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Effect of push handle height on net moments and forces on the musculoskeletal system during standardized wheelchair pushing tasks

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Abstract

The aim of this investigation was to analyze the external forces and biomechanical loading on the musculoskeletal system during wheelchair pushing, in relation to different push handle heights. In addition, recommendations for wheelchair pushing in accordance with push handle height are made.

Eight young, female subjects carried out three different wheelchair transport tasks at five different push handle heights in a standardized laboratory setting. Five pushing heights were selected as a percentage of the subjects shoulder height (61, 69.5, 78, 86.5 and 95%). All three wheelchair transport tasks investigated required higher pushing handles in order to minimise net shoulder moments and external vertical forces on the hands. When pushing a wheelchair on to a pavement, net moments around wrists, elbows, shoulders compression and shear forces at L5-S1 and external vertical forces were lower using higher pushing heights. When low pushing handles are used, elderly female attendants are at risk of L5-S1 low back pain when lifting and pushing the wheelchair on to a pavement. A recommendation is made to reconsider height and position of the pushing handles of attendant propelled wheelchairs. For the investigated tasks, a pushing height of 86.5% (1.191 ± 0.034 m) was most favourable.

Introduction

Pushing and pulling actions during manual materials handling are associated with low back problems, as indicated by Pope (1989), who stated that 20% of the low back problems in the USA are related to pushing or pulling activities. Pushing and pulling tasks are regularly performed by a variety of professions, among which are: refuse collectors (Jager *et al.*, 1984), postmen (Haisman *et al.*, 1972), truck drivers, miners (Williams *et al.*, 1966) and nurses or orderlies (Harber[1,2] *et al.*, 1987; Winklemolen *et al.*, 1994).

Several physiological or psycho-physiological studies of pushing and pulling tasks have been conducted (Haisman *et al.*, 1972; Strindberg and Petersson, 1972; Sanchez *et al.*, 1979; Ciriello and Snook, 1983; Snook and Ciriello, 1991). Also, biomechanical studies have addressed pushing and pulling tasks, predominantly in relation to manual materials handling (Lee *et al.*, 1992; Kerk *et al.*, 1994; Wolstad *et al.*, 1994).

Among nurses, musculoskeletal disorders are a common cause of sick leave. Estryn-Behar *et al.* (1988) examined the causes of sick leave among 1505 female hospital workers. The main causes of sick leave were musculoskeletal disorders which affected 16% of the population during the previous 12 months. Of the investigated population 47% described back pain in the previous year. Several aspects can be identified which contribute to the heavy load of this occupation. In recent research lifting patients is considered to be the main cause of low back pain (Winkelmolen *et al.*, 1994). However, other tasks such as transportation of patients in wheelchairs must be considered as well, since this task is performed during a great part of the working day (Harber[1,2] *et al.*, 1987). Harber[1,2] *et al.* (1987) investigated the relationship between nursing activities and the occurrence of back pain. Carrying and pushing

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were the only tasks significantly associated with occupational back pain. Nurses and orderlies are not the only persons who transport patients in wheelchairs. In many hospital settings porters transport patients to the various hospital departments for treatment. In domestic environments husbands, wives and other family members push wheelchairs. Persons depending on attendant propelled wheelchairs in their home environment are usually older than 65 years as will be their companions, who may thus experience difficulties manoeuvring attendant push wheelchairs, especially outdoors (Abel and Frank, 1991). Apart from personnel, also volunteers in institutions, mostly middle aged, consider pushing wheelchairs a heavy task (Stephan, 1990).

The majority of wheelchair studies are focused upon the optimization of the wheelchair-user combination of manually propelled wheelchairs (van der Woude *et al.*, 1988, 1989; Veger *et al.*, 1991, 1992; Rodgers *et al.*, 1994). In contrast, investigation of attendant propelled wheelchairs is scarce (Stephan, 1990, 1992; Abel and Frank, 1991). In pushing an attendant propelled wheelchair, forces are applied to the handles at the back of the wheelchair to overcome rolling resistance, internal friction and effects of gravity. Preferred positions for wheelchair push handles have been suggested to be in the region of 75% of shoulder height and 1.14 times shoulder width (Abel and Frank, 1991). However to date, experimental analysis has not revealed why some handle positions may cause more strain or be less comfortable for wheelchair pushing than others (Abel and Frank, 1991). Further biomechanical analysis is necessary to draw conclusions on the optimum push handle height in terms of preference and with respect to the level of forces and moments in the upper body joints and trunk (Abel and Frank, 1991). Thus risks for low back problems or musculoskeletal disorders in general may be more readily discerned.

In order to investigate the possible risks of wheelchair pushing tasks on the musculoskeletal system, the current study analyses the external forces and biomechanical loading of the musculoskeletal system during a limited number of standardized wheelchair pushing tasks at different push handle heights. For this purpose eight young, female subjects carried out three different wheelchair transport tasks at five different handle pushing heights in a standardized laboratory setting. In order to calculate the biomechanical loading on upper body joints and the low back, a dynamic two-dimensional linked segment model was used (de Looze[1,2] *et al.*, 1992).

Methods

Subjects

Eight healthy female subjects participated in this study on a voluntary basis (age 23.9 ± 6.3 years, weight 58.6 ± 4.0 kg, height 1.69 ± 0.03 m). The subjects were considered to be physically representative of the nursing population. None of the subjects had a previous history of musculoskeletal disorders of the upper limbs or back. Moreover, none of them had more than an incidental experience of transporting persons in wheelchairs. Informed consent was signed prior to the experiment.

