

The effect of rear-wheel position on seating ergonomics and mobility efficiency in wheelchair users with spinal cord injuries: A pilot study

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Abstract—This study analyzed the effect of rear-wheel position on seating comfort and mobility efficiency. Twelve randomly selected paraplegic wheelchair users participated in the study. Wheelchairs were tested in two rear-wheel positions while the users operated the wheelchair on a treadmill and while they worked on a computer. Propulsion efficiency, seating comfort, and propulsion qualities were registered at different loads during the treadmill session. During the computer session, pelvic position, estimated seating comfort, and estimated activity performance were measured. The change in rear-wheel position affected wheelchair ergonomics with respect to weight distribution ($p < 0.0001$) and seat inclination angle (position I = 5° and position II = 12°). These changes had a significant effect on push frequency ($p < 0.05$) and stroke angle ($p < 0.05$) during wheelchair propulsion. We found no consistent effect on mechanical efficiency, estimated exertion, breathlessness, seating comfort, estimated propulsion qualities, pelvic position, or activity performance.

Key words: ergonomics, manual wheelchair, mobility, SCI, seating.

INTRODUCTION

Many different aspects have to be considered during the prescribing process of a manual wheelchair for the spinal cord injured (SCI) user. Biomechanics, kinesiology, medical aspects, wheelchair design, occupational

performance, and ergonomics are all examples of these aspects. Wheelchair mobility and transfer aspects often dominate the initial prescription process for many therapists and wheelchair users. In addition, many users prefer wheelchairs that can be loaded easily into cars. However, another equally important aspect is the wheelchair's seating comfort and optimal adjusted support. How these mobility and seating aspects interact and affect each other has not been sufficiently analyzed.

Abbreviations: ASIS = anterior superior iliac spine, ECG = electrocardiography, FCF = freely chosen push frequency, HR = heart rate, ME = mechanical efficiency, PO = power output, RER = respiratory exchange ratio, RPE = Ratings of Perceived Exertion, SCI = spinal cord injury, SD = standard deviation, VCO₂ = carbon dioxide elimination, VE = pulmonary ventilation, VO₂ = oxygen consumption.

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Good seating ergonomics require the chair to be designed to suit the user and the task. In modern societies, people use many kinds of chairs designed for unique purposes, environments, or tasks: An office chair supports a user in a declined as well as a reclined position, an armchair mainly supports a user in a reclined position, and a dining room chair supports a user in an upright position. For most people, chair selection occurs every day. Chair design is important to every sitter; yet people with a disability and wheelchair users may sit in the same chair (wheelchair) in every activity every day for many years. Since the wheelchair often becomes the main seat, seating ergonomics should be examined to the same extent that mobility is examined.

In an active wheelchair, the seat is often reclined to ensure good seating stability and to ease propulsion. However, performing daily activities such as eating, cooking, and computer work from a more level seat might benefit a user. Lumbar flexion and load have been found to increase in healthy subjects during a reading activity with a reclined seat angle [1]. Since the anterior-posterior tilt of the pelvis has a major influence on the posture and load of the body, especially the lumbar spine, the seat angle may also play an important role in seat comfort for wheelchair users [2,3]. During recent decades, the knowledge in advantages and risks related to wheelchair seating ergonomics has increased. For instance, common secondary complications in the SCI population such as back pain, spinal deformities, pressure sores, and shoulder pain have been discussed in relation to wheelchair seating ergonomics [4–7]. Studying seating ergonomics and secondary complications requires studying aspects other than those normally discussed in relation to propulsion. For example, the position of the pelvis is important: the optimal seating posture is an upright symmetrical seating posture, with a neutral pelvic tilt with the iliac crests in alignment and level in the lateral plane [8]. The spine should be supported in its natural curvature, reducing the risk of spinal deformities, back pain [9–11], impingement in shoulders, and pressure ulcers [12]. Epidemiological studies indicate the role of mechanical loads on the aetiology of occupational back pain [12]. An upright position also stimulates the cardiovascular function [13,14].

