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Isometric Pull and Push Strengths of Paraplegics in the Workspace: 1. Strength Measurement Profiles

Biman Das[a] & Nancy L. Black[b]

[a] Department of Industrial Engineering Dalhousie University, Halifax, NS, Canada

[b] École de génie, Secteur génie industriel Université de Moncton, Moncton, NB, Canada

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Isometric Pull and Push Strengths of Paraplegics in the Workspace: 1. Strength Measurement Profiles

Biman Das

Department of Industrial Engineering
Dalhousie University, Halifax, NS, Canada

Nancy L. Black

École de génie, Secteur génie industriel
Université de Moncton, Moncton, NB, Canada

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The isometric strength profiles of male and female paraplegics were determined for pull and push strengths in the normal, maximum, and extreme working reach envelopes. A computerized isometric strength measurement system was designed and constructed for the purpose. The strongest pull location was at extreme reach vertically above the shoulder and the strength values for males and females were 473 and 318 newtons (N), respectively. The strongest push location was at maximum reach, at vertical (ϕ) angle of 45° and at horizontal (θ) angle of 45° for males and at 0° for women and the strength values were 235 and 172 N, respectively. The nature of the strength profiles was found to be similar for both the sexes. The pull and push strengths of the female were 77 and 68% that of the male, respectively.

isometric strength measurement pull and push strengths
workspace reach envelopes paraplegics

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Correspondence and requests for reprints should be sent to Biman Das, Department of Industrial Engineering, Dalhousie University, Halifax, NS, Canada. E-mail: <Biman.Das@dal.ca>.

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1. INTRODUCTION

The determination of isometric or maximum static strength in the workspace is important as industrial workers should not generally exceed one third of their isometric strength on a sustained basis in task performance (Putz-Anderson, 1994). The workspace is defined as the space above the table and in front of the operator. When excessive force is involved in a repetitive task with a cycle time less than 30 s, cumulative trauma disorders (CTD) may develop (Putz-Anderson, 1994). Notably workers are required not only to reach, but also to exert a force to perform tasks in the workplace. If a task only required reaching, the task would best be placed within the "normal" reach; if this was not possible, it should be placed within the "maximum" reach, and only as a last choice in the "extreme" reach envelope. The normal reach was defined by the comfortable reach of the lower arm with the upper arm relaxed (Das & Behara, 1995; Squires, 1956). The maximum reach was limited by the outstretched arm (Farley, 1955). The extreme reach was defined by the limiting reach of the outstretched arm with extension of the torso without losing stability (Kozey, 1996; Sengupta, 1995). When both reach and force are required, the normal reach may not be best for the task depending on strength capabilities in the different reach envelopes. Human strength varies with many task-related factors including horizontal distance from the body, height, orientation of exertion, and velocity (National Institute of Occupational Safety and Health [NIOSH], 1981). Although strength has been studied according to varying horizontal distance, it has not been studied specifically according to the anthropometric normal, maximum, and extreme reach envelopes. Consequently, it is necessary to determine a strength profile for the workspaces surrounding the worker.

Human strength capabilities change at different horizontal and vertical angles due to the interactions and orientations of the musculoskeletal system. Studies have shown strength changes with different combinations of horizontal and vertical angles (Davis & Stubbs, 1977; Hunsicker, 1955) and exertion direction. It is therefore necessary to determine the location in the reach envelope where force can be maximized for a given direction, allowing the design of controls to be placed optimally.

Industrial tasks are accomplished in a variety of orientations, and under a variety of conditions. Lift exertions have been studied most frequently. Lift strength alone cannot be used to determine pull or push strength, as each of these varies differently with horizontal distance and height (Hunsicker, 1955). Exertion directions such as pull and push have been less studied, and yet many tasks in a working day require pulling objects or controls toward oneself, or pushing them away. Thus, pull and push radial exertions are representative of working tasks and should be studied to determine optimal workstation design.

Women are on the average approximately one third weaker than men (NIOSH, 1981), although the difference associated with gender depends on the body members involved in the exertion. Sale and Norman (1982) estimate upper body strengths to differ approximately 50% between men and women. As gender has a significant effect on strength, both men and women must be studied to ensure definition of a strength profile relative to the entire working population.

