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N94-24204

REACH PERFORMANCE WHILE WEARING THE SPACE SHUTTLE LAUNCH AND ENTRY SUIT DURING EXPOSURE TO LAUNCH ACCELERATIONS

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INTRODUCTION

Crewmen aboard the Space Shuttle are subjected to accelerations during ascent (the powered flight phase of launch) which range up to $+3G_X$. Despite having 33 missions and nine years experience, not to mention all the time spent in development prior to the first flight, no truly quantitative reach study wearing actual crew equipment, using actual Shuttle seats and restraints has ever been done. What little information exists on reach performance while under acceleration has been derived primarily from subjective comments gathered retrospectively from Shuttle flight crews during their post mission debrief. This lack of reach performance data has resulted in uncertainty regarding emergency procedures that can realistically be performed during an actual Shuttle ascent versus what is practiced in the ground-fixed and motion-based Shuttle Simulators.

With the introduction on STS-26 of the current Shuttle escape system, the question of reach performance under launch accelerations was once again raised. The escape system's requirement that each crewman wear a Launch/ Entry Suit (LES), parachute harness, and parachute were all anticipated to contribute to a further degradation of reach performance during Shuttle ascent accelerations. In order to answer the reach performance question in a quantitative way, a photogrammetric method was chosen so that the actual reach values and associated envelopes could be captured. This would allow quantitative assessment of potential task performance impact and identify areas where changes to our Shuttle ascent emergency procedures might be required. Also, such a set of reach values would be valid for any similar acceleration profile using the same crew equipment. Potential Space Station applications of this data include predicting reach performance during Assured Crew Return Vehicle (ACRV) operations.

METHOD

Four astronaut/pilot volunteers were used as test subjects for the reach evaluations at both 1 and $3G_X$. All were veterans of one or more previous Shuttle flights and had used the crew equipment configuration under consideration numerous times before, including an actual Shuttle mission.

The LES was designed to function as a combination dry-type, anti-exposure suit and a partial pressure, high altitude protection suit. Each subject wore the LES over a set of expedition weight Capilene® underwear. A specially designed torso harness was worn over the LES and connected by quick release fasteners to a personal parachute. This parachute was worn on the crewman's back and also functioned as a seat-back cushion.

Each subject was tested during two runs on the centrifuge at Brooks Air Force Base. One run was done at $1G_X$ (lying on his back while strapped in the seat), and the other was performed at the $3G_X$ level.

The reach sweeps performed by each subject were captured by four video cameras. One camera was secured in each corner of the centrifuge gondola and oriented for an optimum view of the subject. The four views of each recorded motion were subsequently digitized and analyzed using the Ariel Performance Analysis System, developed by Ariel Dynamics, Inc.

STATISTICAL METHODS

The data obtained from the motion analysis of left and right reach sweeps was normalized and prepared for statistical analysis. The cartesian coordinates of the left and right shoulder were noted while the subject was at rest during the $1G_X$ loading condition. These coordinates were then used as the origin for reach measurements during both the $1G_X$ and $3G_X$ sweeps. In this way, reach was normalized for each subject.

Reach was defined as the distance, in centimeters, between the shoulder and the knuckles for each coordinate. Maximum reach capability was compared in the forward, lateral and overhead (x, y, and z respectively) directions during 1 and $3G_X$ loading conditions. (Note: The measurement of lateral reach did not reflect a true maximum since all of the subjects were, at less than their full reach, able to touch the sidewalls of the gondola during the 1 and $3G_X$ exposures. Therefore, the y and Δy values were not considered for evaluation.) Changes in reach between the two G_X levels (Δx and Δz) were calculated by subtracting the $3G_X$ reach data from the $1G_X$ values. Changes in reach between the two $3G_X$ arm sweeps (Δx and Δz) were calculated by subtracting the right arm reach data from the left arm values.

Paired-t tests were used to statistically analyze reach differences in the x and z directions. This analysis was conducted on three comparisons: the left reach sweeps at 1 versus $3G_X$, the right reach sweeps at 1 versus $3G_X$, and the left versus right reach sweeps at $3G_X$. Because of the small population size (n=4), the use of the paired-t test is limited. For this reason, percent differences were also calculated for these same comparisons.

