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Evaluation of Applied Forces and EMG of the Young, Aged & Stroke Population in a 3D Arm Workspace

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***Abstract*— The objectives of this study were to evaluate 11 muscle electromyograms (EMGs) while performing force application tasks in a 3D workspace, and to identify challenging regions within the workspace in which subjects had difficultly generating forces in desired directions. Each subject (4 young healthy adults, 4 older with stroke-induced disability, 4 age-matched older) applied forces (8 lbs desired) in 6 directions at 19 locations spatially distributed in the workspace. The normals could meet the force threshold levels except for the 2 female aged participants for the Right force direction. The stroke group had common difficult directions of Up and Right. The muscle activations were dependent upon the applied force direction, with Up force being associated with maximum EMGs. Maximum variation in the EMGs was in the right and far region for the young adults and in far and low region for the older adults. The stroke subjects' shoulder-arm EMGs showed less directional variability in the regions of workspace, and considerable compensatory trunk movement, unlike the normals.**

I. Introduction

The upper extremity (UE), including the shoulder complex, provides the ability to generate forces in multiple directions within the arm workspace. The inherent complexity and high functionality make the analysis of arm movements and tasks challenging. This takes on special significance when trying to understand how arm dysfunction relates to accessibility when performing manual operations within the local environment. It is known that arm strength and hand forces are influenced by the orientation of the arm in the workspace [1-3]. Dickerson et al. (2006) evaluated the shoulder loading during reach-push button task manipulations where normal subjects carry out 96 loaded reaches with 78 task conditions that involved push button tasks for near-far reach planes. This study had a large workspace covered; however, the exerted forces were limited only in one direction [1]. Danuta et al. (2005) measured the maximal forces in 24 upper limb postures for lift, push, grip, pronation and supination torques, and identified force directions to be associated with a given posture [3]. However, in daily life people work with the arm in several orientations and apply forces in several directions. Hence, the conclusions of the above studies cannot be generalized for daily life force application tasks in different directions, especially as related to accessibility within the workspace. To accomplish a movement/task, muscles are activated in several patterns depending upon the task, motion and position of the arm [4]. Also due to actuator redundancy of the neuromuscular system, i.e. more muscles than joints, multiple combinations of muscles can be used to generate the same force [5]. Hence, it also of interest to see the muscle activation patterns for different force direction as well as workspace regions.

Apart from the arm orientation and the direction of force application, the performance or the force exerting abilities (and causes of UE injuries) depend upon many factors, including the region and area of workspace, the types of operating controls, requirements of the controls and importantly the functional ability of the individual [4]. The aims of this study are: (1) to identify and compare the accessibility barriers of the able bodied population (young and aged) and neurologically impaired Stroke subjects while performing force application tasks (in six directions) in various regions of the arm workspace; (2) to analyze the activation patterns of 11 arm-torso muscles associated with the force application tasks using surface EMG (especially the hypothesis that EMGs will differ as per force directions); and (3) to analyze the influence of the positions/regions in the workspace on the arm-torso muscle activations (especially the hypothesis that EMGs for a given direction will be different in different regions of the workspace).

