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An Analysis of the Loads Applied to a Heavy Space Station Rack During Translation and Rotation Tasks

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ACRONYMS

ABL	Anthropometry and Biomechanics Laboratory
ANOVA	Analysis of Variance
APAS	Ariel Performance Analysis System
IVA	Intravehicular Activity
JSC	Lyndon B. Johnson Space Center, Houston, Texas
MANOVA	Multivariate Analysis of Variance
NASA	National Aeronautics and Space Administration
PABF	Precision Air Bearing Floor

ACKNOWLEDGMENTS

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SUMMARY

To prepare for Space Station Alpha's on-orbit assembly, maintenance and resupply, NASA requires information about the the crew members' ability to move heavy masses (~680.4Kg, 1500lb) on orbit. Ease of movement in microgravity and orbiter stay time constraints may change the Space Station equipment and outfitting design requirements. Therefore, the time and effort required to perform a particular task and how and where the forces and torque should be applied become critical in evaluating the design effort. Thus, the three main objectives of this investigation were to: 1) quantify variables such as force and torque as they relate to heavy mass handling techniques, 2) predict the time required to perform heavy mass handling tasks, and 3) note any differences between males and females in their ability to manipulate a heavy mass.

By simulating translation movements on the Precision Air Bearing Floor and recording the forces and torque applied to a heavy rack handrail and the resulting motion of the heavy rack, the efforts required to translate the rack were assessed. First, the effort required by two different techniques for rotating the heavy rack 90° were compared; the first was a smooth arcing motion and the second was a zigzag motion. Second, the forces and torque applied to the handrail of the rack as it was translated along a corridor and through a hatch were determined.

Comparison of the smooth and zigzag rotation tasks showed that the effort required by the smooth rotation task was much less and was more consistent across subjects than that required by the zigzag task. There was no difference between the male and female mean times required to complete either of the rotation tasks.

Analysis of variance results of the translation task data showed that all six force and torque condition means (push, pull, right, left, clockwise and counter-clockwise) differed significantly between males and females. When compared by task (translation, alignment, insertion, and extraction), the clockwise, counter-clockwise and push conditions differed significantly, while the pull, left, and right conditions did not. When considering time for task completion, it took the females much longer to complete the translation and alignment tasks than the males, and a little longer to complete the insertion and extraction tasks.

1.0 PURPOSE

The three main objectives of this investigation were to: 1) quantify variables such as force and torque as they relate to heavy mass handling techniques, 2) predict the time required to perform heavy mass handling tasks, and 3) note any differences between males and females in their abilities to manipulate a heavy mass.

2.0 BACKGROUND

In preparation for the on-orbit assembly, maintenance and resupply of Space Station Alpha, NASA requires insight into the ability of the crew to move heavy masses (~680.4Kg, 1500lb) on orbit. Ease of movement in microgravity and constraints on orbiter stay time may change the equipment and outfitting design requirements for the Space Station. Therefore, the time and effort required to perform a particular task and how and where the forces and torque should be applied becomes critical in evaluating the design effort.

The Anthropometry and Biomechanics Laboratory (ABL) at Johnson Space Center (JSC) has the resources to quantify the variables involved in translating a heavy Space Station rack. The effort required to translate the rack can be assessed by simulating the translation movements on the Precision Air Bearing Floor (PABF), and recording the forces and torque applied to the heavy rack handrail and the resulting motion of the heavy rack.

The PABF is one of several zero-gravity simulation facilities available at NASA for conducting tests. The floor, which simulates zero gravity in only one plane of motion, is made of 32 stainless steel plates, assembled to create a 7.32m X 9.75m (24ft X 32ft) surface. These plates are machined smooth to within .025mm (.001in) and are level to within .076mm (.003in). The tight tolerances of the floor create a nearly frictionless surface on which air bearing pads can be floated. A triangular shaped sled supported by three air bearing pads, each being supplied approximately $7.59X10^5 N/m^2$ (110psi) of air, can effectively float a 952.6Kg (2100lb) object .076mm (.003in) above the floor.

3.0 METHOD

3.1 Subjects

Twelve subjects were used in this investigation, six males and six females. Subjects were chosen from three JSC work areas: Human Factors Engineering, Space Station Training and Mission Operations. No requirements were put on an individual's size or strength, and no subject had prior experience manipulating objects on the PABF. All subjects had current Air Force Flying Class III physicals, and had read and signed a consent form acknowledging their awareness of the procedures.

3.2 Apparatus

Mock-ups of the Space Station rack corridor and hatch (1.3m X 1.3m (50in X 50in)) were mounted along the walls of the PABF. A mock-up of a heavy rack (1.0m X 1.1m X 2.0m (39.5in X 41.5in X 80in)) was placed on its side on one of the sleds (fig. 1). It was weighted to 680.4Kg (1500lb), with the center of mass positioned at the center of both the length and width dimensions. This location placed the center of mass well within the center of mass envelope defined for an integrated Space Station rack with a 700Kg (1543lb) payload (U.S. Standard Equipment Rack Interface Development Document, SSP-41090, October 1, 1992). Throughout performance of the tasks, the subjects sat in the upright chair, which was also floated on air bearings.

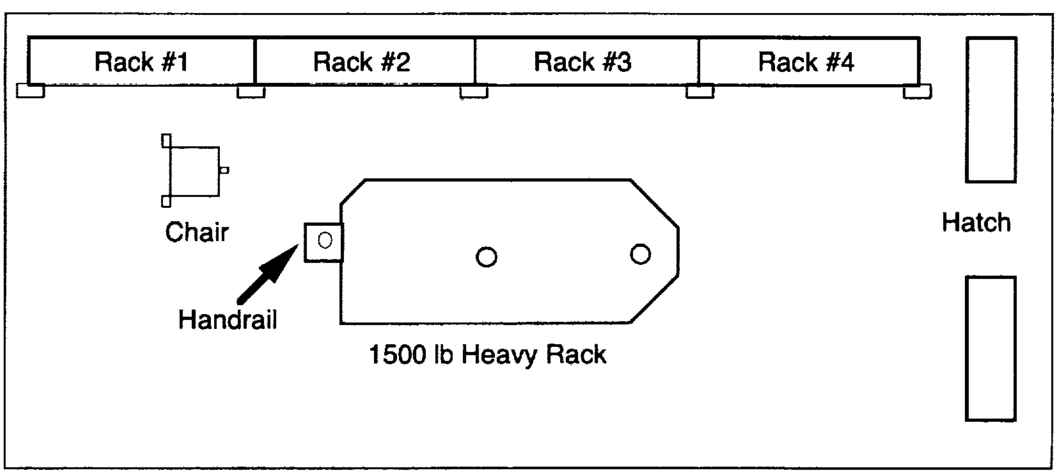


Figure 1. Top View of the Mockups on the Air Bearing Floor

To measure the loads exerted on the intravehicular heavy rack handrail, load cells were mounted at both ends of the handrail. These load cells measured the forces in the X, Y, and Z directions (F_x, F_y, F_z) and the moment around the Z axis (M_z) (see excerpts from Kistler 9273 Operating and Service Instruction manual, Appendix A). A right-handed system was used, with positive X being out, positive Y being to the right, and positive Z being up. A test fixture was used to clamp the handrails to the load cells and to mount the handrail and load cells to the heavy rack (fig. A-1).