Based on other related studies, it is believed that the strength profile of paraplegics is not the same as that of able-bodied persons due to their increased use of upper-body musculature, and use of a wheelchair (Calmels, Berthouze, Barral, Domenach, & Minaire, 1992). This may result in higher strength for a seated paraplegic compared to a seated able-bodied population. However, in absolute terms, the strength of seated paraplegics is currently unknown and hence cannot be compared objectively with a seated able-bodied population. Furthermore, Calmels et al. (1992) studied only dynamic strength in cases similar to wheeling. If the paraplegic population has greater strength, this population is even better suited to tasks requiring strength exertions, and should have precedence over the able-bodied population for such tasks. This would allow standards for strength to be set higher than the 5th percentile of the general able-bodied population. Additionally, this knowledge of greater strength would provide more options for designers of workstations. However, in the extreme reach, there is a reversal of the trend, that is, paraplegics are likely to be less strong in pull and push strengths than the able-bodied seated individuals. This is because, whereas paraplegics have stronger arms, they have poor posture in the extreme reach positions, this instability limiting strength as suggested by Duval-Beaupère and Robain (1991). Thus, strength profiles of paraplegics should be studied in their reach envelopes.

Paraplegics have paralyzed lower limbs but an overall retention of at least 60% of able-bodied motor power (Buchanan & Nawoczenski, 1987). Using a manual wheelchair for propulsion increases upper-body muscle training among paraplegics. Muscle training can increase strength up to 50% (Sale & Norman, 1982). Paraplegia is also associated with an upward shift in body centre of gravity (Duval-Beaupère & Robain, 1991), which could reduce strength in less stable postures. Paraplegics

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should be studied specifically as they tend to be young adults, are relatively easily incorporated into a workplace, and number over 200,000 in the United States (Buchanan & Nawoczenski, 1987). Unfortunately, as strength studies regularly require participants to have no history of back injury, paraplegics have been systematically excluded from research studies. Consequently there is a need to study the strength profiles of male and female paraplegics in their reach envelopes for the optimum design of workstations.

The past research has demonstrated objectively that the worker physiological cost was least when the task was performed within the normal reach envelope (Sengupta, 1995). The worker physiological cost during task performance increased significantly with the increase in reach envelope from normal to maximum and from maximum to extreme (Sengupta, 1995). However, when force or strength is included in performing a task, normal reach envelope may not be the optimum location for the task performance. An able-bodied operator is able to exert more force in the maximum or extreme workspace reach envelope (Wang, 1994). However, for a wheelchair mobile individual, the strength capabilities in the maximum and extreme workspace reach envelopes may not be the same as able bodied persons due to posture or stability constraints. In a real life work situation, operators are required to perform tasks in the normal, maximum and extreme reach envelopes. For optimum workstation design, it is necessary to determine the location(s) within the various reach envelopes, where the operator can exert greatest force. Conversely, it is also important to determine the location(s) within the reach envelope, where the operator is able to produce least amount of force or strength due to body or other constraints.

The main objective of this investigation was to determine the three dimensional isometric strength profile of paraplegic individuals of working age to assist in workstation design optimization. Specifically, the study measured how anthropometric workspace reach distances, horizontal, and vertical angles, and gender affect maximum voluntary isometric pull and push strengths among paraplegics.

2. METHOD

A detailed discussion of participant characteristics and measurement methods are found in Black (1994). The method used in this study is presented briefly in terms of the participant and wheelchair characteristics, strength measurement system, experimental procedure, data collection, and data analysis.

2.1. Participants and Wheelchairs

The participants studied consisted of 8 men and 8 women who were paraplegics of working age. All were residents of Nova Scotia (Canada), and used a manual wheelchair for mobility. A questionnaire documented personal and wheelchair characteristics (Table 1). The body mass among those tested differed more than the wheelchair mass. The level of spinal lesion among participants varied between L1 to T4, with two cases of spina bifida (Table 2). The participants used their right hand for strength generation. All participants were volunteers, but were reimbursed for their time at $10 (Canadian) per hour.

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TABLE 1. Characteristics of Participants and Wheelchairs

Variable	Men		Women	
	M	*SD*	*M*	*SD*
Age (years)	37.4	7.9	35.0	11.6
Years since injury	14.4	8.2	15.9	12.7
Body mass (kg)	74.4	13.9	69.8	14.7
Wheelchair mass (kg)	16.5	2.5	20.0	5.4
Right-left rear wheel distance (mm)	583	62	533	58
Front-back rear wheel distance (mm)	494	48	507	52

TABLE 2. Nature of Spinal Cord Injury Among Participants

Injury Type	Men	Women	Total
T4	1	—	1
T7	1	—	1
T8	1	1	2
T9	1	—	1
T10	1	—	1
T11	2	1	3
T12	1	2	3
L1	—	2	2
SB	—	2	2

Notes. T—thoracic region of spine, L—lumbar region of spine, SB—spina bifida.