II. Methods

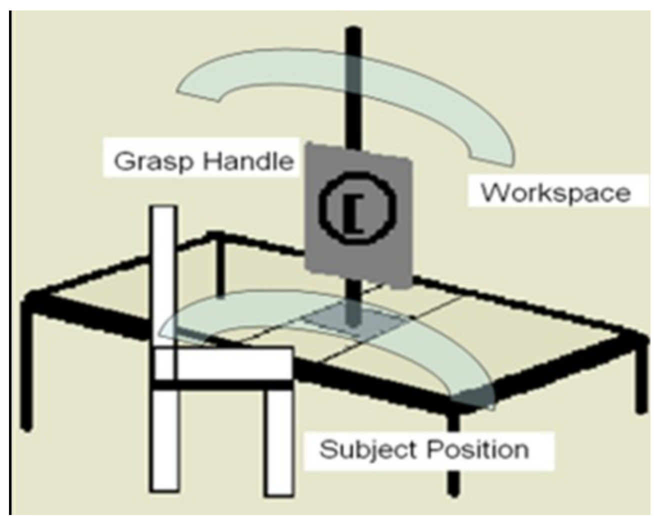

Fig 1 Experimental set-up showing the grasp handle and workspace area

The workspace model included a grid of 19 locations based on cylindrical arm curvature (See Fig1). The 3 horizontal planes in the volume were calculated on the basis of percentages of arm lengths; 95% (far), 75% (normal) & 55% (near) arm length. 3D contact forces were sensed by an ATI 6-axis load cell and collected at 100 samples/sec using a custom program written in LabView. EMG signals were collected using Delsys Preamplifier Surface EMG electrodes (gain 300) using Delsys Myomonitor III at 1000 samples/sec from anterior and posterior deltoid, bicep, lateral head of the triceps, wrist flexors, wrist extensors, clavicular head of the pectoralis, upper trapezius, latissimus dorsi and over the postural low back to represent the left and right Erector Spinae muscles (in the L3 region). Video data of the subjects during task were captured. The RMS filtered EMGs were normalized for each subtask by the maximum value of the EMG anywhere during the 19 location trials, and the forces were normalized for each subtask by the resultant force for that subtask. The tasks involved applying forces (8lbs desired, with a light indicator informing subjects when this threshold was met) in each of six directions (left-right, up-down, push-pull) using their dominant hand (and the paretic hand for stroke) at the randomly sequenced workspace locations. Four young healthy adults, 4 older adults with stroke-induced disability, and 4 older aged-matched adults; in each category there were 2 males and 2 females; were recruited for the study.

III. Results

Video Observation - Shoulder-Elbow-Hand Orientations: Based on visual inspection of videos from 3 directional perspectives, for the workspace region at the eye level height, the shoulder flexion typically ranged from approximately 30 (near plane) to 70 (far plane) degrees, and elbow extension from approximately 40 (near) to 90 (far) degrees. The arm orientation was roughly the same for the entire young and old normal population group at the time of grasp. While performing the subtasks, the 'Left-Right' direction force thresholds were obtained with some degree of shoulder internal-external rotation (assuming neutral as the arm stationary position while grasping the handle). Scapular elevation-depression was observed with the Up-Down force directions. Video analyses of stroke subjects indicated pronounced torso use, both to reach certain target locations and most especially to apply directional forces.

Force Data: The normal population achieved the 8lbs threshold for all the force directions without any level of difficulty in any region of the workspace. Two of the four aged participants (both females) could not achieve Right force directions at some locations (<5). All the four stroke subjects had difficulty in applying forces in the Up direction. The second most difficult direction was Right, where 2 of 4 could not reach the threshold levels anywhere in the 19 locations. The force analyses indicated the occurrence of undesired off axes forces amongst all the three groups (Table 1 and Fig 2).

	Sub1	Sub2	Sub3	Sub4	Young	Aged
Left	D, PL	U,D,PL	D, PL	D, PL	D, PL	D, PL
Right	D, PL	D, PL	D, PL,U	D, PL	P, U	D, P
Up	L, PL	R, P, PL	L, PL	L ,PL	L,P	P
Down	R, PL	R, PL	R, PL	PL	R ,PL	PL
Push	L, D	L, D	L, U,D	L, D	L, U	U
Pull	R, D	R, D	R, D	R, D	R, D	D

Table 1 Summary of the primary Off Axes Forces of the young and aged Normal populations and for each of the 4 stroke subjects for the 6 subtasks over the entire workspace. Left-L, Right-R, Up-U, Down-D, Push-P, Pull-PL

Muscle Activations as per Subtasks/Force Directions: Based on the median plot of the normalized EMGs of all (n=4) participants in each population group for different regions in the workspace, muscles with peak activity were identified as Prime Movers (Table 2 and Fig 3). Because of low EMG variation and coactivation, stroke subjects' EMGs were not classified into a prime movers.