Motion of the subject and rack was recorded by a camera mounted approximately 16.5m (54ft) above the PABF. Retroreflective markers were placed on top of the heavy rack and vertical posts for tracking the rack's motion and defining calibration points, respectively. A studio light was also mounted above the floor to provide a light source for the retroreflective markers.

The Ariel Performance Analysis System (APAS), a motion analysis system located in the ABL, was used to record the analog data from the load cells and to digitize the motion recorded with the overhead camera. A switch was used to synchronize the analog and video systems. When the switch was momentarily connected, a +5V pulse was sent to the APAS to trigger the analog system and a flash was released to signify the start of the video sequence.

3.3 Procedure

To evaluate both technique and timing, two tests were performed. First, the effort required by two different means of rotating the heavy rack 90° was compared; the first was a smooth arcing motion and the second was a zigzag motion. Second, the forces and torque applied to the handrail of the rack as it was translated along a rack corridor and through a hatch were determined. The subjects were instructed to maintain a 1.25cm to 2.5cm (1/2in to 1in) clearancs during translation down the wall and insertion into the hatch.

The test subjects were seated in the upright chair and instructed to use their left hand on the handrails mounted on the Space Station corridor mockup to translate themselves along the floor. The right hand was used to manipulate the heavy rack. During the translation task, in which the body directly faced the rack, most subjects kept their feet on the chair, and did not use them on the wall. For the rotation tasks, in which the subjects were initially turned 90° from the rack, most subjects used a three-point stance, created by bracing their feet along the wall on opposite sides of the handrails. Although during the rotation tasks the subjects were positioned 90° from what is expected on orbit, the loads transmitted into the rack handrail were assumed to be similar in magnitude to those that would be produced if the body were in line with the rack.

For the rotation tasks, the rack was initially positioned parallel to the Space Station wall, and located so that the subjects could position themselves around a wall handrail. This position was best suited for creating the three-point stance. The subjects were then instructed to rotate the rack 90°, so that it ended up perpendicular to the wall.

The first rotation, termed smooth rotation, was performed using only a torquing action, with no X or Y translation. Torque was initially applied in a clockwise motion until the rack began to rotate at a constant velocity due to its inertia. The rack was then allowed to coast, until finally a counter-clockwise torque was applied to bring the rack to a complete and controlled stop at 90° (figs. 2 and B-1). This task required that the rack be rotated about the handrail, not the center of mass.

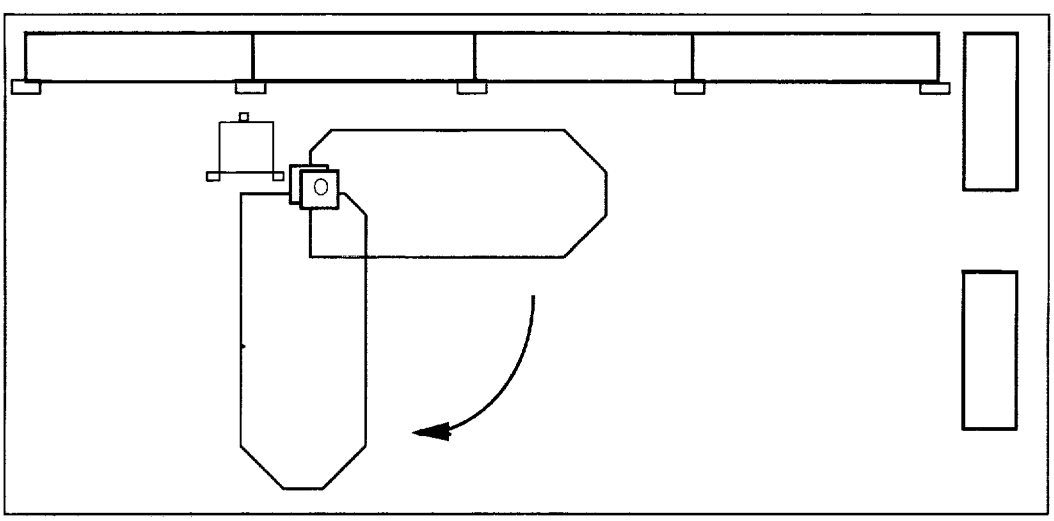


Figure 2. Smooth Rotation Task

The second rotation, termed the zigzag rotation, was performed by alternating yaw and X and Y translations. This technique utilized rotation about the center of mass, rather than about the handrail. The rack was initially rotated, then pulled toward the subject, again rotated, then pushed away, etc. In this repetitive fashion, the rack was walked through 90^{o} (figs. 3 and B-1). The subjects were allowed to develop their own technique for performing this task. The number of steps required to rotate the rack through a complete 90^{o} therefore varied from subject to subject.

