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Isometric Pull and Push Strengths of Paraplegics in the Workspace: 2. Statistical Analysis of Spatial Factors

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The effect of reach levels, horizontal angles, and vertical angles on isometric pull and push strengths of male and female was determined. Highly significant increases in men's push strength were found between extreme to maximum reaches, and from extreme to normal reaches. However, for women's push strength, a significant increase was found only between extreme to maximum reach. Significant or highly significant increases were found in men's and women's pull strength between the horizontal angle (θ) sagittal through the active shoulder (90°) and other angles (0, 45, and 135°). However, for men's push strength, highly significant increases were found between the horizontal angle 45° from the frontal plane, and other angles. For women's push strength, significant or highly significant increases were found between the horizontal angles 0° and angles of 90 and 135°. For men's and women's pull strength, significant or highly significant increases were found between the vertical angle (ϕ), 90°, and other angles (–20, 0, and 45°). Similar increases were found for women's push strength between the 45° angle and other angles. In the design of a workstation for paraplegics that requires pull and push forces, consideration must be given to the spatial factors.

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isometric strength   pull and push strengths   workspace reach levels
horizontal and vertical angles   paraplegics

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1. INTRODUCTION

Measuring maximum voluntary isometric strength can help to determine potential strain to a worker in a given workplace situation (Chaffin, Herrin, & Keyserling, 1978). A profile mapping maximum strength values to an individual's workspace can help to plan task layout to avoid overexertion (Hunsicker, 1955). Where such a profile is defined under controlled conditions, the roles of factors that may affect strength can be studied. Factors affecting strength include location and direction of the exertion relative to the person (Hunsicker, 1955). Exertion locations may be characterized relative to a person's anthropometry using reach, and horizontal and vertical angles to completely define measurement locations. Direction can be similarly defined relative to individual anthropometry using radial push and pull exertions centred on body joint locations (Evans, 1990). Testing the statistical significance of each of these factors will help define key variables for workstation layout optimization for both comfort and productivity.

As posture and anthropometry affect potential strength, like postures they should be compared (Evans, 1990). The strength measurement would be affected by arm reach and trunk extension. Consequently, arm reach and posture should be defined precisely for strength measurement. Thus, normal, maximum, and extreme functional reach envelopes provide a logical basis for strength measurement. Although motion economy principles (Niebel & Freivalds, 1999) favour use of the normal reach envelope (within reach of the lower arm alone) to that of the maximum envelope (at arm extension) or that of the extreme envelope (with trunk extension), the significance of this relationship is less clear for strength measurement. Notably push and pull strengths generally increase with separation from the body (Hunsicker, 1955) although these spatial variations have not been documented for statistical significance using anthropometric reach definitions. Furthermore, this relationship has not been studied beyond maximum reach conditions.

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Push and pull exertions are frequently used forces in a working day. Studies of able-bodied individuals have found significant variation in strength when vertical and horizontal angles vary (Davis & Stubbs, 1977; Hunsicker, 1955), although such tendencies are dependent on the direction of exertion relative to the body.

To date, most studies have concentrated on analysing able-bodied populations, ignoring any differences associated with physical disabilities. Whereas paraplegics account for 200,000 workers in the United States (Buchanan & Nawoczenski, 1987), no studies have developed a model representing the strength capacity of paraplegic individuals. Lacking such a model, paraplegics are often incorporated with few adaptations to standard workspace areas, suffering regular discomfort (Abdel-Moty & Khalil, 1989). Notably paraplegics are subject to additional factors affecting strength capacity, these relating to mobility (Floyd, Gutlmann, Wycliffe-Noble, Parkes, & Ward, 1966), spasticity, and sensation differences, in addition to basic location and exertion direction definitions. Given the intensive muscular training associated with both genders using manual wheelchairs, strength comparisons by gender may need to be revised prior to application to paraplegics. Furthermore, the stability constraints associated with lower limb paralysis, including wheelchair stability and vertical displacement of body centre of gravity would potentially have drastic effects on spatial strength tendencies relative to able-bodied populations (Duval-Beaupère & Robain, 1991).