2.2. Strength Measurement System

Each measurement session was conducted using a specially designed computerized data collection system and apparatus (Figure 1). The details of the isometric measuring system are described elsewhere (Black, 1994) with only the essentials of the system relevant to the present research highlighted here. The apparatus was specially designed to record isometric strength and stability data at adjustable angles and distances.

The participants used their own wheelchair, which was secured from rolling on a special rotatable platform. The platform was positioned to align the participants' active shoulder with the force measurement system. Force

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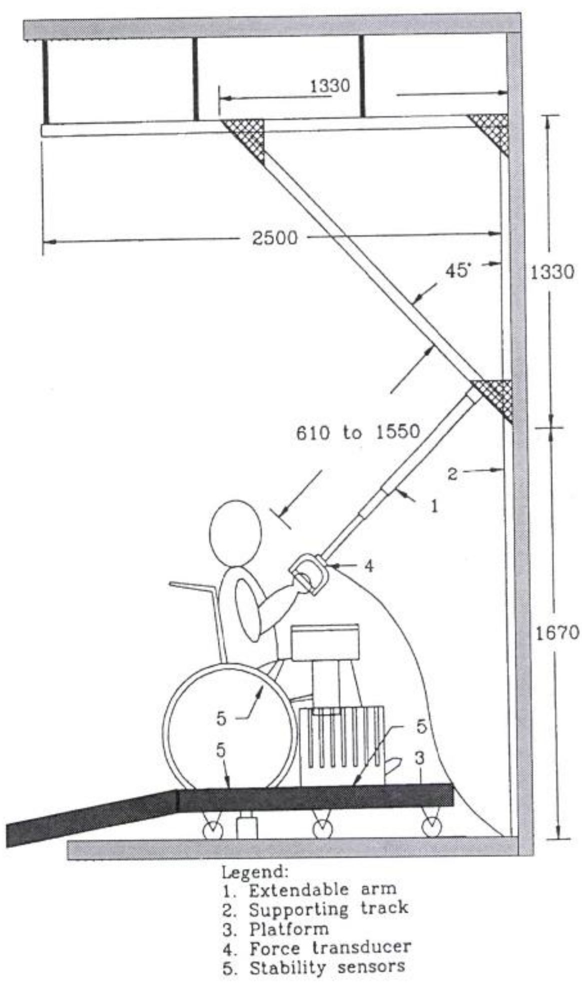

Figure 1. Computerized isometric strength measurement system for paraplegics. All dimensions in mm.

was measured using an MLP200 (Durham Instruments, Canada) force sensor transducer, which was mounted between a handle and an extendible locking metal arm. The 2.5 cm diameter handle allowed a comfortable cylinder grip. The extendible metal arm was mounted on a channel secured to the wall and ceiling to allow height variations while remaining stable throughout all exertion conditions. A locking gear at the interface of the channel and the extendible arm allowed angular changes of the arm. Thus, the force recording system was positioned for each test, locating the handle relative to the participant's arms at each reach. This ensured exertions along the hand-forearm axis for normal reach and hand-arm axis for maximum and extreme reaches.

Wheelchair and body stability were monitored using sensors that were connected through an auditory alarm to the computer. Instability was recorded when either a wheel of the chair broke contact with the floor, or when the participant's buttocks separated from the chair cushion. All measurement sessions were conducted in the Nova Scotia Rehabilitation Centre, Halifax, NS, Canada.

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2.3. Experimental Procedure

Each measurement session consisted of (a) measuring individual anthropometric and wheelchair characteristics, and (b) recording radial maximal isometric strength exertions of the right arm and hand for 5-s periods. All participants were told to pull (or push) as hard as they could without jerking. Pull and push exertions alternated at each test location, although the ordering of these locations was randomized between participants. A minimum of a 1-min rest period separated each exertion to ensure muscular fatigue recovery. Each test series for a participant lasted approximately 3 hrs. To control for stability, participants were not permitted to lean or grab onto any fixed object (including any portion of the wheelchair) during exertions. Otherwise they were free to assume the posture they felt was most effective for force generation. This was necessary for normal variations in posture, which allowed each participant to exert maximum force or strength.