Because the wheelchair aids mobility and serves as seating furniture, these aspects should be studied in relation to one another. In clinical practice, it often becomes confusing to reconcile both mobility and seating aspects

into the same wheelchair without knowing how an adjustment to optimize one aspect interferes with another aspect. When fitting a wheelchair to a user, one should consider seat inclination. A more reclined seat increases the load on the lumbar spine whenever the subject needs to perform activities that require trunk flexion, such as eating, writing, or computer work [15]. Because most of the motion in bending forward is performed in the lower lumbar spine, the spine makes the disc bulge on the concave side of the spinal curve and retract on the convex side. The torque will increase in a reclined seat position, since the lever arm for the force will increase [15,16]. Bending forward, allows the spine to fully flex, which leads to anterior shear forces and the person “hanging by his or her soft tissues” [17], which could occur also in a “slumped” seating position. Active hand-rim wheelchairs do not allow for an easy change in seat inclination, making seat inclination difficult to adjust in relation to both propulsion and seating ergonomics.

Previous studies of rear-wheel position and propulsion efficiency have focused on different aspects and used different study settings. In two studies, the possible association between seat height and oxygen cost was examined [18,19]. In both studies, a significant effect of seat height on oxygen cost was observed. Oxygen cost increased with higher seat position. In a biomechanical analysis of wheelchair propulsion in five male paraplegics for various seating positions, Masse et al. defined three horizontal rear-wheel positions at two seating heights on a single-purpose-built racing wheelchair [20]. Kinematic analysis revealed that joint motions of the upper limbs were smoother for the low positions. By lowering the seat position, the authors found that less integrated electromyogram (EMG) was recorded and the degrees of contact were lengthened. Richter used the SMART^{Wheel} mounted on five wheelchair users’ own wheelchairs and a quasi-static wheelchair propulsion model to collect data on hand-rim forces and moments, joint kinematics, joint torques, push frequency, and push angle [21,22]. Decreasing the distance between shoulder and hub increased push angle and elbow extension torque and decreased push frequency and shoulder torque. Because a more reclined seat benefits propulsion ergonomics, we decided to measure the effect on mechanical efficiency (ME) and to estimate exertion breathlessness as well as seating and mobility ergonomics. We performed the measure in two commonly used rear-wheel positions while using a typical active wheelchair.

METHODS

Hypothesis and Design

With the hypothesis that seat inclination affects propulsion efficiency and seating in wheelchairs, this study analyzes the effects of rear-wheel position on wheelchair propulsion and seating aspects. We used a randomized experimental crossover design to perform this analysis.

Subjects

Twenty-five wheelchair users with paraplegia caused by a SCI were randomly selected from the records of the Unit of Neurological Rehabilitation at the University Hospital in Linköping, Sweden. Thirteen agreed to participate in the study. Because one subject was unable to use the wheelchair intended for the study, he was not included in the study. The results of the study are based on 12 subjects, 2 women and 10 men. All clients had an injury at the thoracic or lumbar level. Seven subjects were classified as Frankel A, and five were classified as Frankel D. Two had an injury because of spina bifida, and ten had a traumatic SCI. The mean age of the studied group was 48 ± 18 years (range = 22 to 78 years). Eleven subjects operated their wheelchairs without assistance indoors and outdoors. One subject only independently used the wheelchair indoors. The average time spent in the wheelchair per day was 11.6 ± 4.1 hours.

Material

All subjects used the same type of wheelchair during the experiment (XLT Power, INVA CARE, Spånga, Sweden) (**Figure 1**) in two ordinary standard rear-wheel positions (**Figure 2**): two seat angles of inclination 5° and 12° and two wheel positions in relation to the backrest. The vertical distance between positions I and II is 55 mm, and the horizontal distance is 12 mm. We chose these two standard wheel positions assuming that a more level surface (5°) would facilitate occupational performance, including forward bending while one uses a computer. The more reclined position (12°) would make wheelchair propulsion easier because we assumed that the user would increase the angle of the hand rim, since the seat would be lower in relation to the rear wheels. This reclined position would also facilitate postural stability. The backrest angle was adjusted to fit each individual; the mean backrest angle change between positions I and II was $5.3^\circ \pm 4.0^\circ$. Three seat widths were used to fit the wheelchair to each subject. Each subject used the same