Experimental tasks

Three wheelchair pushing tasks were performed, each of them at 5 different push handle heights.

Thus, each subject performed fifteen trials, according to a standardized procedure. The three tasks were performed under laboratory conditions with an instrumented test wheelchair, loaded with an ISO-dummy, on a standardized test circuit. They were as follows:

1. increasing the velocity of the wheelchair from zero to walking speed starting on a flat circuit and finishing on the higher part of the circuit, using a slope of 6.74° (flat pushing);
2. increasing the velocity of the wheelchair from zero to walking speed starting in front of the slope up to the higher platform (slope pushing);
3. tilting the wheelchair backwards before pushing and lifting it on to the curb up to the higher platform (lifting).

The five pushing heights were chosen as a percentage of the subjects shoulder height. Pushing heights were 61, 69.5, 78, 86.5 and 95% of shoulder height. These percentages were based on realistic proportions between female body length and frequently used wheelchair pushing heights. The Joint Medical Services in the Netherlands suggest a push handle height of which equals the elbow height of the attendant and allows push handle heights for wheelchairs between 0.9 m and 1.2 m (GMD, 1992). The highest push handle height of the experimental wheelchair was determined from shoulder height of a 5th percentile (of body height) Dutch woman and a 1.2 m handle height. The lowest push handle height was derived from the shoulder height of a 95th percentile Dutch woman and a 0.9 m handle height (Molenbroek and Dirken, 1986). The other percentages were chosen at regular intervals between the highest and the lowest percentage.

The sequence of pushing heights was randomised. The sequence of the tasks was as mentioned before. All subjects were trained to perform the tasks at a certain pace, thus to a certain extent standardising walking velocities. The first task was performed in about 5.8-6.3s, the second task in 5.2 -5.8s, the third task in 5.8-6.9 seconds. The subjects were also trained to keep the arms in the sagittal plane as much as possible.

One subject performed an additional series of trails using the 78% push handle height, while the ISO-dummy was replaced by a young male person of 76 kg.

Anthropometry

Before starting the experiments, age, body weight, body height, and shoulder height were measured. The application of the linked segment model (de Looze[1,2] *et al.*, 1992) requires individual anthropometric data of trunk, head, upper arm, forearm and hand. Therefore, segment length, volume, mass, centre of gravity and moment of inertia were established using the regression equations of Young (1983). Thus, for each subject 18 anthropometric measurements were obtained in order to apply these regression equations. The distal section plane of the trunk according to Young is positioned at the level of the L3-L4 intervertebral disc. One of the aims of the present study was to measure net forces and net moments at the L5-S1 level. Therefore it was necessary to establish the anthropometric data of a segment bounded by the L3-L4 and the L5-S1 level. This was done by means of the method described by Yeadon (1990).

Linked segment model

A dynamic two dimensional Linked Segment Model (LSM) was used for calculation of net reaction forces and net joint moments (de Looze[1,2] *et al.*, 1992). These calculations were made for the wrists, elbows, shoulders and L5-S1 intervertebral disc centre. For L5-S1 the compression forces and the shear forces were also calculated. The LSM is based on inverse dynamics. The segments of the body are represented by linear rigid links connected by joints. The two dimensional model was built of links representing the hands, lower arms and upper arms, the head, trunk and pelvis. Newtonian principles are applied in order to calculate net forces and moments working upon every joint: $\sum F_y = m.a_y$, $\sum F_z = m.a_z$, $\sum M = I.\alpha$

Using external hand forces from the instrumented push handles of the experimental wheelchair, position data and anthropometric data, net joint forces and net moments were calculated. The results of these calculations are net joint forces and net moments for two hands, forearms and upper arms. Compression forces of L5-S1 were calculated assuming that extensor muscles of the lower back exert their resultant force at a distance of 0.062 m from the centre of the L5-S1 disc (Nemeth and Ohlsen, 1985; Susnik and Gasvoda, 1986). During positive resultant forces of the abdominal muscles the compression force values were set at zero.

Reflective markers were placed on the right side of the head (just in front of the bitragion), seventh cervical vertebra, shoulder (lateral part of the spina scapulae), elbow (lateral humeral epicondyle), lower arm halfway between the elbow and wrist (ulnar styloid process), L5-S1 as seen in sagittal plane, hip (upper margin of trochanter major) (de Looze[1,2] *et al.*, 1992) side of the pushing handle, and finally two on the frame of the wheelchair, placed in a vertical line. While the subjects performed their trials, the marker positions were recorded with a video-based 3-dimensional motion registration (and analysis) system (VICON@; 4 camera's; sample frequency: 60Hz).