2.4. Data Collection

Radial pull and push isometric exertions were measured for each of 32 locations defined by reach level (normal, maximum, and extreme), vertical

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angle (ϕ) relative to the elbow (normal reach) or shoulder (maximum and extreme reaches), and horizontal angle (θ) relative to the right shoulder in slump posture. The slump posture is defined for the purpose of this research as approximately 15° forward from the vertical relative to the seat reference point (SRP; Keyserling, 1986). Participants were instructed to maintain this relaxed slumped posture, and posture was visually monitored throughout the data collection. This allowed a relatively natural posture permitting realistic variations in posture anticipated in a work environment while imposing minimum controls for scientific validity. Notably, the use of the slump posture versus an upright posture is more critical when defining reach, and would only minimally affect strength production. Reach envelope (normal, maximum, and extreme), ϕ angle (–20, 0, 45, 90°), θ angle (0, 45, 90, 135°), direction of exertion (push and pull) and gender (male and female) were the independent variables, whereas recorded strength was the dependent variable. Notably, not all angles were tested at all reach levels due to the areas of reach accessible. Thus, in the normal reach envelope, only $\phi = 0$ and 45°, and $\theta = 45$, 90, and 135° were tested. Similarly, at maximum and extreme reach when $\phi = 90°$, only $\theta = 90°$ was tested. The measurement locations were defined along the outside limit of each individual's normal, maximum and extreme reaches.

Recorded ϕ angles ranged from work-surface height ($\phi = -20°$ in maximum and extreme reaches, or $\phi = 0°$ in normal reach) to 0, 45° (Figure 2),

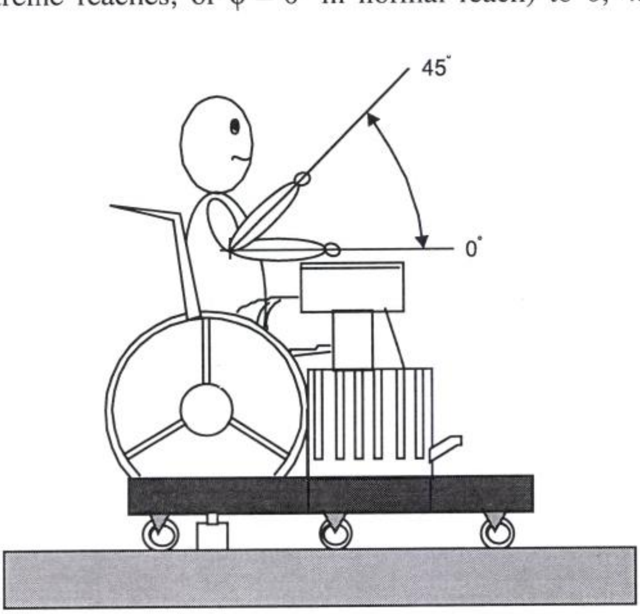

Figure 2. Location of vertical (ϕ) angles for the normal reach envelope. Strength measurements taken at 0 and 45°.

and the vertical 90° (for maximum and extreme reaches only; Figure 3). Radial θ angles were recorded from the frontal plane on the right hand side (θ = 0°) for maximum and extreme reaches only, to 45, 90, and 135° for all reach levels (Figure 4).

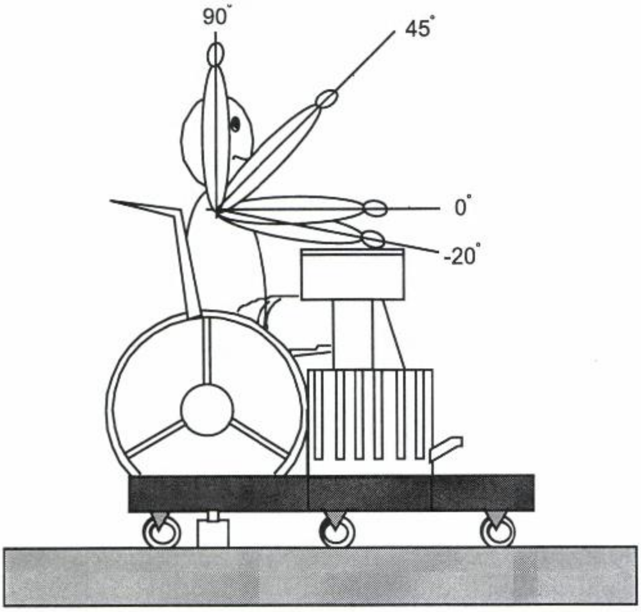

Figure 3. Location of vertical (φ) angles for the maximum and extreme reach envelopes. Measurements taken at −20, 0, 45, and 90°.

