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Loads Produced During the Ingression and Egression of the Portable Foot Restraint on the Hubble Space Telescope

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Contents

Section **Page**

ACRONYMS v
1.0 INTRODUCTION 1
1.1 Background 1
1.2 Purposes of the Study 2
2.0 GENERAL METHODOLOGY 2
2.1 Subjects 2
2.2 Apparatus 2
2.3 Experimental Design 3
2.4 Experimental Procedure 3
2.5 Data Treatment 5
2.6 Analysis 5
3.0 RESULTS 8
3.1 Sustained Force and Moment Analysis 8
3.2 Spike Force and Moment Analysis 9
4.0 DISCUSSION 10
5.0 CONCLUSION AND APPLICATION 12
APPENDIX A: COMPARISON OF NOMINAL VERSUS REDUCED-LOAD TRIALS A-1
APPENDIX B: ADDITIONAL FORCE AND MOMENT DATA B-1

Figures

Figure **Page**

1 Load cell apparatus setup (attached to the HST mockup in the NBL) 3
2 Crewmember ingressing the PFR on the HST mockup 4
3 Orientation of Cartesian planes according to the AMTI load cell and its placement on the HST 5

Graphs

Graph **Page**

1 Force versus time graph – ingress (example) 6
2 Torque versus time graph – ingress (example) 7
3 Sustained forces: nominal versus reduced loads 11
4 Spike forces: nominal versus reduced load 12

Tables

Table		Page
1	Percent Difference Comparison Between Sustained Nominal and Most Efficient (Lowest Reduced-Load) Forces and Moments – Ingress	8
2	Percent Difference Comparison Between Sustained Nominal and Most Efficient (Lowest Reduced-Load) Forces and Moments – Egress	8
3	Percent Difference Comparison Between Spike Nominal and Most Efficient (Lowest Reduced-Load) Forces and Moments – Ingress	9
4	Percent Difference Comparison Between Spike Nominal and Most Efficient (Lowest Reduced-Load) Forces and Moments – Egress	10
5	Overall Sustained Force Values – Ingress	A-1
6	Overall Sustained Force Values – Egress	A-2
7	Overall Sustained Moment Values – Ingress	A-3
8	Overall Sustained Moment Values – Egress	A-4
9	Overall Spike Force Values – Ingress	A-5
10	Overall Spike Force Values – Egress	A-6
11	Overall Spike Moment Values – Ingress	A-7
12	Overall Spike Moment Values – Egress	A-8
13	Sustained Force and Moment Values Collected in Addition to Ingress/Egress Values	B-1
14	Spike Force and Moment Values Collected in Addition to Ingress/Egress Values	B-1

Acronyms

AMTI	Advanced Mechanical Technology, Inc.
EVA	extravehicular activity
FCSD	Flight Crew Support Division
GSFC	Goddard Space Flight Center
HST	Hubble Space Telescope
NASA	National Aeronautics and Space Administration
NBL	Neutral Buoyancy Laboratory
PFR	portable foot restraint
STS	space transport system

1.0 Introduction

1.1 Background

The Hubble Space Telescope (HST) was the first mission of NASA's Great Observatories Program. It was deployed from the Space Shuttle *Discovery* on April 25, 1990, as the primary payload of space transport system mission (STS)-31. It is a 2.4-m, f/24 Ritchey-Chretien telescope capable of performing observations in the visible, near-ultraviolet, and near-infrared (1150 A to 1 mm). The HST weighs 12 tons, and collects light with an 8-ft-diameter mirror. The attitude control and maneuvering is performed by four of six gyroscopes, or reaction wheels. In addition, the telescope contains fine guidance sensors, which are used to lock onto guide stars to reduce the spacecraft drift and increase the pointing accuracy. Two 2.4- × 12.1-m solar panels power the two onboard computers and scientific instruments aboard the HST. The solar panels also charge six nickel-hydrogen batteries that provide power to the spacecraft during the approximately 25 minutes during which the HST is within the Earth's shadow.

The HST was designed to last 15 years, with crewed service missions approximately every three years. The first service mission, STS-61, took place aboard the Space Shuttle *Endeavour* in 1993, with the main purpose to repair a faulty mirror that was blurring photographs downlinked from the telescope. The second service mission, STS-82, took place aboard the *Discovery* in February 1997.

In October 1999, the crew of STS-103 performed the third service mission to the HST aboard the *Discovery*. Although a servicing mission was planned for some time during late 1999 or early 2000, planners moved this mission up to repair failing HST gyroscopes. Three of the six gyroscopes had failed, and the loss of a fourth would cause a significant reduction in the telescope's ability to collect science data. This mission's primary purpose was to replace the right sensor units, each of which contains two gyroscopes. In addition, the crew would make improvements on the fine guidance sensors to use the most current technology and correct the optics problems.