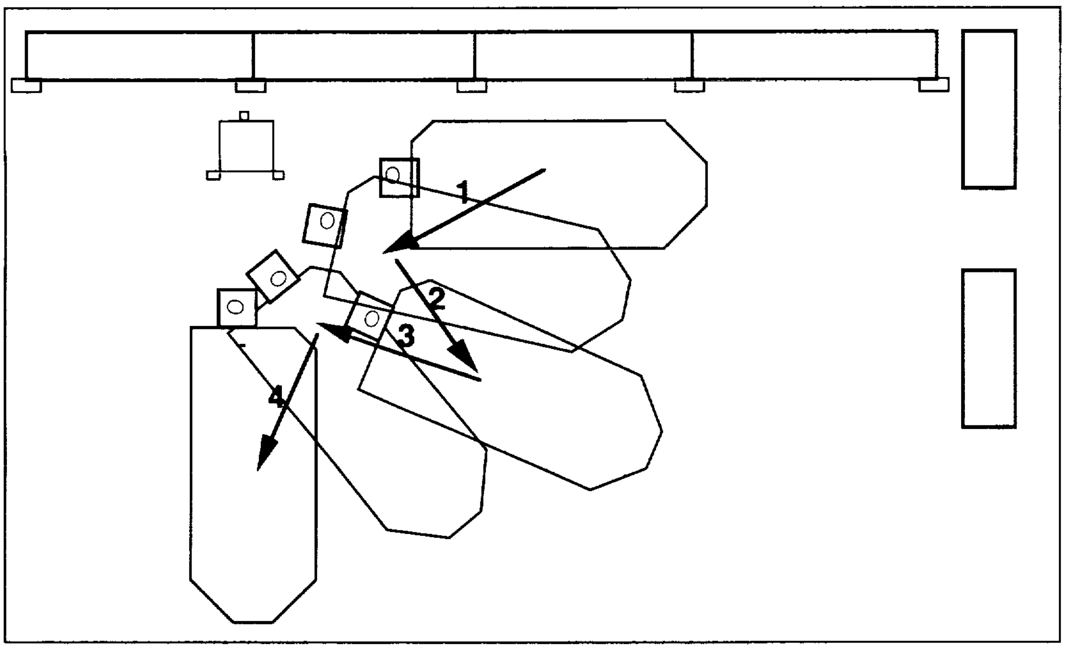


Figure 3. Zigzag Rotation Task

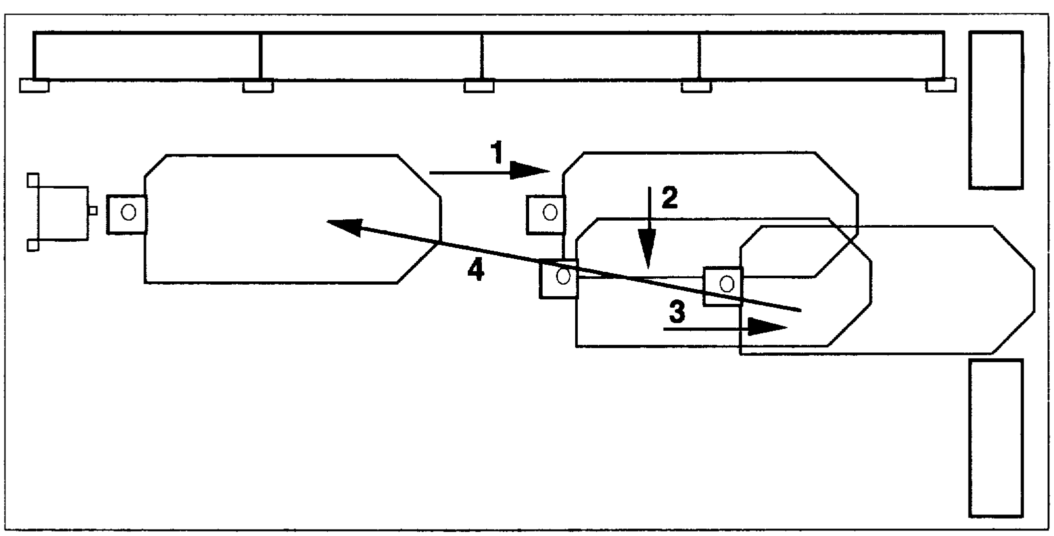


Figure 4. Translation Task

For the translation task, the rack was initially positioned parallel to and at the end of the Space Station wall. The subject was instructed to consider the task in four distinct events. The first was to translate the rack to the end of the wall, attempting to maintain the rack within 2.54cm (1in) of the wall; the second was to align the rack with the hatch; the third was to insert the rack into the hatch and bring it to a complete and controlled stop; and the fourth was to extract the rack from the hatch and return it to the initial position, this time not maintaining the rack position within 2.54cm (1in) of the wall (figs. 4 and B-2).

Before beginning the data collection, the subjects were given time to become comfortable with manipulating the rack. Three trials of each of the previously described test sequences were then performed. Each trial was timed and both analog and video data were recorded.

4.0 RESULTS

4.1 Rotation Task

For the rotation tasks, a quantification of the effort required to perform the tasks was calculated using the work equation, which sums the products of the forces/torque and the distances/angles over which they were applied. Analysis of the analog data provided the forces and torque applied to the heavy rack handrail, and digitization and analysis of the video data provided the linear and angular positions of the rack (see Appendix C for example data plots).

The general equation used to calculated the effort was:

$$E = \Sigma \left[F_x (\Delta P_x) + F_y (\Delta P_y) + M_z (\Delta \beta) \right]$$

where F_x is the force in X direction, F_y is the force in the Y direction, M_z is the moment around the Z axis, ΔP_x is the change in position of the handrail in the X direction, ΔP_y is the change in position of the handrail in the Y direction, and $\Delta \beta$ is the change in the angular position of the handrail-center segment. Various constants were added to this equation as necessary to maintain consistent units. In order to sum the segments properly, the analog and video data were synchronized at 20Hz.

Due to time constraints and the impracticality of digitizing all of the video data, only one trial from each of the six male test subjects was used in the effort analysis. Table 1 shows the effort required to complete the smooth and zigzag tasks for the six trials analyzed.

Table 1. Effort Required to Complete the Smooth and Zigzag Rotation Tasks

SUBJECT	SMOOTH (Nm)	ZIGZAG (Nm)
A	1.11 (.82)	14.09 (10.39)
B	.61 (.45)	53.41 (39.39)
C	.16 (.12)	1.46 (1.08)
D	.26 (.19)	2.90 (2.14)
E	.87 (.64)	.52 (.38)
F	.38 (.28)	.94 (.69)
AVERAGE	.57 (.42)	12.22 (9.01)
STANDARD DEVIATION	.37 (.27)	20.81 (15.35)

Ft-lb in parenthesis

As seen from table 1, the effort required by the smooth rotation task was much less and was more consistent across subjects than that required by the zigzag task. The variability of the effort required by the zigzag task was most likely due to the inconsistent maneuvering techniques used by the test subjects.

4.2 Translation Task

For the translation task, the four segments (translation, alignment, insertion and extraction) were separated by finding on the video the point at which the movement stopped and noting the corresponding time. These times were then used to window off particular segments of the analog data when determining the maximum forces and torque. A statistical analysis was then performed on the maximum forces and torque applied to the handrail in both directions, i.e. analog signals $\pm F_X$, $\pm F_Y$, $\pm M_Z$ (see Appendix C for example data plots). The orientation of the handrail defined the following six conditions:

$+F_x$ - Pull force
$-F_x$ - Push force
$+F_y$ - Right force
$-F_y$ - Left force
$+M_z$ - Counter-clockwise torque
$-M_z$ - Clockwise torque

A multivariate analysis of variance (MANOVA) was performed on the maximum force and torque data using a Statistical Analysis Software package. The tests revealed overall significant differences between sexes and among tasks, i.e., translation, alignment, insertion, and extraction (all $p \leq 0.0001$).

Subsequent analysis of variance (ANOVA) showed all six conditions differed significantly between males and females (all $p \leq 0.001$). For both the clockwise and counter-clockwise torque conditions, the male torques were significantly larger than the female torques (table 2). By contrast, for the left, right, push, and pull force conditions, the females forces were significantly larger than the male forces (table 3). These differences suggest that the females either had more difficulty controlling the X and Y movement of the rack or were overcontrolling the rack, while the males tended to apply more torque than necessary.