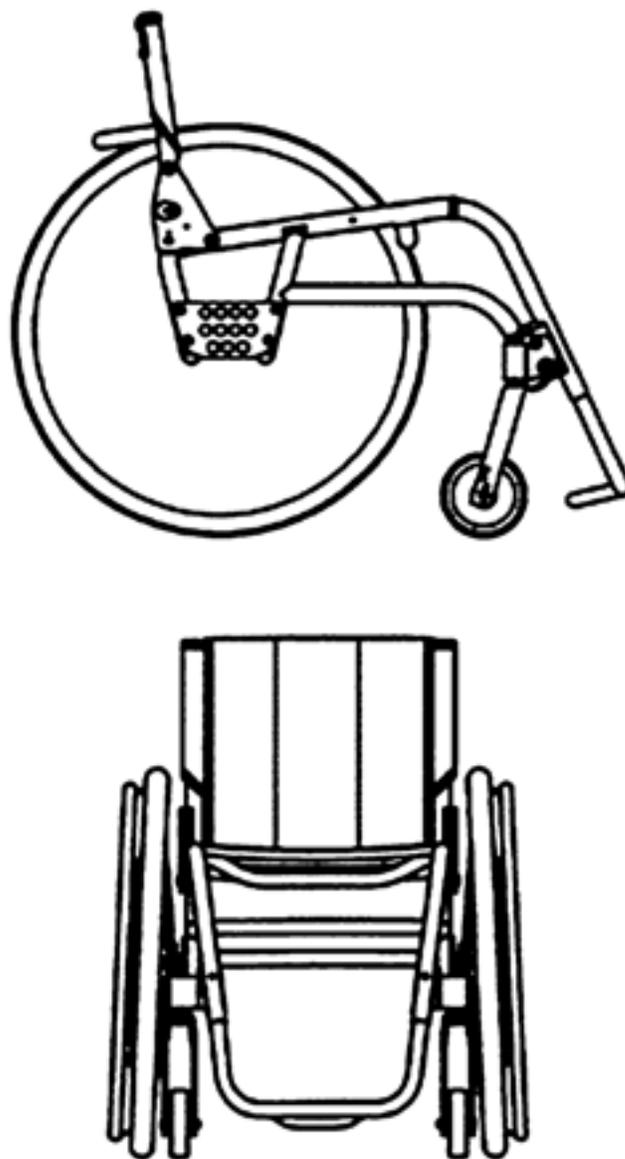


Figure 1. Wheelchair used in study (XLT Power, Inva Care, Spånga, Sweden).

wheelchair during the testing. The wheelchair manufacturer used in this study was not the wheelchair manufacturer the subjects used at home. Subjects used their own seat cushion in both seat positions.

Procedures

All subjects were randomly selected to start the experimental session in one of the two seating positions and in one of the two activities. Before performing any activity, we weighed each subject while sitting in the

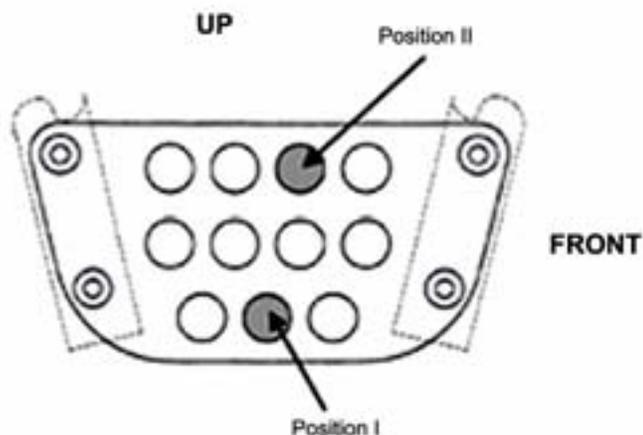


Figure 2.

Two standard positions of rear wheels in rear-wheel attachment. Position I: giving a reclined seat angle of 5° and position II: giving a reclined seat angle of 12° .

wheelchair on a wheelchair-weighing machine to define weight distribution between wheel pairs in each seating position. The two activities were wheelchair propulsion on a treadmill and computer work for 30 minutes. After performing the two activities in one position, the subject had an hour of rest before changing rear-wheel position and repeating the activities. Wheel camber and wheel alignment were not affected by the position change. Tire pressure was the same between positions, and castor orientation was adjusted.