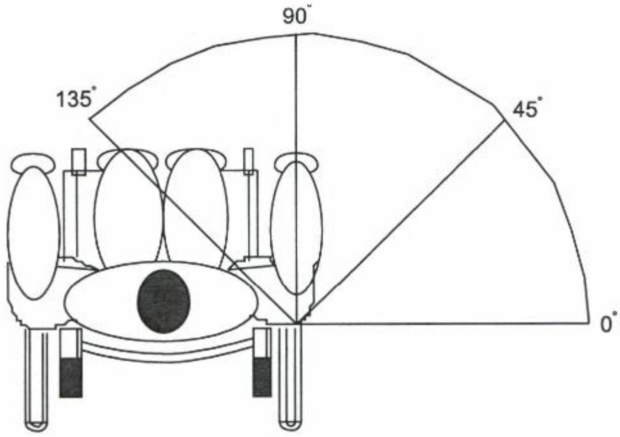

Figure 4. Location of horizontal (θ) angles for all reach levels. Strength measurements taken at 0, 45, 90, and 135°.

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2.5. Data Analysis

Raw strength data were collected by a force transducer defined in section 2.2 and transferred via a low pass filter to a 386 SX personal computer for recording and subsequent analysis. Strength and stability sensors were sampled at 10 hertz throughout the 5-s exertion. Immediately following each exertion, data were displayed graphically on the computer screen to visually verify that the participant had attained maximum strength (a plateau or repeated peak). Where necessary, the trial was repeated. Following the completion of a measurement series, maximum values for each condition were calculated. Average strength values were not used for analysis due to large variations associated with wheelchair or body instability.

3. RESULTS

A review of the data revealed that overall women exerted 73% the force of men. Different variations in strength occurred depending on each of the independent variables: direction, reach, and vertical and horizontal angles. Thus, results are presented by combinations of independent variables, beginning with separate discussion of male pull and push strengths, and female pull and push strengths, and comparisons of each.

3.1. Male Pull Strength

Table 3 shows the pull strength measurements of male participants by location. The maximum overall pull strength was 473 newtons (N) exerted in the extreme reach at the overhead position where the vertical angle, $\phi = 90^\circ$ and the horizontal angle, $\theta = 90^\circ$. The minimum overall strength was 158 N occurring in the maximum reach, where $\phi = 0^\circ$ and $\theta = 135^\circ$. Strengths at maximum and normal reaches increased with increasing ϕ angle, but were least where $\theta = 135^\circ$. Maximum strength in the normal reach was 239 N at $\phi = 45^\circ$ and $\theta = 90^\circ$ and the corresponding value in the maximum reach was 426 N at $\phi = 90^\circ$ and $\theta = 90^\circ$.

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TABLE 3. Pull Strength (N) of Males

		Normal Reach		Maximum Reach		Extreme Reach	
ϕ	θ	*M*	*SD*	*M*	*SD*	*M*	*SD*
– 20°	0°	—	—	203	56	196	42
– 20°	45°	—	—	195	60	181	61
– 20°	90°	—	—	211	76	182	58
– 20°	135°	—	—	192	50	163	57
0°	0°	—	—	208	49	208	45
0°	45°	214	45	205	52	194	45
0°	90°	218	61	215	56	221	55
0°	135°	207	45	158	40	180	30
45°	0°	—	—	274	62	263	59
45°	45°	229	59	250	67	250	69
45°	90°	239	72	271	76	282	66
45°	135°	234	53	240	53	237	62
90°	90°	—	—	426	101	473	115

Notes. Overall male pull strength = 232 N, ϕ—vertical angle, θ—horizontal angle.

3.2. Male Push Strength

Men's push strengths by location are shown in Table 4. Table 4 reveals that men's push strengths were generally weaker in the extreme reach than in

TABLE 4. Push Strength (N) of Males

		Normal Reach		Maximum Reach		Extreme Reach	
ϕ	θ	*M*	*SD*	*M*	*SD*	*M*	*SD*
– 20°	0°	—	—	194	63	199	58
– 20°	45°	—	—	220	44	203	36
– 20°	90°	—	—	181	60	156	44
– 20°	135°	—	—	152	43	131	29
0°	0°	—	—	212	72	227	80
0°	45°	224	57	216	71	231	41
0°	90°	162	56	189	46	170	43
0°	135°	156	40	131	47	145	42
45°	0°	—	—	184	88	101	32
45°	45°	217	53	235	92	154	59
45°	90°	223	66	233	72	172	76
45°	135°	205	56	188	45	184	93
90°	90°	—	—	192	101	125	84

Notes. Overall male push strength = 185 N, ϕ—vertical angle, θ—horizontal angle.

normal or maximum reach and did not increase significantly with ϕ angle. The maximum overall exerted strength was 235 N in maximum reach at $\phi = 45^\circ$ and $\theta = 45^\circ$. The minimum exerted strength was 101 N in the extreme reach at $\phi = 45^\circ$ and $\theta = 0^\circ$. The maximum strengths in the normal and extreme reaches were 224 and 231 N, respectively, both at $\phi = 0^\circ$ and $\theta = 45^\circ$.