RESULTS

The results for 1 and $3G_X$ left reach sweeps are shown in Table 1. No statistically significant differences ($p < 0.05$) existed between the 1 and $3G_X$ left reach sweeps. The difference in average forward reach (Δx) for this study population was 3.3 +/- 5.0 cm. This value indicates that a greater left forward reach was achieved during the $1G_X$ loading condition. The difference in average overhead reach (Δz) was 3.9 +/- 3.4 cm. However, in this case, greater left overhead reach capability occurred during the $3G_X$ exposure.

TABLE 1.

LES Left Sweep $1G_X$ versus $3G_X$

Subject	Dominant Hand	$1G_X$		$3G_X$	
		X_{dir}	Z_{dir}	X_{dir}	Z_{dir}
1	Right	28.16	55.30	25.55	55.30
2	Right	38.29	53.30	40.33	60.38
3	Right	49.66	54.18	39.55	60.42
4	Left	49.59	50.88	46.97	53.03

Subject	Dominant Hand	ΔX_{dir}	ΔZ_{dir}	$\%\Delta X_{dir}$	$\%\Delta Z_{dir}$
1	Right	12.61	0	-9.27	0
2	Right	-2.04	-7.08	5.33	13.30
3	Right	10.11	-6.24	-20.36	11.52
4	Left	2.62	-2.15	-5.28	4.23

Percent differences were calculated using $1G_X$ data as the control variable (% difference = [(experimental-control)/control] x 100). While percent differences in reach for the entire population did not exceed 10%, significant (> 10%) individual differences between 1 and $3G_X$ left reach capability did exist. Specifically, subject 2 demonstrated a 13.3%

greater left overhead reach at $3G_X$ than at $1G_X$. Similarly, subject 3 displayed an 11.5% greater left overhead reach capability at $3G_X$. This same participant showed a 20.4% greater left forward reach at $1G_X$ than at $3G_X$.

No statistically significant differences were found to exist between the 1 and $3G_X$ right reach sweeps (Table 2). The Δx for the study group was 6.3 +/- 5.6 cm. That is, a greater forward reach occurred at $1G_X$ than at $3G_X$. The Δz was 6.2 +/- 7.6 cm. However, overhead reach capability was greater during the $3G_X$ loading conditions.

TABLE 2.

LES Right Sweep $1G_X$ versus $3G_X$

Subject	Dominant Hand	$1G_X$		$3G_X$	
		X_{dir}	Z_{dir}	X_{dir}	Z_{dir}
1	Right	42.98	56.40	28.58	57.23
2	Right	41.74	56.21	38.22	71.62
3	Right	49.10	66.11	43.56	75.32
4	Left	43.17	73.71	41.43	72.95

Subject	Dominant Hand	ΔX_{dir}	ΔZ_{dir}	$\%\Delta X_{dir}$	$\%\Delta Z_{dir}$
1	Right	14.40	-.83	-33.50	1.47
2	Right	3.52	-15.41	-8.43	27.42
3	Right	5.54	-9.21	-11.28	13.93
4	Left	1.74	.76	-4.03	-1.03

Once again, percent differences were calculated using lG_X data as the control variable. There was a significant percent difference in right forward reach for the entire population. This calculation indicated that forward reach was 14.2% greater at $1G_X$ than at $3G_X$ for the entire group. Significant individual percent differences in right reach also occurred. Subject 1 demonstrated a 33.5% greater right forward reach at $1G_X$ than at $3G_X$. Subject 2 displayed a 27.4% greater right overhead reach during the 3Gx exposure. Similarly, subject 3 showed a 13.9% greater right overhead reach at the $3G_X$ level. However, this same astronaut exhibited an 11.3% greater forward reach during $1G_X$ loading conditions.

Comparison of reach at $3G_X$ in the LES revealed that a statistically significant difference ($p = .037$) did exist between left and right sweeps under $3G_X$ loading conditions (Table 3). This difference indicated that a greater right overhead reach was obtained in the LES suit. This was true for both right and left hand dominant subjects.