Driving on a Treadmill

Propulsion efficiency was analyzed with the subjects propelling the wheelchair on a treadmill (Rodby innovation AB, Enhörna Sweden). To become familiar with the test situation, each subject had a test period on the treadmill for about 5 minutes before data collection. During this period, belt speed was tested and the propulsion technique was practiced. Speed selection started at 1 m/s. If the subject objected to this speed, an individually fitted speed was tried. Rolling resistance was affected with the use of extra loads. This external force acted on the wheelchair via a pulley system to obtain a stepwise submaximal test of power output (PO) (**Figure 3**). We defined rolling resistance at each load using a force gauge (FLUKE 8060 Multimeter, ELFA produkter, Järfälla, Sweden). We calculated PO at each load using the measures from rolling resistance and belt speed ($PO = Fd \times$

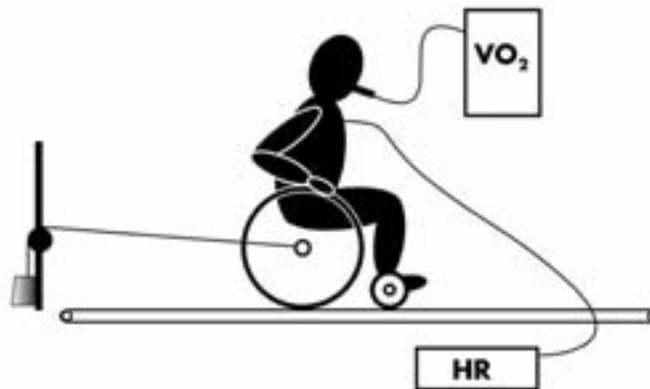


Figure 3.

Treadmill experimental design. Rolling resistance is affected with use of extra loads. This external force acts on wheelchair via a pulley system. During wheelchair propulsion, electrocardiography, including heart rate (HR), is registered. Oxygen consumption (VO_2), carbon dioxide elimination (VCO_2), and pulmonary ventilation (VE) are measured during 6 min of wheelchair propulsion.

V). Electrocardiography (ECG) was registered in each client during the procedure, and heart rate (HR) was measured using the ECG recordings. When the client felt comfortable with speed (V) and drag force (Fd), respiratory exchange and HR were measured during 6 minutes of wheelchair propulsion.

We measured oxygen consumption (VO_2), carbon dioxide elimination (VCO_2), and pulmonary ventilation (VE) using the MedGraphics CPX system XX (Spiropharma, Denmark). The respiratory exchange data were averaged every 15 s, and the average of these observations from 2 consecutive minutes of stable exercise was used to represent each workload. Each client was studied at a minimum of two loads. The oxygen consumption (VO_2) per minute was calculated. To ensure aerobic exercise, we followed the respiratory exchange ratio (RER). Loads with $RER \leq 1.0$ were chosen. Load was increased to achieve a near-maximal aerobic performance. The procedure was videotaped, and freely chosen push frequency (FCF)/minute and stroke angle were determined from the video. We calculated a mean value of push frequency over a period of several cycles of propulsion and defined stroke angle by calculating the mean difference between the release angle and the contact angle during several cycles of propulsion at the appropriate load [23]. In direct reference to each load, the client estimated perceived exertion on the Ratings of Perceived Exertion (RPE) scale [24] and breathlessness on the CR10 scale [24]. After each trial, the

subjects reported their opinion on wheelchair propulsion qualities using a 10-point scale (1 = “very poor propulsion qualities” to 10 = very good propulsion qualities “) and seating comfort using a 10-point scale (1 = “very poor seating comfort” to 10 = “very good seating comfort”).