Table 2. Mean Maximum Torque for Clockwise and Counter-Clockwise Conditions When Compared by Gender

MOTION	MALE	FEMALE
CLOCKWISE (Nm)	3.36 (2.48)	2.39 (1.76)
COUNTERCLOCKWISE (Nm)	2.62 (1.93)	1.95 (1.44)

Ft-lb in parenthesis
There were significant differences between males and females

Table 3. Mean Maximum Forces for Left, Right, Push, and Pull Conditions When Compared by Gender

MOTION	MALE	FEMALE
LEFT (N)	10.45 (2.35)	19.44 (4.37)
RIGHT (N)	11.79 (2.65)	16.95 (3.81)
PUSH (N)	21.43 (4.82)	28.11 (6.32)
PULL (N)	21.75 (4.89)	35.58 (8.00)

lb in parenthesis
There were significant differences between males and females

ANOVA analysis also showed that, when grouped by task, the clockwise ($p \leq 0.0071$), counter-clockwise ($p \leq 0.0014$), and push ($p \leq 0.0001$) conditions differed significantly, while the pull ($p \leq 0.2602$), left ($p \leq 0.3857$), and right ($p \leq 0.3107$) conditions did not (tables 4 and 5).

Table 4. Mean Maximum Torque for Clockwise and Counter-Clockwise Conditions and Maximum Forces for Push Condition When Compared by Task

MOTION	TRANSLATION	ALIGNMENT	INSERTION	EXTENSION
CLOCKWISE (Nm)	3.15 (2.32)	2.96 (2.18)	2.37 (1.75)	3.17 (2.34)
COUNTER-CLOCKWISE (Nm)	1.74 (1.28)	2.51 (1.85)	2.81 (2.07)	2.20 (1.62)
PUSH (N)	23.62 (5.31)	22.37 (5.03)	19.39 (4.36)	32.78 (7.37)

Ft-lb and lb in parenthesis
There were significant differences among tasks

Table 5. Mean Maximum Forces for Pull, Left, and Right Conditions When Compared by Task

MOTION	TRANSLATION	ALIGNMENT	INSERTION	EXTENSION
PULL (N)	29.00 (6.52)	27.18 (6.11)	24.29 (5.46)	31.94 (7.18)
LEFT (N)	13.61 (3.06)	16.95 (3.81)	13.70 (3.08)	14.01 (3.15)
RIGHT (N)	14.06 (3.16)	14.63 (3.29)	12.50 (2.81)	15.43 (3.47)

lb in parenthesis
There were no significant differences among tasks

4.3 Time

The average and standard deviation of the times required to complete the tasks were reported for all sequences (table 6). While there was no difference between males and females in the time required to complete the rotation tasks, females took much longer to complete the translation and alignment tasks, and a little longer to complete the insertion and extraction tasks.

Table 6. Average and Standard Deviation for Time to Complete Tasks

	SMOOTH	ZIGZAG	TRANSLATION	ALIGNMENT	INSERTION	EXTRACTION
MALE	58.6 (10.7)	50.8 (13.1)	39.9 (22.6)	28.8 (20.7)	40.2 (19.2)	61.6 (18.9)
FEMALE	58.3 (18.3)	53.7 (15.1)	51.2 (12.6)	40.8 (22.1)	47.7 (13.1)	66.1 (14.1)

Average time in seconds, standard deviation in parenthesis

Physical constraints of the PABF allow movement, and therefore analysis, in only three dimensions: X, Y, and yaw. Simulation fidelity is thus compromised. For instance, while a subject may be applying a roll motion to the handrail, the object being manipulated does not respond accordingly. The subject therefore does not react and compensate as he/she would if in a true zero-gravity environment. Although the data reported in this document gives ballpark figures for the expected forces and torque, it still only pertains to movements on the PABF and cannot be extrapolated directly to an on-orbit situation.

5.0 CONCLUSIONS AND RECOMMENDATIONS

To evaluate both the technique and timing associated with the manipulation of a 680.4Kg (1500lb) Space Station rack, two tests were performed during this evaluation. First, the effort required by two different techniques for rotating the heavy rack 90^{o} were compared; the first was a smooth arcing motion and the second was a zigzag motion. Second, the forces and torque applied to the handrail of the rack as it was translated along a corridor and through a hatch were determined.

Comparison of the smooth and zigzag rotation tasks showed that the effort required by the smooth rotation task was much less and was more consistent across subjects than that required by the zigzag task. The variability of the effort required by the zigzag task was most likely due to the inconsistent maneuvering techniques used by the test subjects. There was no difference between males and females in the time required to complete either of the rotation tasks.

ANOVA results of the translation task data showed that all six conditions (push, pull, right, left, clockwise, and counter-clockwise) differed significantly between males and females. When tested by task (translation, alignment, insertion, and extraction), the clockwise, counter-clockwise, and push conditions differed significantly, while the pull, left, and right conditions did not. When considering time for task completion, it took the females much longer to complete the translation and alignment tasks than the males, and a little longer to complete the insertion and extraction tasks.

It is recommended that rotational tasks be approached with smooth torquing movements rather than push/pull movements. Not only does the smooth technique require less effort, it also better controls the rack, lessening the possibility of the rack colliding with the other Space Station hardware.

If the study is repeated, there are improvements that should be made. First, the translation portion of this study should be performed by two subjects together since it is highly unlikely that any of these tasks will be attempted by a single crew member while on orbit. Second, the rack hardware should be suspended by pulleys or on a pivotball so that five degrees of freedom are available, i.e., add the pitch and roll motions.

APPENDIX A

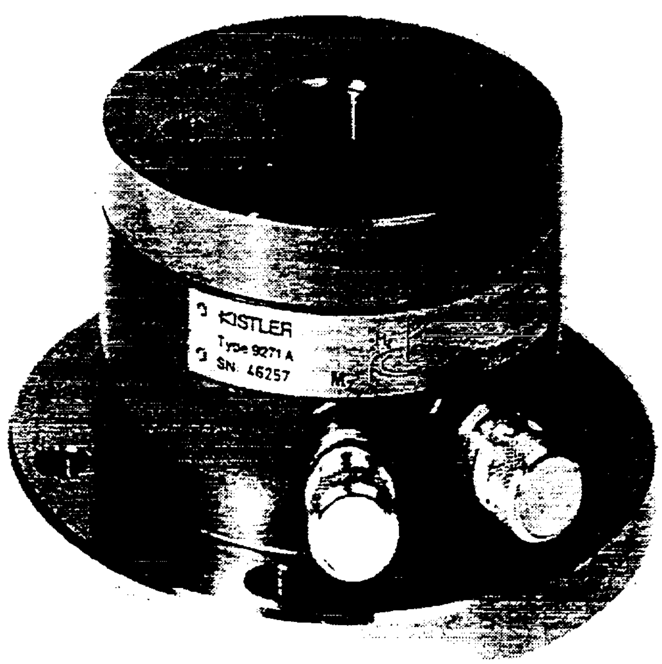
Specifications for Handrail Instrumentation

I DESCRIPTION

I - 1 Introduction

The two-component measuring platform 9271A is a piezo-electric transducer capable of measuring simultaneously a force parallel to the transducer axis and a moment in the plane normal to the line of application of the force. The inbuilt quartz measuring cell of high rigidity permits working with minimal mesuring displacements and also with relatively wide frequency range.

