) and for pulling the empty (21 kg) standard and the empty redesigned container on the pavement (★ significant difference).

Figure 6. Mean and standard deviation of contact force at the glenohumeral joint (GH) (sustained and peak) for tilting (before pulling and pushing) the standard and the redesigned container with the three different weights (40 kg, 45 kg and 74 kg) (★ significant difference).

4.2.3.4 Subjective ratings
The participants experienced pushing and pulling the redesigned container as more easy than pushing and pulling the standard container (figure 7). No differences in subjective ratings were found between the two containers for rotating and pulling the empty container on the pavement.
Figure 7. Mean values of the subjective ratings for pulling, pushing and rotating the standard and the redesigned container with different weights and for pulling the empty standard and the empty redesigned container on the pavement (1 = 'more easy', 2, 3 = 'comparable', 4, 5 = 'less easy') (★ significant difference).
4.2.4 Discussion

4.2.4.1 Limitations of the study

The objective of the present study was to compare the exerted forces, mechanical loading of the low back and shoulders and perceived workload while working with a standard and a redesigned two-wheeled container. In order to increase the external validity of the study, the most frequent daily activities with a container were performed in the laboratory. However, due to the setting in the laboratory and the presence of measuring devices on the body of the refuse collectors, absolute values might be higher in daily practice. Because this effect is probably independent of the type of container, it has probably no consequences for the comparison made between the two types of containers. A possible source of bias, which might be dependent on the type of container, is the working technique. Although the participants practised with the redesigned container, this training period might have been too short. A longer period of practice with the redesigned container might have resulted in a more efficient working technique. Most likely, this would correspond to an even further reduction of the exerted forces and mechanical loading. For instance, a study on the handling of boxes indicated that strategies used by experienced workers permit better control of the load and a more efficient use of box momentum. In addition, Gagnon et al. found that expert handlers of boxes choose a strategy that was more efficient in terms of mechanical energy expenditure. Chaffin et al. examined the effect of short-term practice on low back stresses during working with a materials handling device. They concluded that, if learning occurs in these tasks, it is at a slow pace.

The way the COM was created in both containers resulted in a small difference in total weight of the containers of up to 3%. However, the effect size of the type of container was calculated independent of the effect size of weight and the possible interaction effect of both variables, using GEE analysis. Therefore, this difference did not affect the results. For a detailed discussion on the use of GEE analysis and the biomechanical models used in this study, we refer to the study of Hoozemans et al. The COM position was created using blocks of foam and lead. In reality, the filling is more homogeneously distributed in the container. The percentage underestimation of the exerted hand forces for pushing, pulling and rotating the standard two-wheeled container was calculated to be 8%, 8% and 12% and for the redesigned two-wheeled container 7%, 7% and 9%, respectively. Therefore, despite an increase in width of the redesigned container, the estimated moment of inertia is smaller for the redesigned two-wheeled container than for the standard two-wheeled container. This is caused by the smaller height of the redesigned container.

Working as a refuse collector of two-wheeled containers is not only considered to be physically demanding in terms of mechanical workload, but also in terms of energetic workload. In this study, only the biomechanical effects of handling a two-wheeled container...
container were studied. Therefore, the effect of the design of the container on the energetic workload during the day cannot be established. However, a prediction of the possible benefits can be made on the basis of the results of a study by Van der Beek et al. \textsuperscript{144}. For pushing and pulling of carts during 15 minutes, they found that the exerted forces varied between 50 N and 140 N and the corresponding percentage of the maximum oxygen uptake (\(\%\text{VO}_2\text{max}\)) varied between 31\% and 53\%, respectively. A decrease in exerted forces resulted in large reduction of the \(\%\text{VO}_2\text{max}\). The average decrease in exerted forces for sustained pulling and pushing a redesigned container compared to the standard container was about 25\% in this study. Applying the relationship between exerted force and \(\%\text{VO}_2\text{max}\) from the study by Van der Beek et al. \textsuperscript{144} on our data, a reduction in \(\%\text{VO}_2\text{max}\) of about 18\% during pushing and pulling can be expected. On a working day of about 500 minutes, the duration pushing and pulling a loaded two-wheeled containers is about 60 minutes \textsuperscript{77}. Therefore, we expect a reduction in energetic workload due to the introduction of a redesigned container albeit very small.