To compare propulsion efficiency during wheelchair propulsion under different seating conditions, we calculated and compared ME at comparable PO, achieved by adjusting the load. The ME of a system is defined as the ratio of PO to energy expended (PI^{-1}) [25]. Calculations of the ME assume that energy requirements are met by aerobic respiration. Therefore, PO values at which an anaerobic energy delivery is involved have to be avoided. In this study, ME was calculated as $ME = (PO \times PI^{-1}) \times 100\%$. Working for 1 minute at 1 W is equivalent to 60 J, and each liter of oxygen used is equivalent to about 20.934 J. The ME is calculated as

$$ME(\%) = \frac{60 \times PO}{20.934 \times VO_2} \times 100 .$$

PO = Power output (W), was calculated as $Fd \times V$, where Fd = the measured drag force and V = the belt speed of the treadmill. VO_2 = oxygen consumed per minute, corrected for calculated basal metabolic rate according to Shepard [25].

Computer Work

Each subject did 30 minutes of computer work in each wheelchair position. We measured pelvic position immediately after the session using a specially manufactured inclinometer (**Figure 4**) (Rodby innovation AB, Enhörna, Sweden). We measured pelvic rotation using the anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS) as references and measured pelvic lateral tilt using ASIS as references as described by Crowell et al. [26]. One therapist did all the pelvic inclination measurements to increase the reliability of the measurements. All clients estimated seating comfort and activity performance after the session in each seat position on a 10-point scale ranging from 1 = “very poor seating comfort” and “cannot perform the activity” to 10 = “very good seating comfort” and “can perform the activity very well.”

Statistical Analysis

Statistica 5.5 was used in all statistical analysis. In the text and **Tables 1** and **2**, mean (M) values ± 1 standard deviation (SD) are given. When appropriate, ranges have also been reported. We used nonparametric statis-

tics, such as Spearman’s rank correlation and Wilcoxon signed rank sum test in the analysis of all data, since the studied group was quite small and most variables are considered to be ordinal scales. The significance level was set at $p < 0.05$.

RESULTS

Wheelchair Propulsion on Treadmill

When the rear wheels changed from position I to position II (**Figure 2**), the distribution of weight changed significantly, $p < 0.0001$. The mean weight distribution over the rear wheels in position I was 75 ± 5 percent. The mean increase in weight over the rear wheels in position II was 5 ± 0.04 percent.

Ten subjects propelled their wheelchair at 1 m/s, one subject at 0.8 m/s, and one subject at 1.5 m/s. We found no difference in ME (**Figure 5**) at comparable loads in paired analysis of the two seating positions ($p = 0.08$, ns [nonsignificant]). However, in position II, a tendency toward decreased ME was found. Eight of twelve subjects had decreased ME in position II. One subject had the same ME in both positions. Estimated breathlessness and perceived exertion did not correlate significantly with ME in any position. FCF was significantly less in position II, $M = 53.8 \pm 10$, compared to position I, $M = 58.6 \pm 7.4$ ($p = 0.03$). The stroke angle was larger in position II, $100.8^\circ \pm 26.6^\circ$, compared to position I, $87.1^\circ \pm 16.8^\circ$ ($p = 0.03$). The push frequency and stroke angle significantly showed negative correlations in both positions: position I, the Spearman rank-order correlation $r_s = -0.67$ ($p = 0.02$); and position II, $r_s = -0.61$ ($p = 0.03$).

We found no significant consistent differences in physiological data between the two seat positions (**Table 1**). We did not find any difference in perceived exertion or breathlessness ($p = 0.23$, ns, and $p = 0.68$, ns, respectively). Neither estimated seating comfort nor estimated propulsion qualities differed between the two positions ($p = 0.1$, ns, and $p = 0.1$, ns, respectively).

Computer Work

The pelvic inclination did not uniformly differ between the two positions either in the frontal or in the sagittal planes ($p = 0.12$ and $p = 0.16$, respectively). No difference was found in users’ estimated seating comfort or activity performance ($p = 0.1$ and $p = 0.1$, respectively) (**Table 2**).