The main objectives of this study were to

1. Analyse the significance of location factors (as combinations of reach, vertical ϕ angle, and horizontal θ arm angle) on radial push and pull strength among male and female paraplegics based on data collected under controlled conditions. This analysis would include other factors relating to individual anthropometrical variations as covariates.
2. Where such ANOVA tests revealed factor significance by gender and exertion direction, analyse the source of intra-factor variations.
3. Compare the significance of these factors for the paraplegic population studied with able-bodied design criteria to define ajustment needs for working areas used by paraplegics.

Based on previously recorded data for able-bodied adults, certain hypotheses were formulated. These included that

1. Pull strength will be significantly greater than push strength.
2. Men will be significantly stronger than women for all cases, whereas both groups will have similar strength profiles.

3. Variations in vertical and horizontal angles of exertion in all three reach envelopes (normal, maximum, and extreme) will be significant in determining push and pull strength values.
4. Strength in maximum reach locations will be significantly greater than the normal reach values in similar planes of exertion.

2. METHOD

In order to obtain data for this analysis, a series of isometric strength measurements were made. The experimental method in terms of the participant and wheelchair characteristics, strength measurement system, experimental procedure, data collection, and data analysis was described earlier (Das & Black, 2000). Consequently, it will not be repeated here.

3. RESULTS

3.1. Summary of Raw Results by Location

Earlier research results had shown that strength values clearly vary differently for push and pull directions (Das & Black, 2000). Indeed, analysis of variance (ANOVA) tests showed that strength was (highly) significantly ($p < .01$) affected by direction with push = 75% pull on average (155 and 205 N, respectively). Women's strength was significantly less than men's (on average women exerted 72.9% of men's force), although both follow similar trends in space. As neither exertion direction nor gender accounted for more than 13% of the total variation in data, further analyses for data divided by gender and exertion direction were made using ANOVA and Fisher's test tables on location factors.

3.2. Men's Pull Strength

The GLM (General Linear Model) three-factor model of men's pull strength was complemented with 7 covariate terms (body mass, role of spasticity, seated stature, handedness, presence or absence of regular exercise, and distances front-back and right-left between wheelchair tires), leaving only 17.5% unexplained variation (Table 1). Although reach was not a significant factor, both θ and ϕ were highly significant. Average strength at normal reach was only slightly less (224 N) than maximum and extreme reaches (234 and 233 N, respectively). The constancy of strength with increasing reach distance contrasts the results of pull strength tendencies for able-bodied male adults (Davis & Stubbs, 1977). This difference may be the result of increased instability in the extreme reach posture preventing an absolute increase in exerted pull values.

TABLE 1. Multifactor ANOVA of Men's Pull Strength with Covariates

Source	*df*	*MS*	*F*	*Pr* > *F*
Reach level	2	93	0.07	.94
θ	3	10,605	7.66	.01
ϕ	3	262,566	189.65	.01
Covariates	7	—	—	—
Error	240	1,031		
Total	255			

Notes. θ—horizontal angle, ϕ—vertical angle.

3.2.1. Horizontal angle significance on men's pull strength

Pair-wise analysis of differences showed strength at θ = 90° (273 N) to be (highly) significantly greater than at all other angles (Table 2). This may be partly due to the superior strength at the vertical ϕ = 90° test position, which was only tested at θ = 90° (449 N average), although Davis and Stubbs (1977) also found the sagittal position to be strongest among able-bodied males. Biomechanically, the sagittal plane in front of the active shoulder corresponds to the most natural muscular length for extensor and flexor muscles around the shoulder, and this could contribute to the superior strength at this location.

TABLE 2. Fisher's Test of Differences in Paired Means—Men's Pull on θ Angle

θ	Difference in Mean Strength (N)[b]↑			
	135°	45°	0°	90°
135°[a]	—	13.53	23.97	72.39**
45°		—	10.44	58.86**
0°			—	48.42**
90°				—

Notes. a—the minimum mean was 201.30 N at θ = 135°, b—differences in mean strength are presented in increasing order, **—highly significant ($p < .01$), θ—horizontal angle, ↑—increasing order.

3.2.2. *Vertical angle significance on men's pull strength*

Vertical angle showed at least significant differences between all pairs except the weakest ones: $\phi = -20$ and 0° (190 and 202 N, respectively; Table 3). These were the lowest angles tested, making them the angles introducing most body torque during exertions. Higher angles allow greater use of the body weight to augment arm strength without instability.