To perform these tasks on the HST, the STS-103 crewmembers used a portable foot restraint (PFR) to anchor themselves to the HST in the zero-gravity environment. The solar arrays currently used on the telescope are second-generation, and therefore susceptible to loads placed on the telescope. The crew and their support in Mission Operations Directorate worried about the damage that the crew could possibly cause during ingress and egress of the PFR and by transferring loads to the solar arrays. The purpose of this study is to inform the crewmembers of the loads they are imparting on the HST, and train them to decrease these loads to a safer level. Minimizing these loads will significantly decrease the chance of crewmembers causing damage to the solar arrays while repairing the HST. A similar test was successfully done with the crew of STS-82, the second HST servicing mission.

1.2 Purposes of the Study

Specifically, this study proposed to:

1. Determine the level of forces and moments that each of the crewmembers selected to perform extravehicular activity (EVA) work on the HST during STS-103 applied to the outside of the HST during nominal ingress and egress of the PFR.
2. Determine the level of forces and moments applied to the outside of the HST as each crewmember attempted to decrease ingress and egress loads.
3. Evaluate the spike loading and sustained loading for applied forces and moments for each crewmember during each ingress and egress trial.

2.0 General Methodology

2.1 Subjects

Four astronaut subjects, the crewmembers qualified to perform an EVA on the STS-103 HST repair mission, participated in this study: Mike Foale, John Grunsfeld, Claude Nicollier, and Steve Smith.

2.2 Apparatus

The primary testing apparatus was a force plate setup built in the Anthropometry and Biomechanics Facility. This apparatus comprised a small waterproof AMTI (Advanced Mechanical Technology, Inc.,) load cell mounted on two L-shaped iron angles. A PFR socket connector connected this apparatus to the PFR socket on the HST. We placed an adapted PFR socket on top of the load cell for the actual PFR testing unit to be attached. See Figure 1 for the mounted force plate setup. The entire force plate apparatus was attached to a full-size HST mockup submerged in the Neutral Buoyancy Laboratory (NBL). We then attached a PFR to the apparatus for the crewmembers to use during ingress and egress.

The load cell amplifier was connected to a portable data acquisition computer. A LabVIEW-based data acquisition program collected data for this experiment. We collected data points for force and moment at a frequency of 100 Hz, or at a 0.01 time interval.

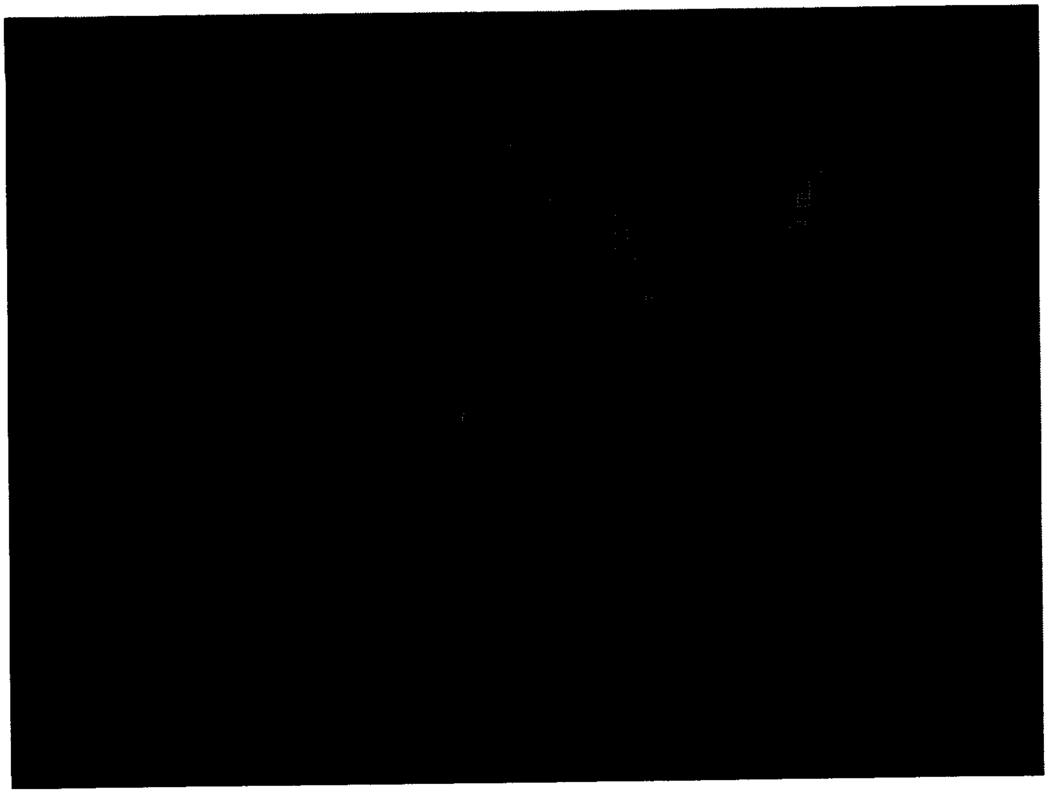


Figure 1: Load cell apparatus setup (attached to the HST mockup in the NBL).