TABLE 3.

At $3G_X$ in LES Left versus Right Sweep

Subject	Dominant Hand	LX	LZ	RX	RZ
1	Right	25.55	55.30	28.58	57.23
2	Right	40.33	60.38	38.22	71.62
3	Right	39.55	60.42	43.56	75.32
4	Left	46.97	53.03	41.43	72.95

Subject	Dominant Hand	LX-RX	LZ-RZ	$\%\Delta X$	$\%\Delta Z$
1	Right	-3.03	-1.93	-10.60	-3.37
2	Right	2.11	-11.24	5.52	-15.69
3	Right	-4.01	-14.90	-9.21	-19.78
4	Left	5.54	-19.92	-11.79	37.56

Percent differences were calculated using dominant hand data as the control variable (% difference = [(nondominant)/dominant] x 100). There was a significant percent difference (17.3%) between left and right overhead reach for the entire population. This value indicates that, under $3G_X$ loading conditions, the right overhead reach was greater than the left. No other significant percent differences in mean population reach occurred. However, significant individual differences did exist. Subject 1 showed a 10.6% greater right than left forward reach. Subject 2 demonstrated a 15.7% greater right overhead reach. Similarly, subject 3 exhibited a 19.8% greater right overhead reach. Subject 4, the only left-handed person in this group, displayed an 11.8% greater left forward reach. This participant also demonstrated a 37.6% greater right overhead reach.

SUMMARY

Since all subjects had significant previous experience using the equipment under evaluation, it is unlikely that any training effect is responsible for the results which were obtained.

The changes in reach in the +x (forward) direction were qualitatively what had been anticipated based on anecdotal reports received during Space Shuttle mission debriefings. Three of four subjects during left arm motion and four of four subjects during right arm motion experienced reduced reach capability in the +x direction at $3G_X$ versus $1G_X$. The magnitude of this change was not as great as was expected, in all cases, ranging from an improvement of 2.04 cm to a 10.11 cm decrease on the left to a 14.4 cm decrease on the right. While these differences between right and left are striking, they are not statistically significant.

It was unexpected that any reach envelopes at $3G_X$ would have been greater than that observed at $1G_X$. However, this was definitely the case in the +z (overhead) direction for three of four subjects during both left and right arm motion. The absolute range of reach difference in the +z (overhead) direction ranged from 0 to 7.08 cm on the left and -.76 to 15.41 cm on the right. These represented 13.3% and 27.4% increase in left versus right reach respectively. Operationally this would seem to indicate that any task which can be accomplished during $1G_X$ in the simulator should be achievable during actual flight.

Interestingly, there was a statistically significant difference ($p = .037$) between the left and right overhead reach with the right being greater. This unanticipated finding, which was unrelated to the subject's handedness, raises several points for consideration. Since the LES is symmetrically constructed, it is unlikely that it was, by itself, responsible for the asymmetry observed. The torso harness which is worn over the LES is not symmetrical (which is also the case with the parachute). It is felt that further analysis in the future of the asymmetry of the equipment may identify a course of action which will improve the left overhead reach to the point where it is equivalent to the right.

CONCLUSIONS

These data indicate that ground-based simulator training is adequate as far as verifying the feasibility of overhead activities are concerned. The same is not true of activities involving forward reach. Accordingly, to make training realistic, crewmen should be instructed that tasks involving forward reach should not be attempted during simulator runs if they exceed 66-80% of the maximum $1G_X$ forward reach capability of the crewman.

Also, more generically, this study has demonstrated the utility of using photogrammetric techniques to quantify magnitudes of reach in any direction. Further, since this data is handled and ultimately stored digitally, it is fully "portable" and can thus be used to predict reach performance in any environment where the subject is exposed to similar accelerative loads, etc.

In future work, we will merge our reach information with a graphics data base describing the Space Shuttle cockpit panels. This will allow us to find the intersection of these two data bases and represent actual panel positions reachable by a specific subject.