TABLE 3. Fisher's Test of Differences in Paired Means—Men's Pull Strength on ϕ Angle

ϕ	Difference in Mean Strength (N)↑			
	−20°	0°	45°	90°
−20°[a]	—	12.36	61.58**	259.09**
0°		—	49.22**	246.73**
45°			—	197.51**
90°				—

Notes. a—the minimum value was 190.19 N at $\phi = -20°$, **—highly significant ($p < .01$), ϕ—vertical angle, ↑—increasing order.

3.3. Men's Push Strength

The GLM three-factor model of men's push strength was complemented with 7 covariate terms (age, years since injury, body mass, level of injury, handedness, width of wheelchair, and spasticity) leaving less than 56% unexplained variation (Table 4). Thus, men's push strength showed more than 3 times the unexplained variation of pull exertions. Reach level and θ were both highly significant factors, although ϕ was not significant.

TABLE 4. Multifactor ANOVA of Men's Push Strength with Covariates

Private Source	*df*	*MS*	*F*	*Pr > F*
Reach level	2	20,205	7.43	.01
θ	3	28,355	10.42	.01
ϕ	3	3,072	1.13	.34
Covariates	7	—	—	—
Error	240	2,720		
Total	255			

Notes. θ—horizontal angle, ϕ—vertical angle.

3.3.1. Reach significance on men's push strength

Fisher's pairwise significance test on reach level showed extreme reach to be (highly) significantly inferior (169 N) to either normal or maximal reach (194 and 200 N, respectively; Table 5). The strength reduction at extreme reach corresponds to exertion locations, which are inherently less stable than locations within arm reach. In extending the trunk to access the extreme reach, the centre of body gravity is shifted forward of the wheelchair's centre of gravity, resulting in instability of the system even before attempting a push. At or within maximum reach stability is greater, allowing use of body mass to assist in the arm exertion.

TABLE 5. Fisher's Test of Differences in Paired Means—Men's Push Strength on Reach Level

Reach Level	Difference in Mean Strength (N)↑		
	Extreme	Maximum	Normal
Extreme[a]	—	25.40**	30.90**
Maximum		—	5.50
Normal			—

Notes. a—the minimum mean in the table was 168.97 N at extreme reach, **—highly significant ($p < .01$), ↑—increasing order.

3.3.2. Horizontal angle significance on men's push strength

Push at $\theta = 45°$ was (highly) significantly greater than at all other angles (Table 6). Push at $\theta = 0°$ was also (highly) significantly greater than 135° (161 and 186 N, respectively). At $\theta = 135°$, the adduction of the shoulder was the highest of the angles tested. This adduction prevents use of

TABLE 6. Fisher's Test of Differences in Paired Means—Men's Push Strength on θ Angle

θ	Difference in Mean Strength (N)↑			
	135°	90°	0°	45°
135°[a]	—	18.86	24.99**	51.99**
90°		—	6.13	33.13**
0°			—	27.00**
45°				—

Notes. a—the minimum strength value in table was 161.37 N at $\theta = 135°$, **—highly significant ($p < .01$), θ—horizontal angle, ↑—increasing order.

upper-body muscles for support of the push exertion. Furthermore, in normal reach, $\theta = 135^{\circ}$ sometimes induced wrist extension during exertion. Conversely, the moderately abducted position at $\theta = 45^{\circ}$ would permit leaning into the exertion adding body mass to the push effort.

3.4. Women's Pull Strength

The GLM three-factor model of women's pull strength was complemented with 7 covariate terms (age, body mass, handedness, seated height or chair mass or spasticity, chair length or injury level, chair width, and exercise) resulting in just 24.4% unexplained variation (Table 7). Thus, women's pull strength had more unexplained variability than men's pull. The increased error term may be related to the greater variability of anthropometric characteristics of the female participants studied. As with men's pull strength, reach level was not significant, but both ϕ and θ were highly significant. Like men, women's pull at normal reach was somewhat less than at maximum and extreme reach (168, 178, and 182 N, respectively).

TABLE 7. Multifactor ANOVA of Women's Pull Strength with Covariates

Source	*df*	*MS*	*F*	*Pr* > *F*
Reach level	2	2,590	2.51	.08
θ	3	4,155	4.03	.01
ϕ	3	152,974	148.34	.01
Covariates	7	—	—	—
Error	240	1,031		
Total	255			

Notes. θ—horizontal angle, ϕ—vertical angle.