Wheelchair and circuit

The experimental wheelchair (Fig. 1) was a foldable attendant push wheelchair (Poirier 3 A 41; weight 20 kg; height push handles: 0.905 m; front wheel size 0.20 x 0.05 m; rear wheel size 0.30 x 0.06 m; front tyre pressure 300 KPa; rear wheel pressure 250 KPa; rolling resistance of ISO-dummy loaded wheelchair on a motor

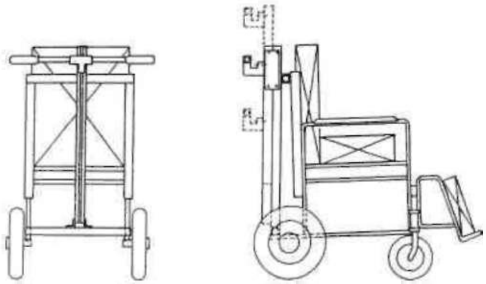


Fig. 1. Experimental wheelchair with pushing bar, which is adjustable in height.

driven treadmill: 7.89 N, v=1.11 ms^{-1}). A special purpose push handle replaced the standard push handles and was mounted on the experimental wheelchair on a special frame which allowed adjustment of the push handle in a vertical direction over a sufficiently large range (total weight wheelchair was 30kg). The push handle was instrumented with a set of two dimensionally arranged strain gauges allowing the measurement of the horizontal and vertical force components in the sagittal plane (F_y and F_z). Total width of the push bar was 0.58 m. Rubber hand grips were placed at the ends of the bar (diameter: 0.035 m). The experimental wheelchair was loaded with a 75 kg dummy according to ISO/DIS 1776-11, fixed to the wheelchair.

The test circuit (Fig. 2) was made up of two parts, each consisting of series of 4 x 8 paving stones, each measuring 0.30 x 0.30 m. The two parts differed 11.5 cm in height. The higher part was placed in series with the lower part. A removable board of 1 m length was designed to connect the lower to the higher part (slope 6.74°).

Data processing

The position data of the VICON-system were synchronized with the external forces from the calibrated force transducers of the push handle. Data of positions and forces were filtered with a digital low-pass second order recursive Butterworth filter with an effective cut-off frequency of 5 Hz. In order to allow visual verification of the data during data processing, all trials were also recorded on ordinary video tape. F_y and F_z forces were calculated in fixed horizontal and vertical directions.

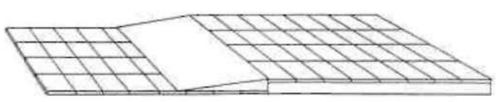


Fig. 2. Test circuit consisting of paving stones, the higher part connected to the lower by a removable board.

Mean and peak values of net external forces, net joint moments (wrists, elbows, shoulders, L5-S1) and L5-S1 compression and shear forces were determined with the two dimensional dynamic linked segment model for all trials, three tasks and eight subjects.

Statistics

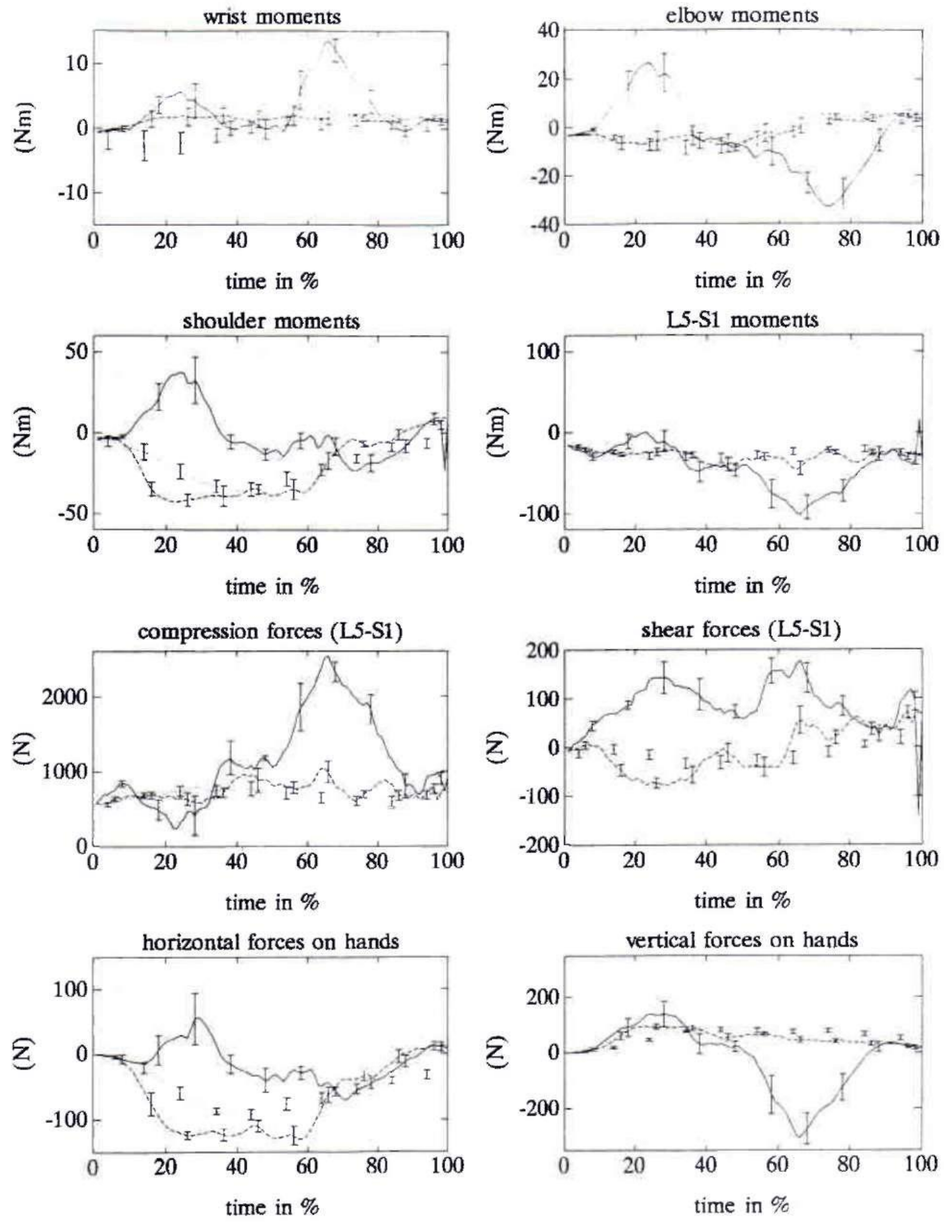
Effects of push handle height on mean and maximum net moments around wrists, elbows, shoulders and on L5-S1 compression and shear forces and the external hand forces were evaluated for the three tasks separately with an analysis of variance for repeated measures ($P<0.05$). When push handle height appeared significant, a Tukey post-hoc test was used to determine which handle heights differed significantly from each other.