The electrical charges generated by the platform are strictly proportional to the loads to be measured; charge amplifiers convert them into analog dc voltages, which may be recorded, read out or otherwise processed as required.



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Specifications for Handrail Instrumentation

I - 2 Technical data (Table 1)

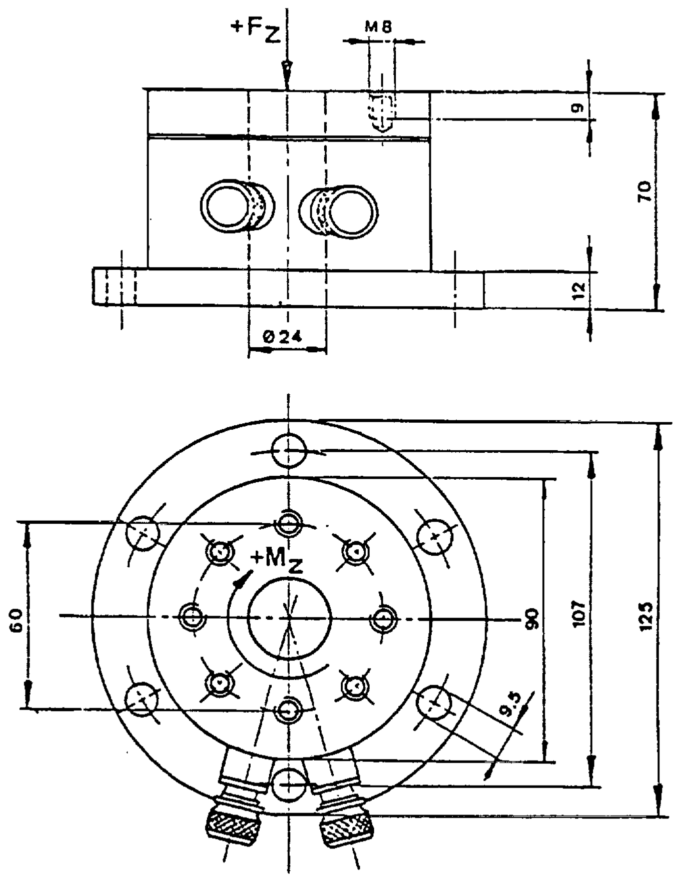

Fig. 2: Dimensions of measuring platform

Max. measuring ranges:

$+F_z$: (pressure) line of application within 20 mm of center	kp	0 to 2000
line of application within 40 mm of center	kp	0 to 1000
$-F_z$: (tension) line of application within 40 mm of center	kp	0 to -500
M_z: $F_z > 0$ (pressure only)	kpcm	±1000
$F_z \neq 0$ (pressure and tension)	kpcm	±800
Overload capacity of F_z	%	100
M_z	%	50

Calibrated ranges:

F_z	kp	0 to 2000
	kp	0 to 200
	kp	0 to -500
M_z	kpcm	±1000
	kpcm	±100

Secondary loads: see Characteristics

Specifications for Handrail Instrumentation

Sensitivities (nominal values):		
F_z	pC/kp	-19,5
M_z	pC/kp	-15,0
Max. sensitivity variations		
with force application point varying within the limits indicated	%	< ±2
Linearity deviation: all ranges	% of f.s.	< 1,0
Hysteresis: all ranges	% of f.s.	< 0,4
Threshold: corresponding to 0,03 pC		
F_z	kp	~0,002
M_z	kpcm	~0,002

Cross talk:

(mutual influencing of components)

Cross talk signal in channel	Loading with $F_{x,y}$	F_z	$M_{x,y}$	M_z
F_z	<1 %	X		<0,01 kp/kpcm
M_z		0,02 kpcm/kp	<1 %	X

Working temperature range:	°C	0 to 70
Effect of temperature on sensitivities:	$(^{\circ}C)^{-1}$	$\approx -2 \cdot 10^{-4}$
Temperature drift within working temperature range:		
F_z	kp/°C	≈ 20
M_z	kpcm/°C	≈ 0,2
Resonant frequency, measuring platform mounted on large mass, lowest observed	kHz	> 3
Spring constants:		
F_z	kp/µm	≈ 650
M_z	kpm/°	≈ 900
Insulation values: each channel	Ω	$> 10^{13}$
Capacitance: each channel	pF	≈ 350
Requirements for surface on which the measuring platform is mounted:		
Planeness error	µm	<5
Quality	ground or with fine surface	
Material of platform:	stainless steel	
Weight:	kp	2,9

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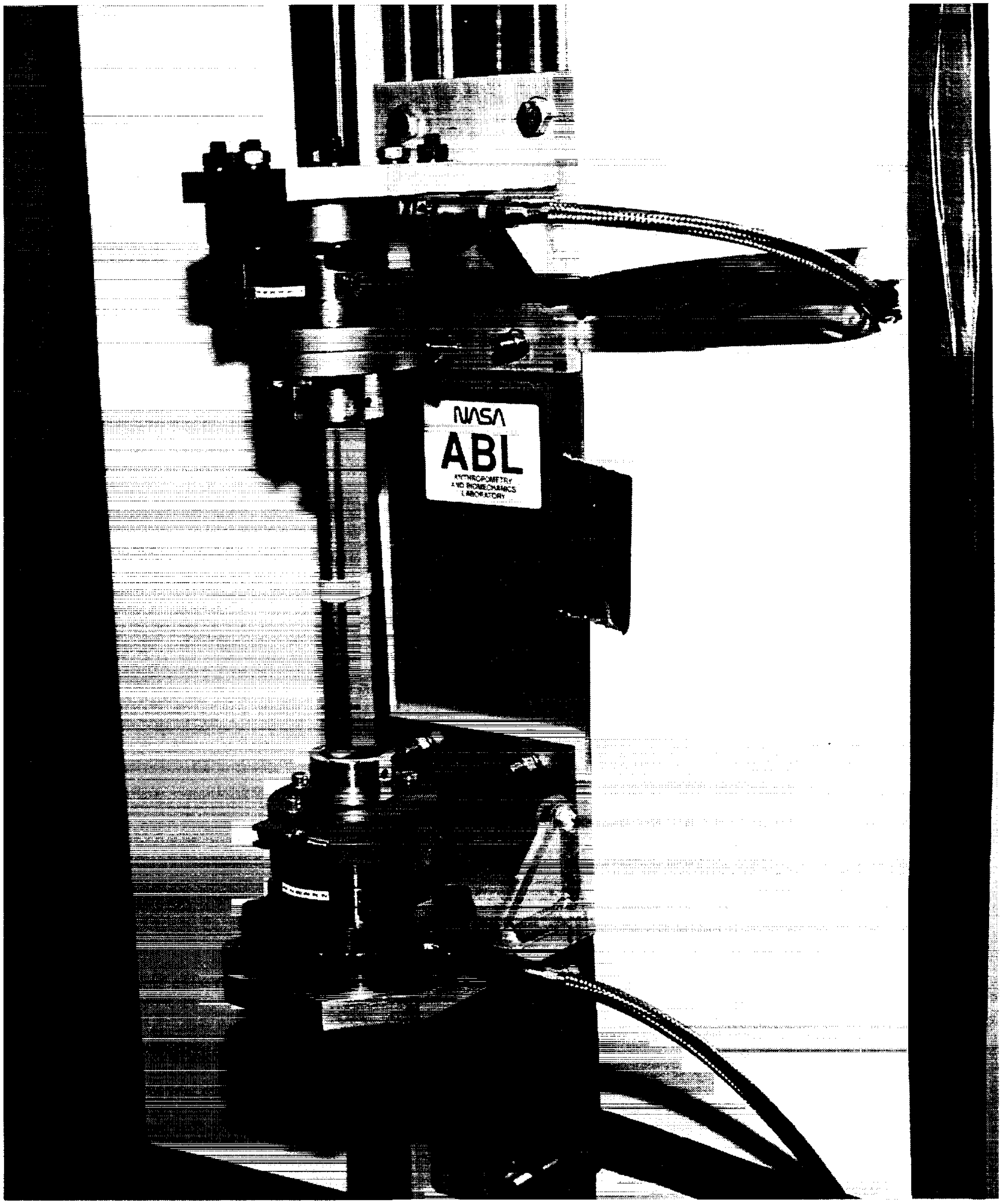