3.2.1. Male pull versus push strength

The average male pull strength (232 N) was 25% greater than the push strength on the average (Tables 3 and 4). Spatial tendencies were different for push and pull exertions. Pull strength was less changed by increasing reach envelope than by vertical and horizontal angles. On the other hand, push strength decreased from normal and maximum to extreme reach, and was less affected by vertical angle. Indeed, recorded push exertions were greatest and least at the same vertical angle ($\phi = 45^\circ$), at different reaches and horizontal angles (maximum, $\theta = 45^\circ$ and extreme $\theta = 0^\circ$). When comparing strength in normal and maximum reaches, both pull and push strengths were similar, exertions at normal reach and $\phi = 45^\circ$ being weaker than at maximum reach. At $\phi = 0^\circ$, no consistent tendency between normal and maximum reaches existed.

3.3. Female Pull Strength

Table 5 presents the pull strength measurements of females by location. Women's pull strength was greatest at 318 N in the extreme reach at $\phi = 90^\circ$ and $\theta = 90^\circ$ (Table 5). The minimum pull strength was 131 N exerted in the extreme reach at $\phi = 0^\circ$ and $\theta = 135^\circ$. The maximum pull strength in the normal and maximum reaches were 193 N at $\phi = 45^\circ$ and $\theta = 45^\circ$, and 284 N at $\phi = 90^\circ$ and $\theta = 90^\circ$, respectively. Pull strengths in normal reach varied less than either maximum or extreme reach, but were on the average inferior.

3.3.1. Male versus female pull strength

The female's pull strength was overall 77% of the male push strength (Tables 3 and 5). The overall maximum values occurred at identical locations (extreme reach, $\phi = 90^\circ$ and $\theta = 90^\circ$) for both genders. The minimum

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TABLE 5. Pull Strength (N) of Females

		Normal Reach		Maximum Reach		Extreme Reach	
ϕ	θ	*M*	*SD*	*M*	*SD*	*M*	*SD*
– 20°	0°	—	—	155	46	151	45
– 20°	45°	—	—	139	36	142	36
– 20°	90°	—	—	139	39	152	28
– 20°	135°	—	—	138	35	144	45
0°	0°	—	—	156	37	149	40
0°	45°	158	46	151	29	142	30
0°	90°	149	47	145	33	150	34
0°	135°	151	55	132	35	131	34
45°	0°	—	—	241	59	236	71
45°	45°	193	70	214	40	228	60
45°	90°	186	60	214	51	225	50
45°	135°	172	52	202	49	205	40
90°	90°	—	—	284	49	318	50

Notes. Overall female pull strength = 178 N, ϕ—vertical angle, θ—horizontal angle.

values occurred for both males, and females at $\phi = 0°$ and $\theta = 135°$ but in the maximum reach level for males, whereas in the extreme reach for females. The difference between the maximum and extreme reach values at this angle for females was negligible (1 N).

3.4. Female Push Strength

Females push strengths by location are shown in Table 6. Table 6 shows the female push strength was greatest at 172 N in the maximum reach at $\phi = 45°$ and $\theta = 0°$. The minimum force exerted was 84 N occurring in extreme reach at $\phi = -20°$ and $\theta = 135°$. The maximum push strengths in the normal reach was 145 N at $\phi = 0°$ and $\theta = 90°$. The corresponding value in the extreme reach was 144 N at $\phi = 45°$ and $\theta = 135°$.