The difference between data obtained from trials using the living person loaded wheelchair, and from the trials using the dummy loaded wheelchair (78%) was tested with a paired T-test ($P<0.05$). To study association between parameters a Pearson's product moment correlation was used ($P<0.05$).

Results

All 8 female subjects were able to perform the three tasks within the required experimental specification. Subjects did experience difficulties in performing the lifting task in a sagittal plane, especially when using the lowest push handle height. Although all trials were carried out, results for one subject performing wheelchair lifting at the lowest pushing height, could not be produced, due to loss of data.

Relative time histories are presented in Figure 3 to show mean curves over time (n=8) of the net joint moments around wrists, elbows, shoulders and L5-S1, and of the compression and shear forces (L5-S1) and external horizontal and vertical forces on the hands for the duration of the tasks (100%) for the lowest pushing height only. Since a two dimensional biomechanical model was used, values of net joint moments in wrists, elbows and shoulders, present the sum of moments around both left and right joints.



Time histories of flat pushing (...), slope pushing (---) and lifting (___) at the lowest pushing height (61% shoulder height). Mean curves of net moments in wrists, elbows, shoulders and L5-S1, compression and shear forces (L5-S1), external horizontal and vertical forces (on hands). Vertical bars indicate the standard error of the means (S.E.M.) (n=8 for flat and slope pushing, n=7 for lifting).

Fig. 3. Time course (mean and standard deviation) of the net moments and compression and shear forces for the three tasks at the lowest push handle height.

Flat and slope pushing at the lowest pushing height showed little variation of moments at wrists and elbows; values were low and slightly positive or negative, meaning small flexion or extension moments, respectively. Moments around shoulders and L5-S1 were negative, indicating an anteflexion moment around the shoulders and an extension moment around L5-S1. During flat and slope pushing, negative values of horizontal forces on hands and positive values of vertical forces on hands were found due to forward and downward pushing, indicating a non-horizontal total force applied to the handle.

The lifting task at the lowest push handle height can be distinguished in two phases; a tilting and lifting phase. During the initial tilting phase the wheelchair is tilted around the axis of the rear wheels and moments of wrists, elbows and shoulders were positive (indicating a dorsal flexion moment in wrists, an extension moment in elbows and a retroflexion moment in shoulders). Negative extension moments of L5-S1 are reduced in this phase compared to the following phase. During the lifting phase, positive wrist moments and negative moments of elbows, shoulders and L5-S1 were found. Highest peak values of compression and shear forces (L5-S1), and vertical external forces on the hands were found during the lifting phase.

Push handle height

Maximum values (mean and standard deviation) of net joint moments around the wrists, elbows, shoulders and L5-S1 are presented in Figure 4 for the different handle heights and the three tasks. Compression forces (L5-S1), shear forces (L5-S1) and external forces on the hands are presented in Table 1a to 1d.

Task 1: pushing the wheelchair on a flat surface

Only data of the first part of the trial were analyzed. During this part the wheelchair had not yet reached the slope. During flat pushing, peak moments were 4.5 Nm (at push handle height 78%) for the wrists, 18.1 Nm (69.5%) for the elbows, -41.9 Nm for the shoulders (61%) and -44.9 Nm for L5-S1 (69.5%) (Fig. 4a). The peak values for compression and shear forces (L5-S1) were 1051.6 N (69.5%) and 93.3 N (78%), respectively. Maximum horizontal and maximum vertical external forces on the hands were -114 N (78%) for F_y and 94 N (61%) for F_z (Table 1a).

Significant differences were found in relation to push handle height for the net moment around the shoulders, the mean moment around the elbows and the vertical forces on the hands.