Figure A-1. Photograph of Handrail and Transducer Hardware

APPENDIX B

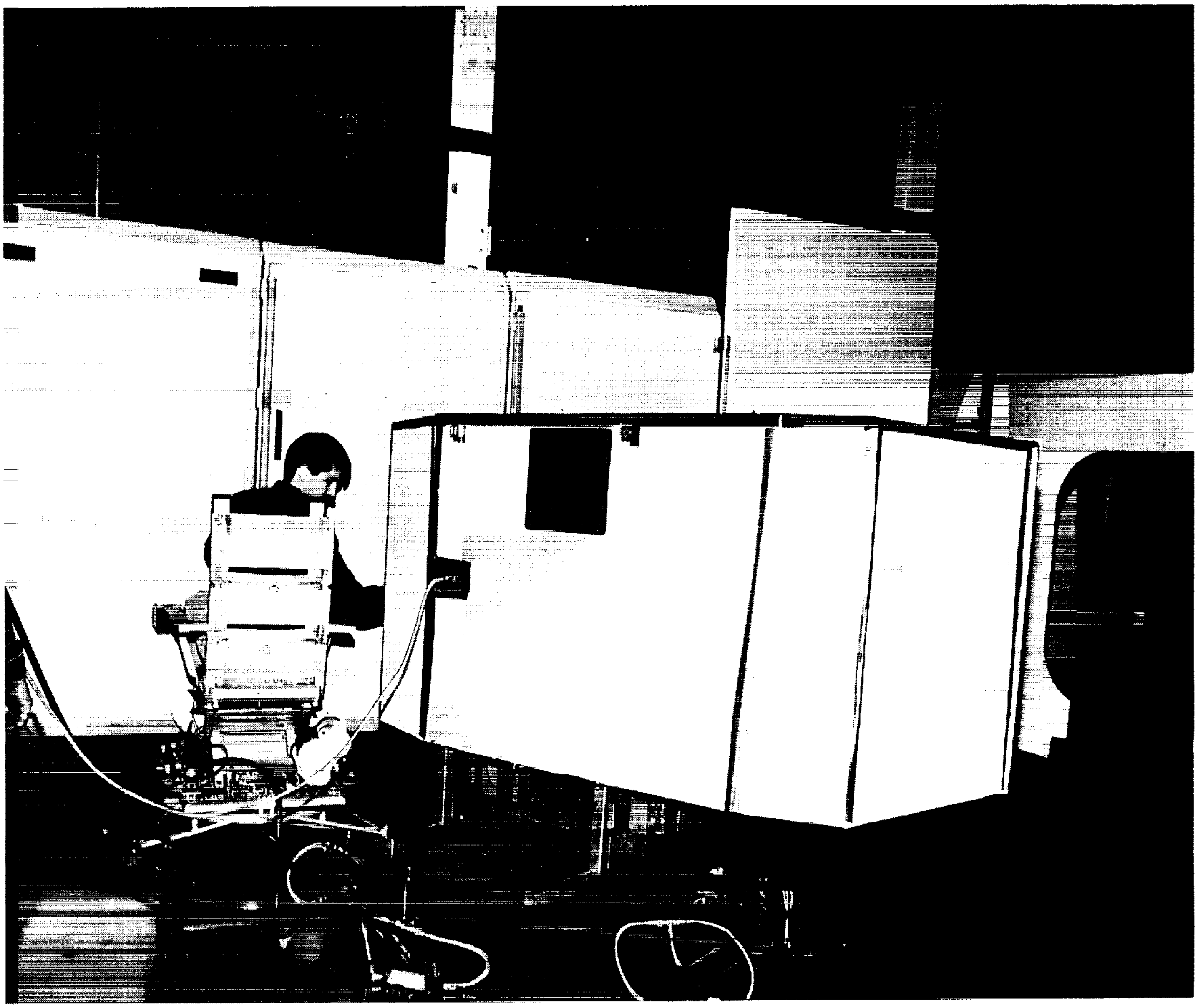