3.4.1. Horizontal angle significance on women's pull strength

As with the men, $\theta = 90^{\circ}$ was the strongest horizontal angle (195 N), being (highly) significantly greater than 135° and significantly greater than 45° (Table 8). The weakest angle corresponds to 135°, following the pattern for the men's pull. The longer wheelchair and lesser degree of wheel camber among women tested may cause earlier instability than among men, resulting in reduced significance in angular variation on strength.

TABLE 8. Fisher's Test of Differences in Paired Means—Women's Pull Strength on θ Angle

θ	Difference in Mean Strength (N)↑			
	135°	45°	0°	90°
135°[a]	—	11.75	24.85*	35.38**
45°		—	13.10	23.63*
0°			—	10.53
90°				—

Notes. a—the minimum strength value in the table was 159.27 at $\theta = 135°$, **—highly significant ($p < .01$), *—significant ($p < .05$), θ—horizontal angle, ↑—increasing order.

3.4.2. Vertical angle significance on women's pull strength

Finally, as for men, vertical angle was highly significant between all pairs except $\phi = -20$ and 0° (145 and 147 N, respectively; Table 9). Again, these lowest vertical angles tested were also the weakest vertical angles. Again, body stability is the most important factor allowing for greater strength in postures with the least torsion.

TABLE 9. Fisher's Test of Differences in Paired Means—Women's Pull Strength on ϕ Angle

ϕ	Difference in Mean Strength (N)↑			
	−20°	0°	45°	90°
−20°[a]	—	1.68	65.51**	155.71**
0°		—	63.83**	154.03**
45°			—	90.20**
90°				—

Notes. a—the minimum strength value in the table was 145.01 at $\phi = -20°$, **—highly significant ($p < .01$), ϕ—vertical angle, ↑—increasing order.

3.5. Women's Push Strength

The GLM three-factor model for women's push strength was complemented with 7 covariate factors (years since injury, chair mass, injury level, handedness or chair length, spasticity, seated height, and age) giving an model accuracy of nearly 50% (Table 10). Women's push was thus somewhat better explained than men's push, whereas the remaining half as accurate as the women's pull model. This push strength model showed all of reach level, θ and ϕ to be highly significant.

TABLE 10. Multifactor ANOVA of Women's Push Strength with Covariates

Source	*df*	*MS*	*F*	*Pr* > *F*
Reach level	2	5,699	4.64	.01
θ	3	9,754	7.94	.01
ϕ	3	7,574	6.17	.01
Covariates	7	—	—	—
Error	240	1,229		
Total	255			

Notes. θ—horizontal angle, ϕ—vertical angle.

3.5.1. Reach significance on women's push strength

Extreme reach locations were significantly weaker (118 N) than maximum reach only (133 N, Table 11). The difference between normal and maximum reach, whereas not signficant, is reversed relative to the men's push data. The decrease noted in extreme reach follows the hypothesis of increased instability as it is described for men's push.

TABLE 11. Fisher's Test of Differences in Paired Means—Women's Push Strength on Reach Level

Reach Level	Difference in Mean Strength (N)↑		
	Extreme	Normal	Maximum
Extreme[a]	—	9.36	14.80*
Normal		—	5.44
Maximum			—

Notes. a—the minimum mean in the table was 118.02 N at extreme reach, *—significant ($p < .05$), ↑—increasing order.

3.5.2. Horizontal angle significance on women's push strength

Exertion in the frontal plane $\theta = 0°$ (142 N) was (highly) significantly greater than at $\theta = 135°$ and significantly greater than at 90° (Table 12). The only other significant difference was that of $\theta = 45°$ over 135°. Overall there was less significant distinction between strength at different horizontal angles than there was for men. This may be a result of the narrower and shorter wheelchairs used by women, limiting overall stability.

TABLE 12. Fisher's Test of Differences in Paired Means—Women's Push Strength on θ Angle

θ	Difference in Mean Strength (N)↑			
	135°	90°	45°	0°
135°[a]	—	10.36	21.14*	30.12**
90°		—	10.78	19.76*
45°			—	8.98*
0°				—

Notes. a—the minimum strength value in the table was 111.62 N at $\theta = 135°$, **—highly significant ($p < .01$), *—significant ($p < .05$), θ—horizontal angle, ↑—increasing order.