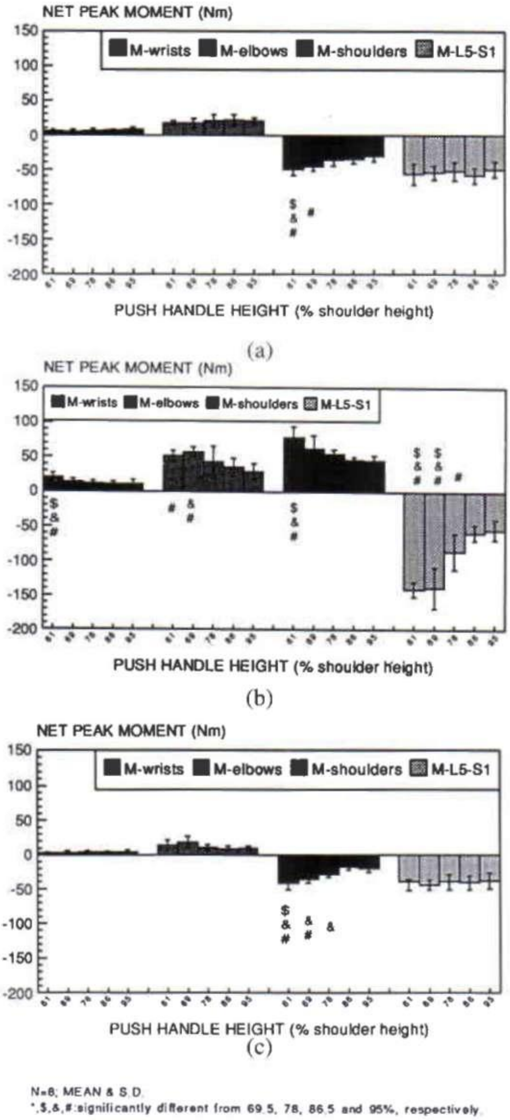


Fig. 4. Net peak moments around wrists, elbows, shoulders and L5-S1 (mean and standard deviation)
(a) flat pushing (Task 1)
(b) slope pushing (Task 2)
(c) wheelchair lifting (Task 3)

The shoulder moments and the external forces appeared to be lower at the higher pushing heights (Table 1a, Fig. 4a).

Task 2: pushing the wheelchair on an inclined surface

As was to be expected, during slope pushing the external forces, the peak net moments and

Table 1a. Flat pushing: maximal values of compression forces, shear forces and external forces in horizontal (Fy) and vertical (Fz) direction (N), depending on push handle height as a percentage of shoulder height (61 to 95%). Significant differences are indicated with *, $, & or #: significantly different from 69.5, 78, 86.5 or 95%, respectively.

Flat pushing (Task 1)	61%	69.5%	78%	86.5%	95%
CompF max					
MEAN	921.5	1051.6	988.8	982.1	971.5
SD	210.0	121.0	143.7	159.4	218.8
ShearF max					
MEAN	72.8	74.9	93.3	81.9	63.5
SD	22.7	10.0	40.5	25.5	24.0
Fy max					
MEAN	−101.62	−110.1	−114.1	−94.5	−102.0
SD	14.9	5.1	18.0	16.4	17.9
Fz max					
MEAN	93.7	62.2	31.3	25.0	12.5
SD	14.2	17.7	12.1	4.2	7.8
Sig. Tukey	*,$,&,#	$,&,#	#		

the forces on L5-S1 were systematically higher in comparison with flat pushing (Task 1). The peak values of net moments were 7.9 Nm for the wrists (95%) and again relatively low. 21.8 Nm at 86.5% for the elbows, -50.8Nm for the shoulders at 61% shoulder height and -59.0 NM for L5-S1 at the highest push handle height (Fig. 4b). Highest values for the compression and shear forces were 1284.0 N and 130.1 N, respectively. Maximum F_y values and F_z values were − 180.9 N and 109.1 N, respectively (Table 1b).

Significant differences in relation to pushing height were found for the net moment around the shoulders, the mean moment around the elbows and L5-S1, the mean horizontal force and maximum vertical forces on the hands. Net moments around shoulders and mean L5-S1 and the vertical forces appeared to be lower at higher pushing heights. Differences in mean net moment around the elbows were caused by a change in direction at the fourth pushing height (86.5%), but peak values showed no differences. Peak horizontal forces were higher

Table 1b. Slope pushing: maximal (or minimal) values of compression forces, shear forces and external forces (N), in horizontal (Fy) and vertical (Fz) direction, depending on pushing height as a percentage of shoulder height (61 to 95%). Significant differences are indicated with *, $, & or #: significantly different from 69.5, 78, 86.5 or 95%, respectively.

Slope pushing (Task 2)	61%	69.5%	78%	86.5%	95%
CompF max					
MEAN	1222.8	1196.9	1184.5	1284.0	1106.6
SD	260.2	179.9	221.4	195.6	175.7
ShearF max					
MEAN	130.1	115.8	126.6	116.6	123.7
SD	28.0	29.4	39.0	27.2	40.2
Fy max					
MEAN	−161.7	−159.9	−167.0	−180.0	−180.9
SD	8.7	10.6	7.6	13.5	15.7
Sig. Tukey	&, #	&, #			
Fz max					
MEAN	109.1	66.9	39.6	33.9	36.6
SD	23.7	11.2	19.7	17.7	11.7
Sig. Tukey	*,$,&,#	$,&,#			

Table 1c Wheelchair lifting: maximal values of compression forces and shear forces (N) and external forces (N) – direction depending on pushing height as a percentage of shoulder height. Significant differences are indicated with *, $, & or #: significantly different from 69.5, 78, 86.5 or 95%, respectively.