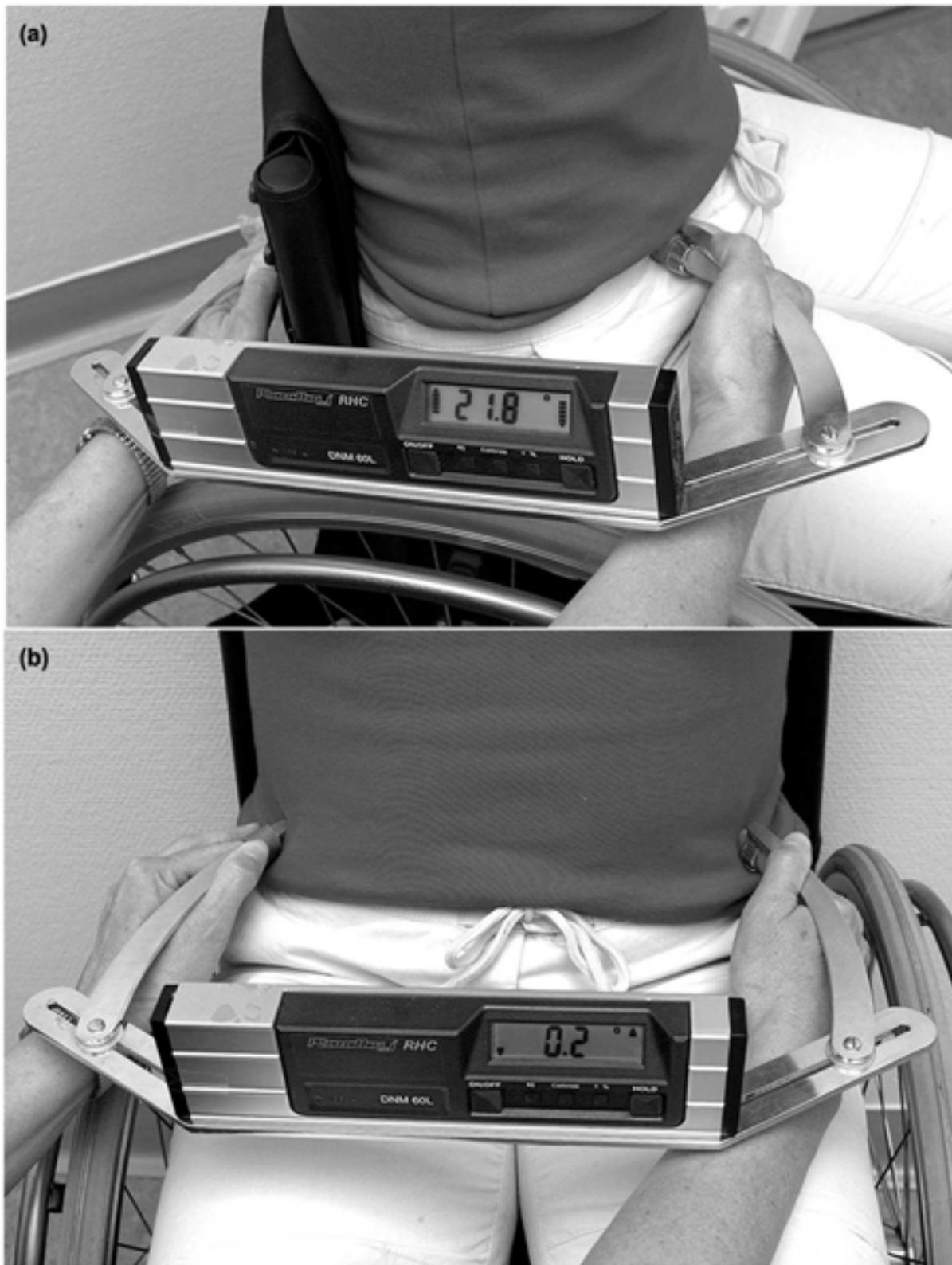


Figure 4.
(a) Measure of pelvic rotation in sagittal plane. (b) Measure of pelvic lateral tilt in frontal plane.

Table 1.

Results from treadmill wheelchair propulsion (position I, seat angle 5°, and position II, seat angle 12°).