\textbf{4.2.4.2 Comparison with other studies}

The exerted forces, moments and compression forces in the present study varied from the results found in three other studies on pulling and pushing of a standard two-wheeled container with a content of 0.240 m\textsuperscript{3} and a weight of about 40 kg (table 1). Differences between the present study and the other studies can be attributed to several causes such as a different positions of COM, differences in surfaces on which the container was moved or measuring procedures. For instance, Donders et al. \textsuperscript{33} reported a peak force of only 98 N for pushing. This was explained by the fact that the two-wheeled container was already tilted before the measurements started (contrary to pulling in their study). De Looze et al. \textsuperscript{28} used a 2D single equivalent muscle model where net moments at the low back are the result of the activity of one muscle, either one back muscle or one abdominal muscle parallel to the trunk position. The distribution model in the present study estimated the compressive forces on basis of several muscle groups with different application angles. Despite these different techniques, the peak compression forces for pulling and pushing were quite comparable, respectively 2051 N and 2217 N and 1818 N and 2219 N. Schibye et al. \textsuperscript{124} calculated the net moment at the shoulder using a 2D biomechanical model. This might explain why the shoulder moment is relatively low compared to the moments found in the present study. No study was found in which the contact force at the shoulder joint was quantified for handling two-wheeled containers. Only a few studies have calculated contact forces in the shoulder. Riding a wheelchair against a slope of 2\textdegree with a speed of 4 km-h\textsuperscript{-1} resulted in a contact force of about 800 N \textsuperscript{164}. Bricklaying with stones varying in weight from 4.3 kg and 16.1 kg resulted in contact forces between 500 N and 1500 N \textsuperscript{38}. Anglin et al. \textsuperscript{3} calculated the contact forces for five activities of daily living in order to derive a suitable load for testing shoulder
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prostheses. The average contact forces ranged between 1240 N for walking with a cane and 1750 N for lifting a suitcase of 10 kg. In comparison, the contact forces in the present study can be classified as relatively low.

Table 1. A summary of results for pulling and pushing a standard two-wheeled container with a comparable weight (about 40 kg) in the present study and in three other studies.

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4.2.4.3 Improved design?
The results showed that, except for the shoulder moment while pulling an empty container on the pavement, the redesigned container resulted in lower exerted hand forces and mechanical loading of the low back and shoulder. The reduction of the hand forces ranged from 13% up to more than 50%. For the mechanical load of the low back and shoulder, the range in percentage reduction was about the same. The refuse collectors rated pushing and pulling of the redesigned container as more easy than pushing and pulling of the standard container. As mentioned, pulling an empty redesigned container on the pavement resulted in a two times higher peak moment at the shoulder compared to pulling an empty redesigned container. The most likely explanation of this result is a more unfavourable direction of the force with respect to the location of the shoulder joint. This effect might be caused by a complex interaction between HP, position of the wheel axis to the kerb of the pavement, position of COM to kerb of the pavement and the wheel axis. In daily practice, the refuse collectors do not place every two-wheeled container back on the pavement. Mostly, the containers are placed against the kerb of the pavement. To reduce the mechanical loading of the low back and shoulder, placing containers back on the pavement should be prevented. In that case, it
can be concluded that the introduction of the redesigned container could result in a reduction of the low back and shoulder load. However, it should be stressed that a reduction in workload does not necessarily mean a reduction in the risk of low back and shoulder complaints.

In The Netherlands, a refuse collector is allowed to collect a maximum of 514 two-wheeled containers in a time period of 5.5 hours. This corresponds to an average of 1.6 two-wheeled containers per minute. The pushing and pulling distance of a two-wheeled container is about 8 meters. According to the guidelines of Mital et al., the maximum acceptable initial and sustained force for pushing with two hands is about 200 N and 100 N, respectively. For both types of containers, these values were exceeded in this study. According to the same authors, the maximum one handed pull force for males should not exceed 100 N. This limit is also exceeded for both types of containers. NIOSH recommends a maximum compression force on the low back of 3400 N. This guideline was exceeded for both types of containers. In addition, exposure to pushing and pulling appears to be related to an increased risk for shoulder complaints. Unfortunately, no guidelines are available for maximum acceptable shoulder loads. In conclusion, both types of container did exceed existing guidelines. Therefore, the question of whether the redesigned container is really better in terms of reducing the risk of musculoskeletal complaints should be raised. In our opinion, the answer to this question should be affirmative. Firstly, the guidelines are hardly based on epidemiological evidence. Secondly, not only daily exposure, but also long-term job exposure determines the risk of musculoskeletal disorders. Every day, year after year, a refuse collector has to handle hundreds of containers a day. Therefore, a relative small decrease in workload might result in a clinically relevant reduction in the risk of low back and shoulder complaints. Hence, the redesigned container might in the long run be an effective measure to (partly) prevent the onset or worsening of musculoskeletal complaints.

Acknowledgements

The Association for Waste and Cleansing Management (NVRD) and the Association of Dutch Waste Management Companies (VNA) financially supported this project. This study could not have succeeded without the contribution of the employees and management of the refuse collecting companies of Alkmaar, Bussum, Geldermalsen and Zaandam. The authors thank Jorrit Jansen for his support in data acquisition and processing and Tom Kalkman for helping build the redesigned two-wheeled container.