Wheelchair lifting (Task 3)	61%	69.5%	78%	86.5%	95%
CompF max					
MEAN	2946.7	2839.8	1844.4	1397.0	1344.6
SD	206.3	443.3	493.0	261.3	308.0
Sig. Tukey	$, &, #	$, &, #			
ShearF max					
MEAN	266.0	274.0	200.7	170.7	138.8
SD	57.9	95.6	27.2	21.5	27.4
Sig. Tukey	&,#	&,#			

Table 1d. Wheelchair lifting: maximal values of external forces Fz and Fy (N) and of forces in horizontal pushing (Fy push) and pulling (Fy pull) direction, and forces in vertical (Fz) direction depending on pushing height as a percentage of shoulder height. Significant differences are indicated with *, $, & or #: significantly different from 69.5, 78, 86.5 or 95%, respectively.

Wheelchair lifting (Task 3)	61%	69.5	78%	86.5%	95%
Fy max push					
MEAN	−105.7	−105.7	−170.9	−153.3	−126.0
SD	32.0	23.8	33.8	24.9	20.1
Sig. Tukey	&, #	&, #	#		
Fy max pull					
MEAN	120.8	130.8	143.6	123.8	108.7
SD	47.8	66.4	17.9	24.9	28.4
Fz max					
MEAN	-425.4	-344.0	-203.9	-200.1	-235.4
SD	33.3	45.5	66.5	60.0	61.2
Sig. Tukey	$,&,#	$,&,#			

at the higher pushing heights (Table 1b).

Task 3: lifting the wheelchair on to a curb

During the lifting task, peak net moments were 20.2 Nm around the wrists (at push height 61%), 57.1 Nm around the elbows (69.5%), 78.2 Nm around the shoulders (61%) and -140.9 Nm around L5-S1 (61%) (Fig. 4c). Peak compression and shear forces were 2946.7 N and 274.0 N respectively (61%) (Table 1c). Mean maximum horizontal push forces were -170.9 and mean maximum horizontal pulling forces were 143.6 N during this task (78%), while peak F_z was -425.4 N (61%) (Table 1d).

Peak net moments around wrists, elbows, shoulders and L5-S1, compression and shear forces (L5-S1) and vertical lifting forces were significantly lower for the higher push handle heights (Tables 1c and 1d; Fig. 4). Horizontal push handle forces tended to be higher with the higher push handle heights. An overview of the significant trends in the data is shown in Table 2 for the different tasks.

No statistical differences were seen between

Table 2. Overview of significant decrease (↓) or increase (↑) of absolute values of maximum net joint moments, L5-S1 compression and shear forces and external forces in relation to increasing pushing heights.

	flat pushing	slope pushing	lifting
wrist			↓
elbow			↓
shoulder	↓	↓	↓
L5-S1			↓
compF			↓
shearF			↓
Fy		↑	↑
Fz	↓	↓	↓

the ISO-dummy test condition and the testing condition with the subject in the wheelchair.

Discussion

Validity of experimental procedures

Wheelchair handling obviously is a three dimensional (3-D) activity, however many problems in 3-D modelling still remain to be solved. Therefore 2-D modelling was used in this study, with tasks largely restricted to the sagittal plane. Obviously, axial rotation and lateroflexion of the trunk, both recognized as hazardous task components with respect to low back pain, cannot be studied.

Subjects in this study were young females without experience in wheelchair pushing. Clearly subjects had to be equally untrained on all push handle heights and tasks. Also the current results must be treated with caution when applied to older and probably more experienced women.

For reasons of standardisation an ISO-dummy was used in this study to prevent the possibly unpredictable role of a subject. Since no statistical differences were found between the ISO-dummy condition and the tests with the subject, it may be concluded that the dummy seems a valid replacement of a living person of the same weight under the given testing conditions. However, some additional remarks can be made. The position of the centre of gravity (COG) of a wheelchair containing a dummy or a living person is of great influence on the rolling resistance (Lemaire *et al.*, 1991) and therefore on the required effective push forces. There is also an important effect on the required pulling and lifting forces (Wawrzinek, 1981; Wawrzinek and Boenick, 1987). A COG positioned rearward with respect to the larger rear wheels generally causes a lower rolling resistance and thus lower push forces. During a tilting action (Task 3) this will cause lower pulling forces (due to a lower rolling resistance) but during lifting it causes higher lifting forces, due to a stronger torque effect of gravity with respect to the handles. Due to the extra weight of about 8 kg of the experimental frame and force transducers at the rear of the test wheelchair, the COG moved backwards in comparison with the standard wheelchair model.

Flat wheelchair pushing (Task 1) and slope pushing (Task 2) tasks as investigated in this study were of a short duration. Therefore results of this study cannot be applied to comparable tasks of long duration. Whether wheelchair pushing tasks in all day practice are primarily of short or long duration is unknown. The duration of task performance was standardized and therefore tasks were performed in a sufficiently relaxed way. Maximum net forces and moments will indeed be influenced by (strong) variations in acceleration and deceleration and thus by the variation in performance time that can be expected in all day practice. It is obvious that the frequency of task components during wheelchair attending is greatly dependent on environmental aspects. It is unknown in what frequency the studied tasks do occur in different environments under daily life conditions. Furthermore, it is possible that different task components occur at the same time, such as flat or slope pushing while negotiating a side slope. These combinations might considerably increase biomechanical loading.

Tasks 1, 2 and 3

Comparison of the three tasks shows differences in course and magnitude of net forces and net moments (Fig. 3). In general, slope pushing causes higher net forces and net moments than flat pushing, although the time course of the data is quite comparable. It is striking that net moments around wrists and elbows can be kept close to zero. Apparently subjects were able to choose a favourable position of wrists and elbows with respect to the resultant external forces at any pushing height. The orientation of the hand grips may have played an important role in this respect.