Patient No.	Wheelchair Position I							Wheelchair Position II						
	VO ₂ Peak (mL/min)	RPE	PO (W)	HR	VE	FCF	Stroke Angle (°)	VO ₂ peak (mL/min)	RPE	PO (W)	HR	VE	FCF	Stroke Angle (°)
1	772	16	27.6	105	22	54	90	772	17	27.8	111	21	54	110
2	1,086	15	33.8	103	40	44	110	1,200	13	31.9	112	35	40	140
3	756	11	22.0	85	25	56	110	840	11	21.6	91	27	40	115
4	616	17	3.4	110	22	62	65	641	17	3.2	112	23	56	60
5	782	11	23.8	93	24	52	105	770	13	23.3	92	21	48	100
6	819	13	17.9	104	35	66	75	782	11	17.3	96	26	72	75
7	1,281	14	48.8	131	32	54	90	1,132	13	46.3	118	29	48	110
8	850	17	29.0	136	28	58	95	858	15	28.8	121	25	56	125
9	540	16	7.4	131	21	64	60	627	16	7.6	139	25	66	50
10	999	17	41.3	115	32	68	90	1,114	13	41.3	122	35	52	120
11	608	11	20.0	106	17	56	85	591	11	18.5	85	18	48	105
12	600	13	16.3	98	19	69	70	685	14	15.8	116	22	66	100
Mean	809	14	24.3	110	26	58.6	87	834	14	23.6	110	26	53.8*	101*
SD ±	220	2	13.0	16	7	7	17	208	2	13.0	16	5	10	27

**p* < 0.05
 VO₂ = oxygen consumption (mL/min)
 RPE = ratings of perceived exertion
 PO = power output (drag force × velocity)
 HR = heart rate
 VE = pulmonary ventilation
 FCF = freely chosen push frequency/minute
 Stroke angle = angle used on hand rim during push phase
 SD = standard deviation

Table 2.

Results from computer work session (position I, seat angle 5°, and position II, seat angle 12°).

Patient No.	Wheelchair Position I				Wheelchair Position II			
	Pelvic Lateral Tilt (°)	Pelvic Sagittal Rotation (°)	Estimated Seating Comfort	Estimated Activity Performance	Pelvic Lateral Tilt (°)	Pelvic Sagittal Rotation (°)	Estimated Seating Comfort	Estimated Activity Performance
1	2.6	8.1	8	8	2.5	16.3	6	8
2	1.3	2.5	7	8	1.7	4.5	10	9
3	1.3	2.3	7	8	1.6	6.2	8	8
4	3.0	13.3	9	9	4.0	2.1	6	9
5	1.5	14.1	8	8	0.8	20.0	5	6
6	10.3	24.1	8	8	10.2	23.8	8	8
7	0.5	10.9	3	7	1.2	12.9	3	6
8	1.2	16.3	7	7	3.4	21.1	5	5
9	4.7	16.5	6	8	5.0	23.0	5	8
10	3.2	3.0	10	10	4.5	5.6	6	6
11	3.1	8.8	6	8	1.3	5.5	8	8
12	2.7	14.7	7	8	5.2	13.9	5	6
Mean	2.9	11.2	7.2	8.0	3.4	12.9	6.2	7.2
SD ±	2.6	6.6	1.7	0.8	2.6	7.9	1.9	1.4

DISCUSSION

One should treat conclusions drawn from this study with some caution because they are based on a small and

quite heterogeneous group of paraplegic wheelchair users. Although the results do not support clinical practice in a clear and uniform way, results show that a position change will affect the user.

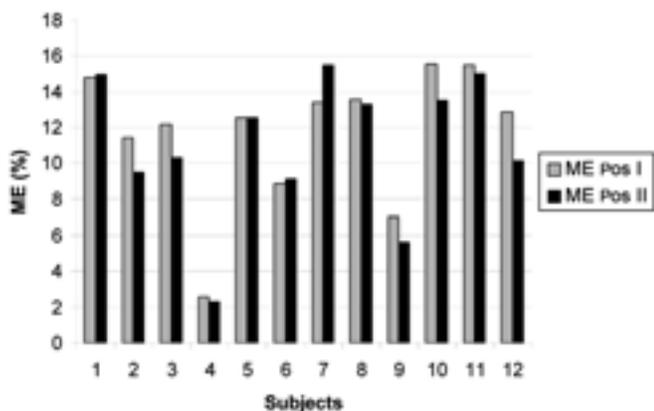


Figure 5. Mechanical efficiency (ME) during wheelchair propulsion. Difference in seat positions did not have a significant effect on ME, $p > 0.08$, ns.