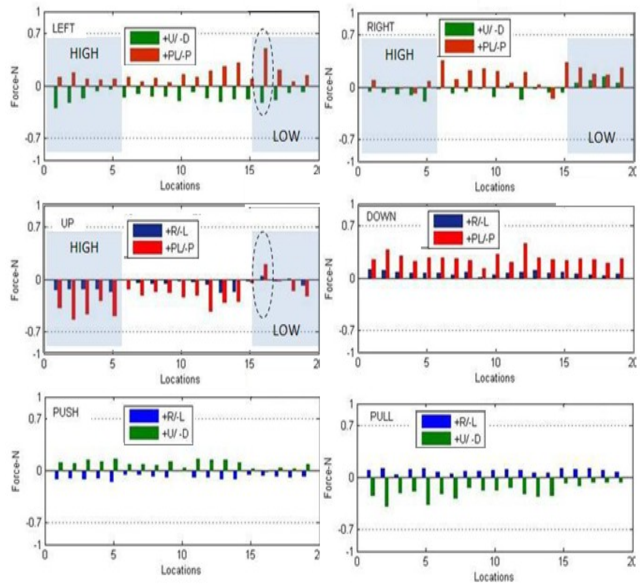

Fig 2. Off-Axes Forces for the Normal Population at 19 locations normalized to the peak force magnitude for each subtask. A value over 0.707 (given as dashed horizontal line) indicates that the subjects provided a higher force in a direction other than that desired. The first regions (as shaded) are all the High locations and the last 5 shaded regions are all the Low locations spread from 'Left to Right'. The circled locations show an inconsistent trend.

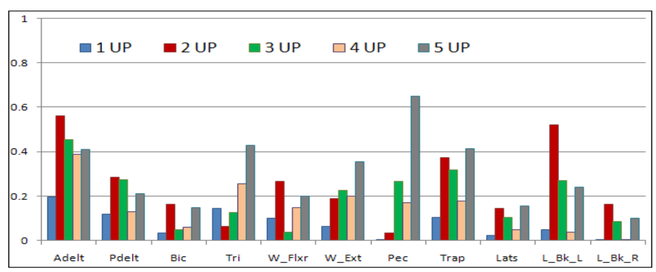

Fig 3. The median values of EMGs (normalized to 1) for High locations for the entire young normal population for forces applied in Up direction. The numbers represent location 1 to 5-eye level plane.

Subtask	Young Normal	Aged Normal
LEFT	W Exts, ADelt	W Flxrs, ADelt
RIGHT	PDelt	PDelt
UP	ADelt	ADelt, W Exts
DOWN	Lats	W Flxrs
PUSH	Tri	Tri, W Flxrs
PULL	Bic, W Ext	W Flxrs

Table 2 Primary Movers for the 6 subtasks generalized throughout the workspace for 'Young' normal and the Aged populations

Effect of force direction and workspace region associated with the EMGs: A paired two-tailed t-test was applied to assess the statistical difference in the muscle activation patterns in different regions of the workspace and the EMGs were compared for opposite force directions for all the locations in the workspace. The force direction effects are summarized in Table 3.

	YOUNG			**AGED**		
	L/*R*	**U**/*D*	**P**/*P*	**L**/*R*	**U**/*D*	**P**/*P*
Adelt	0.37	**0.00**	**0.00**	**0.00**	**0.00**	0.07
PDelt	*0.00*	0.08	0.00	*0.00*	**0.00**	0.67
Bic	**0.00**	**0.00**	*0.00*	**0.00**	**0.01**	0.29
Tri	0.29	0.49	**0.01**	0.13	**0.00**	**0.00**
W_Flxr	0.69	0.77	0.23	0.20	0.19	0.09
W_Ext	0.61	**0.00**	*0.00*	0.90	**0.00**	0.09
Pec	**0.01**	**0.00**	0.11	**0.00**	0.10	0.60
Trap	0.13	**0.00**	*0.00*	0.96	**0.00**	0.61
Lats	*0.00*	*0.00*	*0.00*	0.10	0.37	0.29
L_BkL	**0.00**	**0.00**	0.62	0.55	*0.01*	0.60
L_BkR	0.06	0.52	*0.01*	0.13	0.15	*0.01*