During slope pushing, higher handle heights lead to higher pushing forces, and at the same time caused lower net moments around the shoulders due to a more favourable direction of resultant external forces with respect to the shoulder joint centre of roration.

Concerning net moments around L5-S1 one should realise that during moderate pushing the resultant external force causes an extending moment, which attributes to the extending moment exerted by the trunk extensor muscles. Therefore, pushing may have a decreasing effect on net L5-S1 moments. When pushing forces are high abdominal muscles, being trunk flexors, have to become active in order to compensate for the high extending moments caused by external forces.

During wheelchair lifting a different time course, and much higher net forces and moments occured than during flat and slope pushing. In fact three task components can be distinguished. Firstly when the wheelchair is pulled backwards, immediately followed by a downward pushing of the handles, thus tilting the wheelchair around the rear wheel axis. Then the conjunct forward pushing and lifting action started. This movement caused highest net forces and net moments. During performance of the lifting task the function of the curb is essential: when the rear wheels of the wheelchair are pushed against the curb, a lifting moment is created on the wheel axis by a combination of reaction forces of the curb and the external pushing forces (Wawrzinek, 1981). This lifting moment contributes to the upward movement of the wheelchair. The forward pushing forces cannot be exerted when the push handles are positioned too low (61%), as was derived from the video tapes. Due to the large distance between the hands and shoulders, the shoulder muscles seem unable to exert the required moments.

It is difficult to evaluate the possible consequence of the biomechanical loading during the investigated tasks. No standards have been established to relate net moments around the wrists, elbows and shoulders. With respect to compression forces of L5-S1 many studies have been conducted and standards are established. This will be discussed below.

Push handles

Most attendant push wheelchairs in the Netherlands are equipped with backwards pointing hand grips, approximately 0.90 m high (GMD, 1992). This position is only favourable when used in combination with low push handle heights. On the contrary, when pushing handles are high this handle position is unfavourable with respect to the orientation of the wrists. During pushing, pulling and lifting the wrists are forced into an extreme ulnar deviation when using the conventional grip handles. The test wheelchair had a horizontal pushing bar and hand grips allowing a symmetric and consistent pushing and pulling technique with a comparable orientation of the hands, wrists and lower arm at different pushing heights. The push bar did cause some trouble in lifting the wheelchair using lower handle heights. The wrists were then forced into an extreme dorsiflexed position. The net moments at the wrists during wheelchair lifting using the two lower pushing heights can be expected to be higher during this experiment than in all day practice using conventional grip handles. On the other hand, net moments around the wrists during pushing and pulling using higher push handle positions can be expected to be lower than during ordinary practice, when using backwards pointing handles.

Push handle height

The average absolute push handle heights for the eight female subjects used during the experiments ranged from 0.84m (±0.023 at 61%) to 1.308 m (±0.037 at 95%). Since the average push handle height of an ordinary wheelchair is 0.924 ± 0.014 m (GMD, 1992), this appeared comparable to the second push handle height (69.5%: 0.957 m ± 0.026) of shoulder height) in the current experiment. As is shown in Figure 4 and Tables 1 and 2, most significant differences in net moments and forces appeared to exist between the two lower and the three higher push handle heights. It can be concluded that the three higher push handle heights cause lower net moments than the two lower pushing heights with respect to the investigated tasks. Therefore, the common push handle height of about 0.920 m, being in the lower range of push handle heights of this study, might not be a too favourable pushing height from a biomechanical perspective and should be reconsidered. With respect to variable push handle heights, the pushing height that

Table 3. Compressive strength and damage load for women of 45 to 75 years according to Genaidy (1993) and NIOSH (1981)

Genaidy	age (yr)	45	55	65	75
	body weight (kg)	65	65	65	65
	compressive strength (N)	5958	5221	4484	3747
	damage load (N)	3637	3087	2538	1988
NIOSH	compressive strength (N)	4150	3320	2075	

equals elbow height, as advised by the GMD, matches 78% of shoulder height (Molenbroek and Dirken, 1986) being the third push handle height in the present study and lies just within the favourable pushing height range.

With respect to fixed push handle heights, the fourth push handle height (1.191 m ± 0.034) appears to be acceptable for the 5th to 95th percentile Dutch women (Table 3), because this height remains within the favourable pushing range of 78% to 95% of shoulder height. Whether these higher pushing heights are also favourable with respect to other task components than the ones studied here, remains to be investigated.

Studies of Abel and Frank (1991) have shown that the preferred position for wheelchair handles probably lies in the region of 75 ± 3.8% of shoulder height. This could be in accordance with results of this study, since middle and higher pushing heights (78 to 95%) cause less net moments around shoulders and L5-S1 than lower heights. Abel and Frank (1991) also stated that no difference was found between these moments at both high and low handle heights. This is not in accordance with the present study. Since Abel and Frank (1991) have not published their methods and procedures, it is not clear why different results have been found in their study, particularly because it is unknown which pushing heights have been investigated.