Figure B-1. Photograph of Rotation Task Set-up

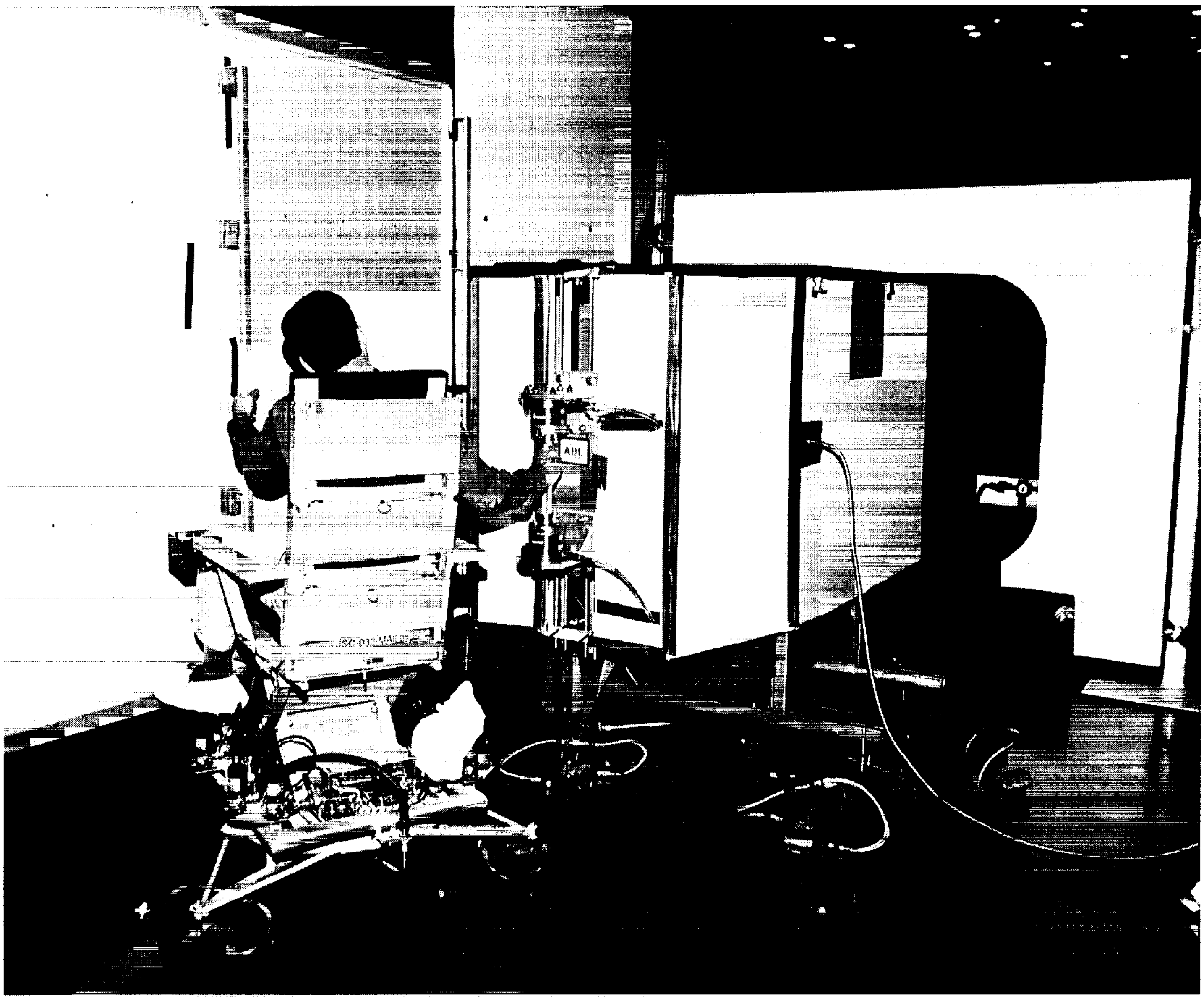
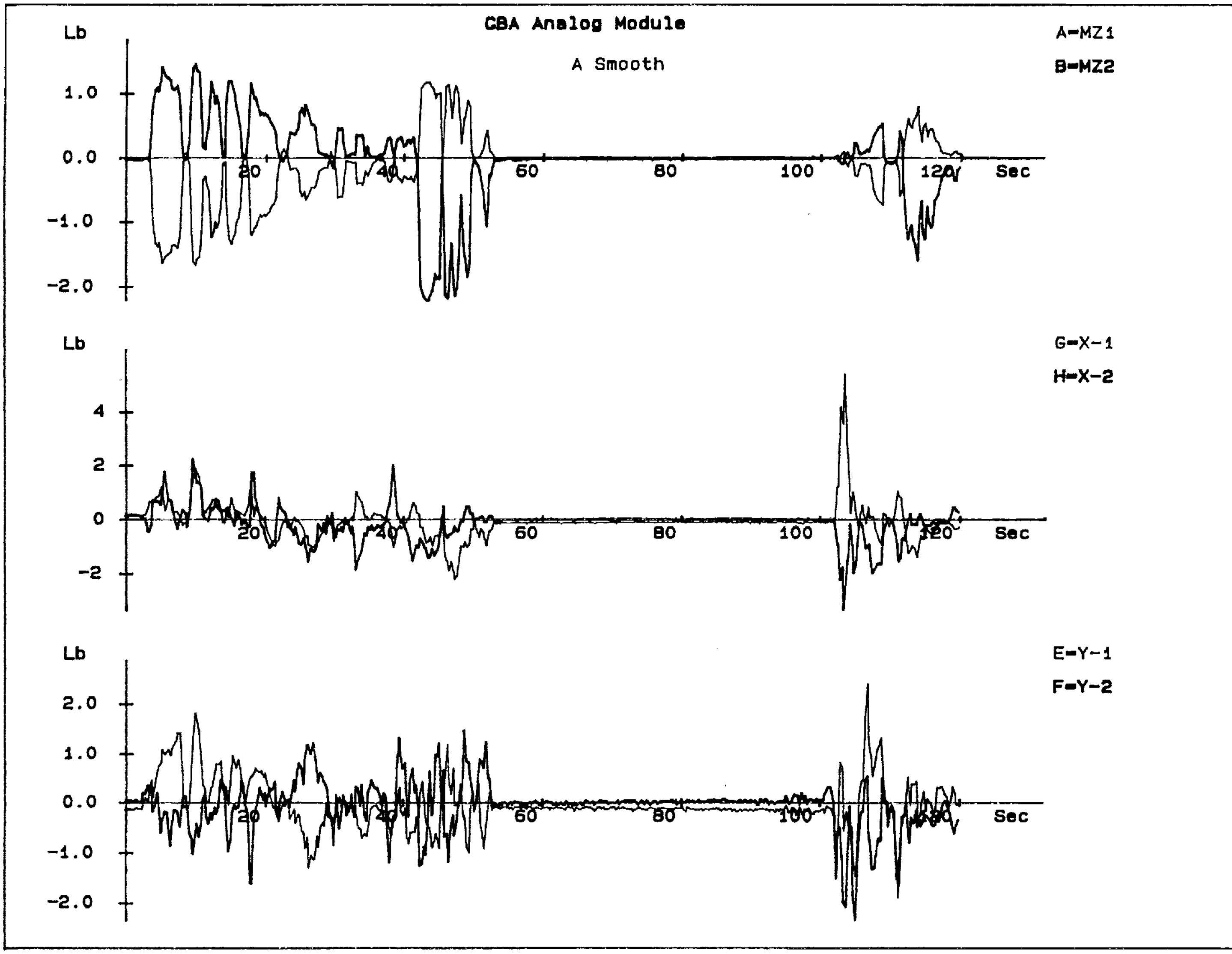