3.4.1. Female pull versus push strength

The pull strength among females was 41% greater than push strength on the average (Tables 5 and 6). As with males, the females strength increased

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TABLE 6. Push Strength (N) of Females

		Normal Reach		Maximum Reach		Extreme Reach	
ϕ	θ	*M*	*SD*	*M*	*SD*	*M*	*SD*
– 20°	0°	—	—	145	57	142	68
– 20°	45°	—	—	109	27	135	56
– 20°	90°	—	—	112	22	106	27
– 20°	135°	—	—	92	39	84	39
0°	0°	—	—	147	65	127	57
0°	45°	138	29	136	41	122	36
0°	90°	145	55	140	51	104	36
0°	135°	101	22	110	39	104	43
45°	0°	—	—	172	58	118	27
45°	45°	137	52	158	49	127	57
45°	90°	136	57	146	49	124	38
45°	135°	124	58	134	59	144	61
90°	90°	—	—	122	56	101	38

Notes. Overall female push strength = 126 N, ϕ—vertical angle, θ—horizontal angle.

with vertical ϕ angle when pulling, but not when pushing. Pull strength between different reach envelopes did not differ substantially at like angles, whereas push strength decreased in extreme reach, particularly at vertical angles at or above the horizontal. In these positions there was less support from the wheelchair for a push exertion.

3.4.2. Male versus female push strength

On the average, women pushed 68% the force of men (Tables 4 and 6). The locations of maximum push strength were similar between male and female data, differing only by the degree of horizontal asymmetry. Women were strongest pushing in the frontal plane ($\theta = 0^{o}$), whereas men were stronger 45° toward the front. This may be due to decreased stability associated with narrower chairs used by women than men (on the average 50 mm narrower, Table 1). The minimum push exerted did not occur at the same vertical or horizontal angle for males and females. Males were weakest (101 N) at $\phi = 45^{o}$ and $\theta = 0^{o}$ and the females were weakest (84 N) below the horizontal at $\phi = -20^{o}$ and $\theta = 135^{o}$. In each case minimum strength occurred at the extreme reach.

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4. DISCUSSION

The implications of the research results involving paraplegics are discussed in the context of able-bodied population and workstation design. Further in the text, the strength of paraplegic adults is compared with able-bodied (seated) population. Subsequently, workstation design implications will be discussed based on the comparative analysis.

The variation on gender was less marked among the paraplegic population than a similar able-bodied seated population (Wang, 1994). Overall comparison revealed that women strength is 72.9% that of men for paraplegics, whereas the relative strength drops to nearly 50% for able-bodied individuals according to Wang (1994), a figure which reflects the expectations of upper-body strength comparisons by Sale and Norman (1982). Thus, the necessary adaptations of strength requirements for a paraplegic population may be less that those required for able-bodied workers.

Comparison of push to pull strength throughout the workspaces as defined here, found push was on average 75.8% of the value recorded for pull for the paraplegic population. Whereas this follows the general trend of the literature (Davis & Stubbs, 1977; Grandjean, 1982; Kumar, Phan, Perry, & Garand, 1991), the similar study conducted by Wang (1994) found the average difference to be 70%. Thus, there is slightly less variation on strength exertion among paraplegics than their able-bodied counterparts. Still, the variations were statistically significant for both populations.

The push and pull exertions across the body ($\theta = 135°$) are significantly reduced relative to angles on the same side as the active arm for both paraplegic and able-bodied populations (Black, 1994; Wang, 1994). Thus, generally tasks requiring push or pull strength should be located on the same side as the active arm. Similar work by Davis and Stubbs (1977) did not consider angles beyond $\phi = 90°$.

For both populations vertical and horizontal angles played significant roles in determining strength potential. For both populations, the greatest pulls occurred in front of the active arm ($\theta = 90°$), although paraplegics exerted significantly greater push at angles less that 90°, whereas able-bodied individuals showed no significant variations in push on horizontal angle.

Maximum strength locations did change from the able-bodied to paraplegic populations. Whereas pull strength was consistently superior in the overhead aligned position ($\phi = 90°$), push strength was greater for paraplegics at $\phi = 45°$ rather than $\phi = 90°$ as for able-bodied persons. This is likely due to the lesser trunk flexibility among paraplegics, and the inability to use the

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lower limbs to assist in creating a vertical push. Still, it is notable that both populations had consistently greater strength at heights above the shoulder, indicating the increased difficulty in pushing and pulling at levels with greater body torsion.

The role of reach on strength was significantly different when comparing the paraplegic to an able-bodied population. Whereas for paraplegics there was no significant variation with increasing distance from the body when pulling, a similar able-bodied seated population showed a highly significant increase from normal values to extreme values (Wang, 1994). The more limited body stability of paraplegics in positions further from the body may act to negate the increase recorded among able-bodied persons. Furthermore increasing reach resulted in significant decreases in push strength between maximum and extreme reach envelopes, whereas no significant variations were recorded for able-bodied persons (Wang, 1994).