Push forces

Recently measurements of the forces necessary to push wheelchairs were made (GMD-TNO 1991). This was done on low piled carpet. The highest force was measured during pushing the wheelchair, loaded with a 75 kg dummy (ISO/DIS 1776-11), quietly from standstill to walking speed (GMD-TNO, 1991). The average horizontal push force for eight different wheelchairs comparable to the wheelchair in the present study (GMD, 1992), was 22.6 ± 4.4N. The average push handle height of these wheelchairs is 0.924 m ± 0.014 (GMD, 1992), which is comparable to the second push handle height in the current study. However, in the present study, push forces in flat pushing using the second push handle height were as high as 110.1 ± 5.1N. Four possible explanations can be offered to interpret this difference:

- the initial position of the castor wheels. In this study, during flat pushing the front wheels were placed back to front, in order to create a realistic situation. GMD-TNO does not mention the position of the front wheels.
- the weight of the wheelcair, which in the current study was about 8kg extra, due to the force transducer and its frame. GMD-TNO only mentions the weight of the wheelchair without equipment.
- the possibility of different accelerations of the wheelchairs which are unknown for the GMD-TNO study.
- differences in floor surfaces and tire pressures may attribute to the difference between push forces found by TNO and this study.

Glaser *et al.* (1980) have established horizontal external push forces of loaded wheelchairs at constant velocity on the level and on 1° to 5° inclined surfaces depending on total weight of the loaded wheelchair. On a flat tiled surface the authors measured a pushing force of about 11 N for a loaded wheelchair of 105 kg total weight. On a 5° inclined surface this wheelchair would require 108 N pushing force. If compared to pushing forces at the end of flat pushing and of inclined pushing tasks, forces measured by Glaser appear to be lower than pushing forces found in this study.

Glaser *et al.* (1980) came to the conclusion that handle height has no influence on the horizontal push force. This is in accordance with the results of the present study (Table 1). It should be mentioned though, that according to the results of this study, push handle height seems to have great influence on external forces in the vertical direction (Fig. 4, Table 1).

Compressive strength

Table 3 shows compressive strength and damage load for elderly women (body weight 65 kg) according to Genaidy *et al.* (1993) and National Institute of Occupational Safety and Health (NIOSH, 1981). Genaidy *et al.* (1993) provide regression equations for compressive strength (compressive force at which tissue failure occurs) and damage load (force which causes first signs of damage) depending on sex and age. Obviously, increasing age results in considerably lower damage loads. NIOSH (1981) presents somewhat lower values for compressive strength. If compared to maximum compression forces during wheelchair lifting at

61 and 69.5% of shoulder height (2946.7 and 2839.8 N) these values appear to exceed the NIOSH compressive strength force and the damage loads according to Genaidy *et al.* (1993) for women of 65 years and older. Moreover, the NIOSH action limit sustains a maximum lifting force of 392 N under most favourable conditions for industrial working people. This is comparable to wheelchair lifting at the lowest pushing height. Average vertical peak lifting forces appear to be as high as 425.4 N. Therefore it can be concluded that lifting a 75 kg loaded wheelchair onto a curb equals or even exceeds the NIOSH action limit and should be avoided. In conclusion, women, especially those over 65 years are at risk when pushing-lifting wheelchairs on to a curb or steep slopes, when using low push handle heights and when the total weight of the wheelchair plus occupant exceeds 105 kg.

Finally, Snook and Ciriello (1991) have established maximum acceptable horizontal push forces for female industrial workers in relation to two push handle heights and two frequencies (every 2 and every 5 minutes) using psycho-physical methods. It is difficult to make a comparison between these pushing tasks and (outdoor) wheelchair pushing, but it does not seem to be unrealistic however, to presume the occurrence of an initial push every 2 or 5 minutes. The maximum acceptable forces as established by Snook and Ciriello were 180 and 200N for the respective frequencies and irrespective of push handle height. It can be concluded that during wheelchair pushing, no maximum acceptable limits are exceeded for industrial working females.

Conclusions

Biomechanical loading when pushing a wheelchair is partly influenced by push handle height. In general higher push handles appear to offer some advantages with respect to the investigated tasks.

Pushing wheelchairs on a flat surface leads to higher net moments around shoulders and to higher vertical external forces on hands with a lower push handle height.

Pushing wheelchairs on an inclined surface leads to the highest maximal horizontal pushing forces when using high pushing handles. Nevertheless, higher net moments around shoulders and L5-S1 and vertical external forces are seen in relation to lower push handle heights.

Low push handles used in moving wheelchairs on to a curb, cause higher net moments, compression forces and shear forces on L5-S1, and higher lifting forces in comparison to higher pushing handles. A high push handle allows the attendant to push the wheelchair upon the pavement rather than to first have to lift the wheelchair. This push technique leads to lower net moments around all joints involved, than seen in lifting.

86.5% of shoulder height in particular appears to offer some advantages with respect to the investigated tasks and parameters. For an average woman this percentage corresponds to a pushing height of about 1.182 m, which is within a favourable range of pushing heights for the 5th to 95th percentile of Dutch women. When pushed by taller or smaller people, an adjustable pushing height might be necessary.

Other adaptations to the design and orientation of push handles and the construction of the wheelchair should be reconsidered in future research. For instance backwards pointing pushing handles do not seem very appropriate at higher pushing heights. Especially elderly female wheelchair attendants may benefit from more appropriately designed wheelchairs, since they appear at risk of L5-S1 damage, when lifting wheelchairs onto a kerb.

Many other aspects of wheelchair pushing remain unclear. Specially biomechanical loading during asymmetric tasks such as turning and pushing on side slopes, and the physiological strain due to static muscular work need further investigation.

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