Table 3a. t-test p values of the EMGs of young and aged normal group for the opposite force directions (0.00 indicates p less than 0.001). Bold values- Left, Up & Push have a higher mean. Italic values- Right, Down & Pull have a higher mean

	Left/Right	**Up/Down**	**Push/Pull**
Adelt	0.03	0.00	0.06
Pdelt	0.08	0.08	0.81
Bic	0.30	0.01	0.00
Tri	0.01	0.11	0.40
W_Flxr	0.00	0.07	0.02
W_Ext	0.11	0.00	0.27
Pec	0.30	0.00	0.77
Trap	0.32	0.00	0.15
Lats	0.00	0.15	0.51
L_Bk_L	0.22	0.03	0.72
L_Bk_R	0.00	0.18	0.01

Table 3b. t-test p values of the EMGs of Stroke subjects for the opposite force directions (0.00 indicates p less than 0.001).

The older normals' averaged EMGs show similarities and some differences when compared with the young normals for their activations in different regions of the workspace. The ADelt(AD) and PDelt(PD) activity show similar trends with the young normals, i.e. the averaged activity is greater in the Far and Lower regions for AD and Far, Lower and Right-sided regions for PD. However, this difference is significant for only 1 subtask for AD and 2 subtasks for PD. The biceps for the older normals, like for the young normals, is more active in Lower and Far regions. The triceps for the older adults, like the young adults, showed no significance in any region of the workspace except, it that was high the Higher and Far regions (for PL). The pectoralis showed no trend for the young normals but did for the aged normals, as its activity was greater in Left and Far regions of the workspace (statistically significant for L). The wrist flexors and extensors show no significant change in any region. There were no conclusive results for the back postural muscles and latissimus activity for the aged, but in young they were more active in the far region. The trapezius, unlike for the young (Right-sided region predominant), shows no position effects except for the Up subtask in the High region. The EMGs of stroke subjects tend to have higher average values, and lower position and force direction dependencies.

IV. Discussion and Conclusions

A. Effect of workspace location and force direction on performance and accessibility

The subjects were instructed to apply forces in orthogonal directions, operating a grasp handle on the manipulandum that was oriented at self-selected angles. There was no feedback of force direction except for the light that went off when achieving the threshold in a direction, and thus application of forces only in the desired direction is not really practically possible, as confirmed by the sometimes-large off-axes forces that were listed in Table 1. There are multiple explanations. One could be perceptual psychophysics, at least for left-right and near-far, as the axis of eyes does differ from the axis of the glenohumeral joint. Another is that the complex upper extremity and shoulder girdle musculature would cause many other associated muscles to act in addition to the likely prime movers for the given task. The presence of a 'Down' off-force as a common trend in the stroke group could be a residual effect of spasticity and rigidity associated with stroke.

The finding that two female aged subjects could not achieve force thresholds in one direction suggests that gender and age influence performance (and thus access) for certain directions. These results are consistent with previous studies that indicate that age, gender, handedness, tool handle surface and intended use are some of the factors that influence grip force. It is also known that the maximum grip force depends upon the arm orientation and the workspace location [6]. The comparable directional forces similarly indicate the trends in the force producing capabilities that affect performance. For subjects with stroke-induced disability, it was clear that compensatory torso forces and movements were an integral part of the subjects' directional strategy.