The main results of the present study were both expected and unexpected. We affected both the seating and propulsion ergonomics of the chair in a systematic way. When the wheelchairs were adjusted, the weight distribution of the wheelchair as well as the interface between user and wheelchair changed with the wheels' position. These changes had a significant effect on propulsion technique, which has been reported in other studies but not on ME. ME tended to decrease in the position that aimed to give the user the relatively best propulsion condition, position II. However, these findings do not agree with other studies where oxygen cost increases with a higher seat position [29]. One possible but not evident explanation of our results concerning the unexpected effect on ME might be that the wheelchair adjusted for propulsion with a reclined seat surface resulted in a more flexed trunk posture, which in turn could have affected the circulatory-respiratory systems of the body [3,13,27]. This hypothesis, however, needs further research.

We found no significant difference on estimated propulsion qualities or seating comfort between the two positions. Since we assumed that a more reclined seat would optimize mobility efficiency and that a more level seat would optimize computer work, we chose two rear-wheel positions that would match this assumption. The results of the study might have been more obvious with a larger difference in wheel position, but that would not be as applicable in a clinical practice. The effects of wheelchair ergonomics on propulsion efficiency and estimated comfort also seem to be related to other aspects [20,21,27,28]. The individual prerequisite for sitting in a certain position,

propelling the wheelchair, or performing other activities might also be related to individual balance, seating habits, postural control, the overall work capacity of the cardio-respiratory system as well as arm, shoulder, and trunk range of motion and muscle strength [30]. Apart from the extent of the disability, seating comfort is a personal sensation and quite difficult to standardize [3].

We know that wheelchair propulsion efficiency is quite low. Previous studies on gross mechanical efficiency of hand-rim wheelchair propulsion have reported values as low as 2 to 10 percent [31,32]. In our study, we calculated ME values between 5.6 and 15.5 percent. Research on wheelchair propulsion has also been described in terms of kinematics. Masse et al. studied the pattern of propulsion in six different seating positions [20]. The kinematics analysis revealed that the joint motions of the upper limbs were smoother when the subject had a low position in the wheelchair, where the distal phalanges of the second fingers of the subject's hands were aligned with the lowest portion of the push rims. These findings might be related to studies focusing on force transmission on hand rims, stroke angle, and push frequency [18,19,21], which support the findings in the present study, where the FCF and stroke angle were affected in a positive way in position II. Similar results were demonstrated in another study of PO and propulsion technique in two different seating positions with the use of a wheelchair ergometer connected to an isokinetic dynamometer on able-bodied men [27]. The results showed that significant differences ($p < 0.001 - 0.01$) in mean power, effective time, angle, and work/propulsion were found between a seating position where the seating support was more level (position I in our study) and a seating position where the seating support was more reclined (position II in our study). However, the present study indicates that there may be no simple correlations between wheelchair ergonomics and propulsion efficiency. Thus, more complicated models allowing for individual needs should be developed to optimize mobility and seating comfort [32].

Boninger et al. found that the location of the shoulder in relation to the rear axle in the horizontal plane was related to the frequency of propulsion [33]. In addition, shoulder position in relation to rear axle in both the horizontal and vertical planes significantly correlated with push angle. Brubaker also described the effects of orienting the subject in relation to the rear wheels so as to influence propulsion efficiency [34]. These findings support the findings

in our study. Propulsion qualities were affected by wheel position, but we could not demonstrate a relation to ME.

In this study, we have used former research and clinical experiences to find structural guidelines to ensure good quality in wheelchair prescription. This study indicates that a simple correlation between wheelchair ergonomics and propulsion efficiency and seating comfort may not exist. The key to a successful prescription is probably to fully understand the relationship between the user, the equipment, and the environment, including the different kinds of activities the user engages.

CONCLUSION

Changing the position of the rear wheels and because of this changing, the weight distribution and seat angle of the wheelchair significantly affected propulsion ergonomics concerning push frequency and stroke angle. Other aspects related to physical effort and estimated ergonomics on propulsion and seating changed but not in a significantly uniform way.

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