3.5.3. Vertical angle significance on women's push strength

Women had significantly greater strength at $\phi = 45°$ (137 N) than at all other angles (Table 13). Interestingly, due to the high variation in strengths recorded at $\phi = 90°$, despite the highest absolute difference recorded, the difference was not more than significant. As for pull exertions, the lower angles are associated with greater torsion, and thus introduction of instability into the system. At the vertical position, whereas without instability, the exertion is in the opposite direction to the body mass. At $\phi = 45°$, these two factors limiting strength are least.

TABLE 13. Fisher's Test of Differences in Paired Means—Women's Push Strength on ϕ Angle

ϕ	Difference in Mean Strength (N)↑			
	90°	−20°	0°	45°
90°[a]	—	3.97	11.84	26.52*
−20°		—	7.87	22.55**
0°			—	14.68*
45°				—

Notes. a—the minimum value in the table was 111.61 N at $\phi = 90°$, **—highly significant ($p < .01$), *—significant ($p < .05$), ϕ—vertical angle, ↑—increasing order.

4. DISCUSSION

All the hypotheses were confirmed excepting the expectation that maximum reach be consistently and significantly superior to strength in the normal reach. This was not the case for either pull or push exertions. Indeed, extreme reach was significantly less than strength at maximum and normal reaches when pushing.

Earlier the implications of the research results involving paraplegics were discussed in the context of able-bodied population and workstation design (Das & Black, 2000). The significance of spatial variations (e.g., the reduced difference according to gender among the paraplegic population) confirms the need for sensitivity to physical disabilities when designing the layout of tasks in a work area. Notably those persons tested showed a greater willingness to use their body mass to augment strength than able-bodied individuals. Nonetheless, body and wheelchair stability severely limited the strength at extreme reach locations and at low angles.

The results of this study underline the role of the wheelchair and muscular training in the force production of both male and female paraplegics. Whereas strength may be increased relative to an able-bodied population due to the upper body training associated with manual wheelchair population, the area of increase is constrained by the stability of the wheelchair, and the individual.

5. CONCLUSIONS

From these data, the following conclusions can be drawn:

1. Whereas the strengths recorded for men and women were not identically distributed, their similarities are very strong, allowing for common design criteria for paraplegics generally.
2. The significance of gender was less among the paraplegic population (73%) than among an able-bodied population (50% for upper body exertions; Sale & Norman, 1982). The muscular training associated with using a manual wheelchair for mobility likely reduces gender-based strength differentiation.
3. When pulling, there was no significant increase in strength with increasing reach level for either men or women. Increases would be expected under similar conditions among able-bodied individuals, however, among paraplegics strength is limited by increased body and chair instability associated with the lengthened moment arm between exertion location and the body's centre of gravity. This instability results in the decrease in push strength (or lack of increase for pull exertions) in the extreme reach envelope.

4. When pushing, there was a significant decrease in strength in the extreme reach envelope. The shift of the body's centre of gravity without a counter-acting force of the lower body to stabilize is likely the cause of this decrease.
5. Horizontal θ angle (angle of asymmetry with respect to the active shoulder) was highly significant for both push and pull, but in different manners. Pull strength was significantly greater directly in front of the shoulder ($\theta = 90^\circ$), whereas push was significantly greater to the side at 45° for men or 0° for women. These differences are likely related to stability limitations of the wheelchair, which are not the same when pushing (using the backrest of the chair for support), and pulling (pressing forward onto the seat cushion). As the back rest will only support exertions perpendicular to it, exertions at other angles are less able to profit from this added support.
6. The significance of vertical angle depended on direction of exertion. When pulling, strength was significantly greater in the vertical (449 N for men and 301 N for women) than other angles. This was likely because participants did not hesitate to use their full body weight to augment their arm strength. However, when pushing such support was not possible and accordingly, push strength was not significantly affected by ϕ for men, and was only significant due to $\phi = 45^\circ$ for women. Both push and pull were weakest at the lowest angles tested ($\phi = 0$ and -20°) although the significance of this weakness was less when pushing. As these angles are closest to the floor, they are least stable for the wheelchair. Higher angles of $\phi = 45^\circ$ or $\theta = 90^\circ$ allow greater use of the chair for support with less torsion.

6. CONCLUDING REMARKS

For locating controls and handles in a workstation design for male and female paraplegics, where pull and push forces are required, due consideration must be given to reach levels, and horizontal and vertical angles in the workspace. Thus, workstation layout optimization for both comfort and productivity can be achieved.

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