B. Effect of force direction associated with the EMGs

The results clearly indicate that EMGs are specific to the direction of the applied force. The high variation in the Up-Down direction, with the maximum in the Up for both the groups, indicate that muscular demands for applying forces is higher for the Up force direction than Down direction. Applying an Up force requires work against gravity irrespective of the arm orientation. Hence, the muscular load and variation due to Up-Down is valid. It is also an indicator that applying forces in this direction will lead to muscle fatigue sooner for repetitive tasks. The wrist flexors do not show force direction dependency in both the groups. A possible explanation is that wrist flexors are essentially used to grasp in both the population groups. As reviewed by Barry et al. (2005), in older adults the force-producing capabilities and muscle coordination abilities reduce with increased complexity of the task [7]. These deficiencies can increase with number of used joints. Based on the lower variability in the shoulder muscle EMGs coupled with these observations from the previous literature, one hypothesis is that in the elderly, performance that involves execution and completion of force producing manipulation tasks, using an unconstrained arm, may be a function of wrist action. Alternatively, this low variability in the shoulder and elbow muscle activations can also attribute to the active use of torso rotation to complete the tasks, as indicated by inspection of videos for some of the subjects. The weakness and loss of strength associated with the aging could cause the use of a simpler system like torso flexion-extension (about the pelvis) to complete to generate the required force. This could also help explain, in part, the tendency toward downward force components. Thus, it is suggested that for a given subject, proximal and/or distal compensation is used as a compensatory strategy when the individual is unable to complete the tasks using conventional activation of shoulder and arm musculature.

C. Effect of workspace location (positional effects) on EMGs

The variation in the relative activations of the muscles was highest in the 'near-far' region for the young and aged normal populations. In the 'far' region where the arm elevation is increased (greater shoulder flexion), for a more proximal joint such as the glenohumeral, this may increase the demands on the muscle performance because to exert the forces in the required directions requires a larger joint moment and subsequently muscle force. In addition, there may be greater challenges to maintain the posture and arm elevation. These results indicate that the young normals had relative torso movement only in the far region, and/or required great stability for the shoulder region, such as maintenance of the scapular position. The aged group had torso movement either for stability or for task completion in both the regions.

A major contrast between the young and aged muscle activations in the different regions of the workspace and in opposite force directions (Table 3a) is that the aged subjects showed greater overall activity, and yet relatively less back muscles position effects for all the subtasks and fewer direction effects. This finding leads to the possibility that postural muscle recruitment in the elderly reflects a greater need to maintain their postural stability along with weaker musculature for arm elevation, hence the constant recruitment of the back muscles irrespective of the task or region in the workspace. It is known that with aging there is a decrease in the percentage of muscle fibers and consequent reduction in muscle strength [8], hence the greater muscle recruitment in the aged subjects.

For the stroke participants, reasons why the EMGs were less dependent upon the region of workspace include excessive muscle coactivation levels during most the subtasks (some involuntary), muscle weakness, and undesirable stroke related synergies patterns. . The force-direction relationships were very subject-specific. In addition, the video analysis reveals that stroke subjects made relatively high use of shoulder shrug (scapula thoracic elevation) and torso bending to complete many of the tasks. Thus in addition to less control as agonists and antagonists, such compensatory strategies also could possibly explain the lower variation in their EMGs.

The results supported the general hypothesis that muscle activations are dependent on force direction and hand position, and the differences in these parameters are affected by age and disability. The results show that the direction in which a certain force is applied influences the performance of the individuals. This inability to apply forces in the more 'difficult' Up and Right directions is prominent in the stroke population. The finding in all three groups that forces in undesired directions accompany the direction specific force application tasks, often with statistically significant trends, suggests that off-axes forces are often involuntary and normal. It is inferred that stroke limits the ability to vary the recruitment of key muscles for force application tasks, and thus the degree of access within the workspace, and that this is evidently compensated for in part by mechanisms like recruitment of additional degrees of freedom (i.e. trunk movement) and recruitment of additional muscles. These results can now be used to help validate various upper extremity biomechanical models, help quantify and validate various functional assessment scales, and help design safe/accessible controls by taking into consideration the position effects/force direction effects of the muscle activation patterns and the desired/undesired force directions.

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