Based on this comparative analysis, recommendations can be made for workstation design optimization especially for the paraplegics populations. The workstation design ought to be based according to the gender(s) of those to be using the design. Whereas paraplegic women showed less reduction in strength than able-bodied women compared to similar men, there was nonetheless a significant reduction in their maximum push and pull capabilities. Generally, the spatial strength distribution did not vary significantly between men and women, so only the absolute strength requirements need be altered according to gender. Wherever possible, use of pull should be favored over push, as the absolute strength values are consistently greater when pulling for both populations.

In designing work or task situations, preference should be given for tasks placed on the same side as the active limb where strength is required. Pulling tasks should be placed in front of the active shoulder where possible, but pushing tasks are better placed slightly more to the side of the active arm so as to account for the greater strength of paraplegics at $\phi = 45^\circ$ for men or 0° for women among this population. As there is no significant variation in push strength with horizontal angle among able-bodied individuals, such changes will be positive to the working population overall.

Where greatest strength is required for a very short duration, tasks may be best placed above shoulder level. Pull strength was consistently greatest directly above the active shoulder compared with lower angles. Push was less affected by vertical height among the paraplegic population, whereas it remained very significant for the able-bodied population tested (significantly greater at $\phi = 90^\circ$). Paraplegic women's push was significantly superior at

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$\phi = 45°$, although significantly weaker in the vertical ($\phi = 90°$). It should be noted that, whereas these heights are recorded as having the greatest maximal strengths for test conditions without fatigue, fatigue is greater when working above shoulder height. As a result, for more general tasks and limited fatigue it may be best to locate tasks below shoulder height despite the maxima recorded here.

Tasks requiring high push or pull strengths are best placed in either the maximum or normal reach envelope volumes. Increasing reach envelope plays a limiting role when pushing beyond the maximum reach for paraplegics. Whereas able-bodied persons similarly tested did not show such a reduction, and indeed showed a significant increase when pulling, it would be better to design work environments to be confined to the maximum reach envelope to ensure maximal work capacity for the entire population. Notably this recommendation is consistent with the principles of motion economy, and postures limiting biomechanical stresses in the trunk.

It should be noted that only Black and Wang have studied strength using the same workspace envelope framework. As a result, the data of Wang (1994) has been used repeatedly as a comparative database to that of Black (1994). Even between these two studies some significant variations in methodology prevent direct comparison of absolute strength values at this time.

5. CONCLUSIONS

In summary, the following conclusions can be drawn:

1. Men's maximum isometric radial pull strength was 473 N, which occurred in the extreme reach in the vertical overhead position.
2. Men's maximum isometric radial push strength was 235 N, occurring in the maximum reach at $\phi = 45°$ and $\theta = 45°$.
3. Women's maximum isometric radial pull strength was at 318 N in the same overhead extreme reach position as men. On the average women's pull was 77% the value of men's.
4. Women's maximum exerted push strength was 172 N occurring in maximum reach at $\phi = 45°$ and $\theta = 45°$.
5. Overall, the forces exerted in the reach envelope by the females were 152 N or 73% those of the males. The pull strength was less affected by gender than push strength; women exerted 77 and 68% the strength of men, respectively.

6. The average pull strength was 25% greater than the push strength for men and the corresponding value was 41% greater than push for women.

6. CONCLUDING REMARKS

This study of isometric strength of paraplegics in the workspace has revealed differences from the able-bodied seated population. Consequently, for optimum design of workstation for paraplegics, it is necessary to determine the location(s) within the various reach envelopes, where such operators can exert greatest as well as least force or strength for task performance.

This investigation has provided isometric strength data to facilitate workstation design for paraplegics. However, it should be recognized that the data were obtained from limited sample size and different levels of spinal cord injury were used as participants for this investigation.

The three-dimensional strength profiles for male and female paraplegics during radial push and pull exertions show significant differences in absolute value as well as spatial locations. Whereas men were stronger than women, and pull strength stronger than push strength, each of these groups showed different spatial strength distributions. On the average, pull strength in the normal reach was less than in the maximum or extreme reach for both genders, but the push strength was similar in normal and maximum reaches and less in the extreme reach. Pull strength was greatest at the angles closest to the vertical, no matter the horizontal angle. Both push and pull strengths tended to be minimum at $\theta = 135°$, the position which required most twisting of the torso. These results clearly show the importance of strength capabilities in the design and placement of controls in the work area.

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