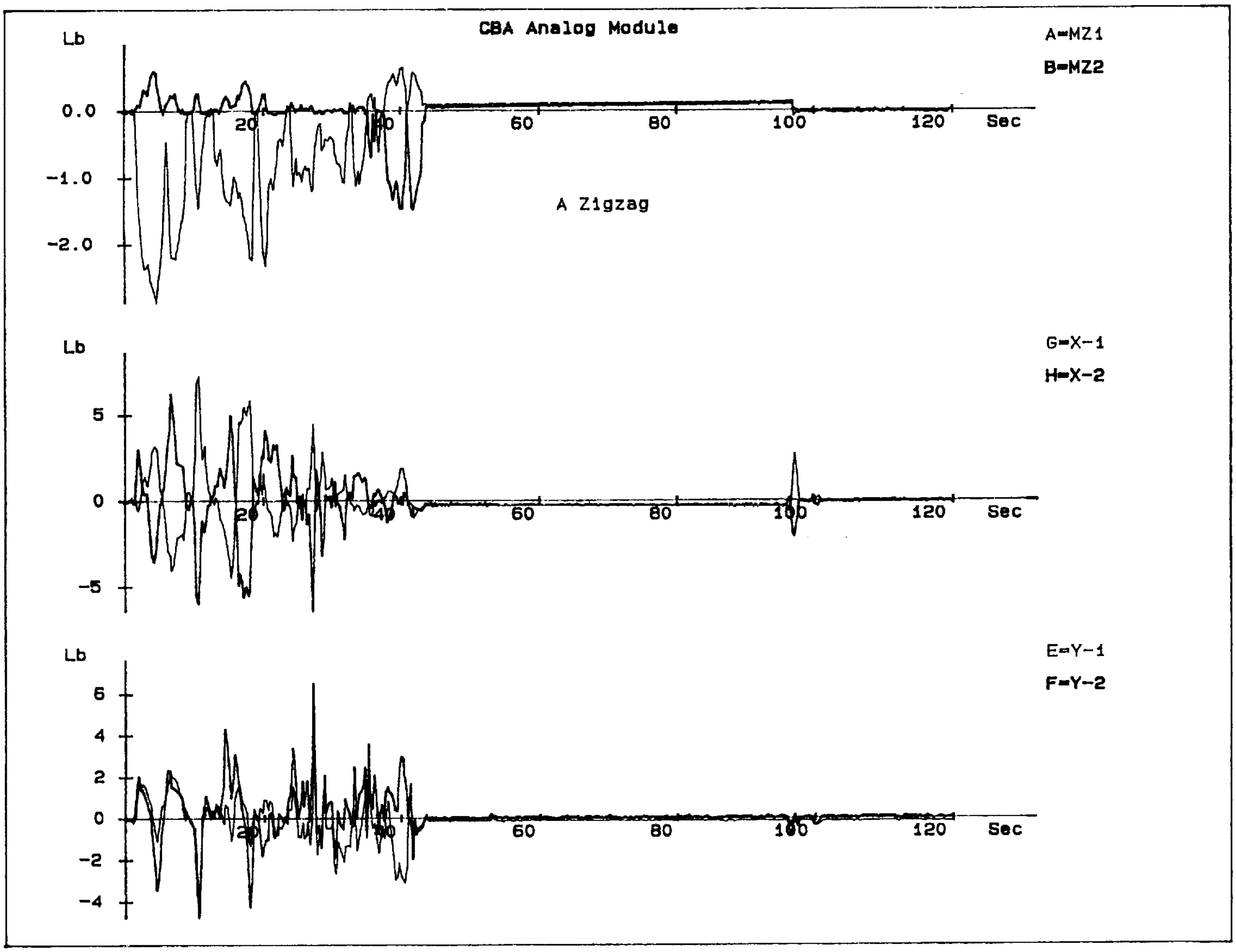
Figure B-2. Photograph of Translation Task Set-up

APPENDIX C

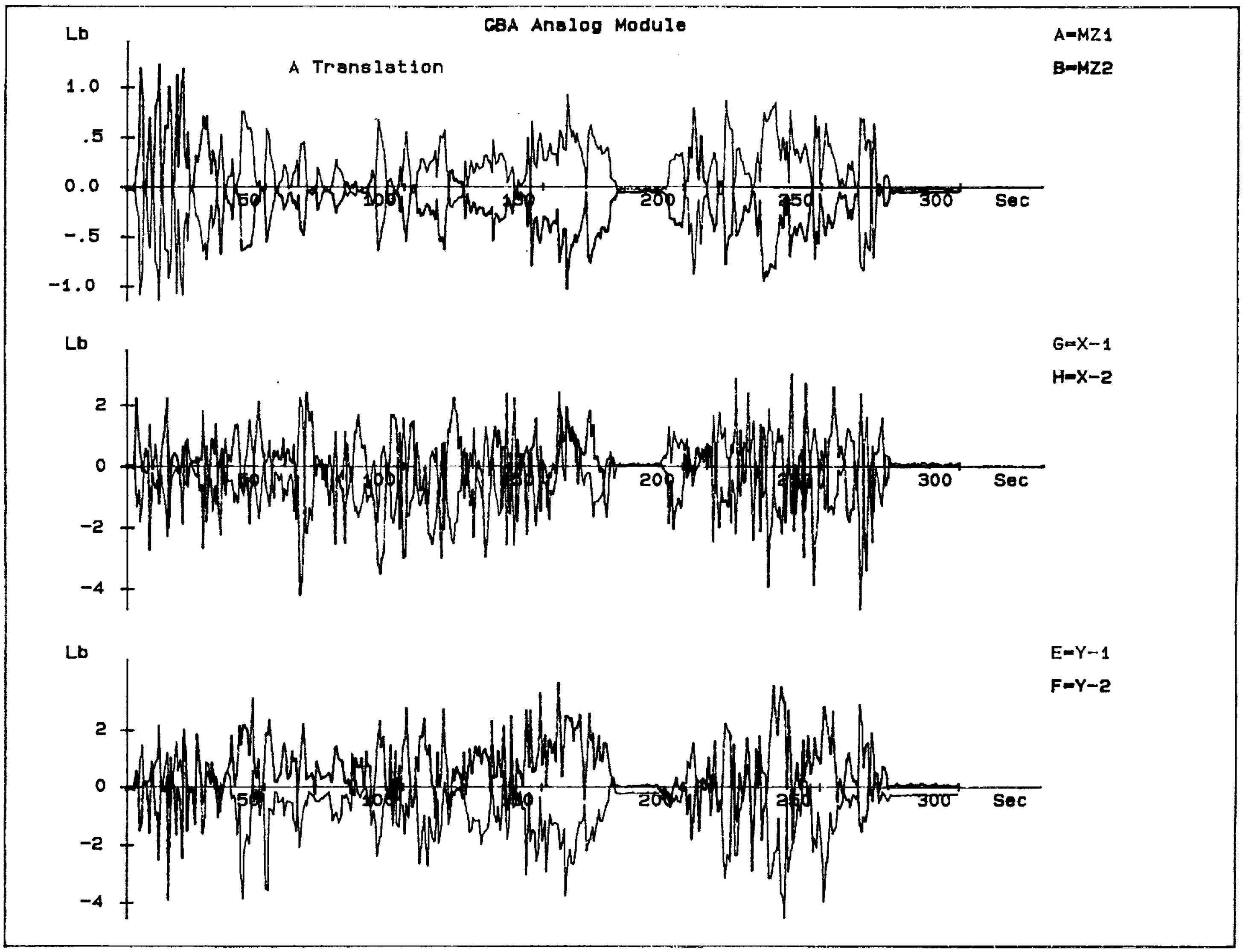
Example of Smooth Rotation Task Data



Example of Zigzag Rotation Task Data



Example of Translation Task Data



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