2.3 Experimental Design

The testing took place at the NBL at the Sonny Carter Training Facility at Johnson Space Center. This training facility is the most accurate simulation of a zero-gravity outer space environment available for crew training.

The extravehicular mobility unit-suited crewmembers were submerged in the NBL and appropriately weighted to achieve neutral buoyancy.

We wanted to determine the loads the crewmembers applied to the HST during ingress and egress of the PFR. Each crewmember performed a nominal ingress and egress trial, and then attempted to minimize his input loads on further trials. The crewmembers received real-time verbal feedback of their input loads after each trial. The crewmembers were not attempting to reach any specific range of forces and moments; the experiment's goal was to provide each crewmember with his own load feedback whereby he could decrease the input load on future trials.

2.4 Experimental Procedure

The STS-103 crewmembers performed this experiment in conjunction with other training efforts at the NBL. Before the actual experiment, one of the NBL divers submerged the load cell apparatus and connected it to the HST mockup on the eleventh PFR socket. The data acquisition computer connected to the load cell amplifier was zeroed at this point. The diver then connected the PFR to the adapted socket on the load cell apparatus, and the computer was zeroed again. This completed the setup for the experiment.

Before beginning the experiment, each crewmember received a verbal briefing of the experiment's steps and the end goal of the project. Once the crewmember and the test director signaled, the data acquisition software was activated on the computer, and the crewmember was instructed to begin nominal ingress. See Figure 2 for PFR ingress. After successful data acquisition, the crewmember received real-time feedback about his ingress forces for that trial. The data acquisition software was then reactivated, and the crewmember was instructed to begin nominal egress. The crewmember then received real-time feedback about egress values. We repeated the testing, with the crewmembers altering different aspects of their ingress and egress procedure each time. Each crewmember completed a minimum of one nominal trial and three test trials of both ingress and egress. Additional trials were performed at the crewmember's request.

Figure 2: Crewmember ingressing the PFR on the HST mockup.

We also collected data at a variety of times while the crewmember was in the PFR. Although these data were not pertinent to this test, they are beneficial to put the maximum ingress and egress values into perspective. See Appendix B for these values.

Each of the four crewmembers participating in this study repeated this procedure.

2.5 Data Treatment

The raw data collected from the data acquisition computer appears in columnar text file format. These columns contain time, force, and moment data, respectively. Each individual trial produced a single file.

For the purposes of analysis, we opened each of the files into a Microsoft Excel spreadsheet format and analyzed them using spreadsheet tools.

2.6 Analysis

We analyzed the data from each of these trials for sustained and spike forces and moments. Spike loads and moments capture the sudden jerk motions transmitted to the HST. Sustained loads and moments capture the summed average of all nominal and jerk forces and moments exerted during ingress and egress. The sustained data will determine if the overall load was reduced due to training. The spike data will determine whether crewmembers were able to prevent any unnecessary impulses to the HST during ingress and egress.

The sustained force was defined as the average force during the given trial in a given direction. We calculated sustained force values based on absolute-value figures for each direction, according to Cartesian planes, and also calculated sustained resultant forces for each time interval. Figure 3 presents the orientation of the Cartesian planes according to the AMTI load cell and its placement on the HST mockup. We performed similar analyses to calculate a sustained resultant moment.

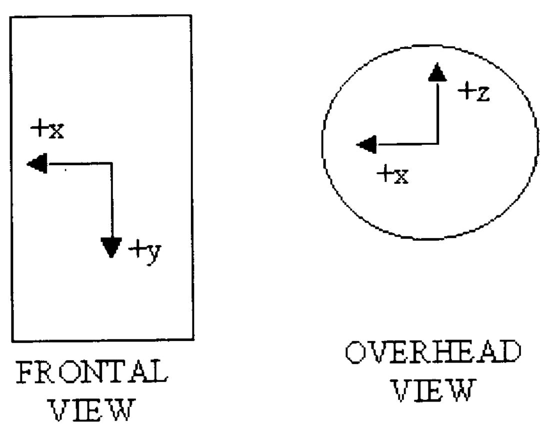
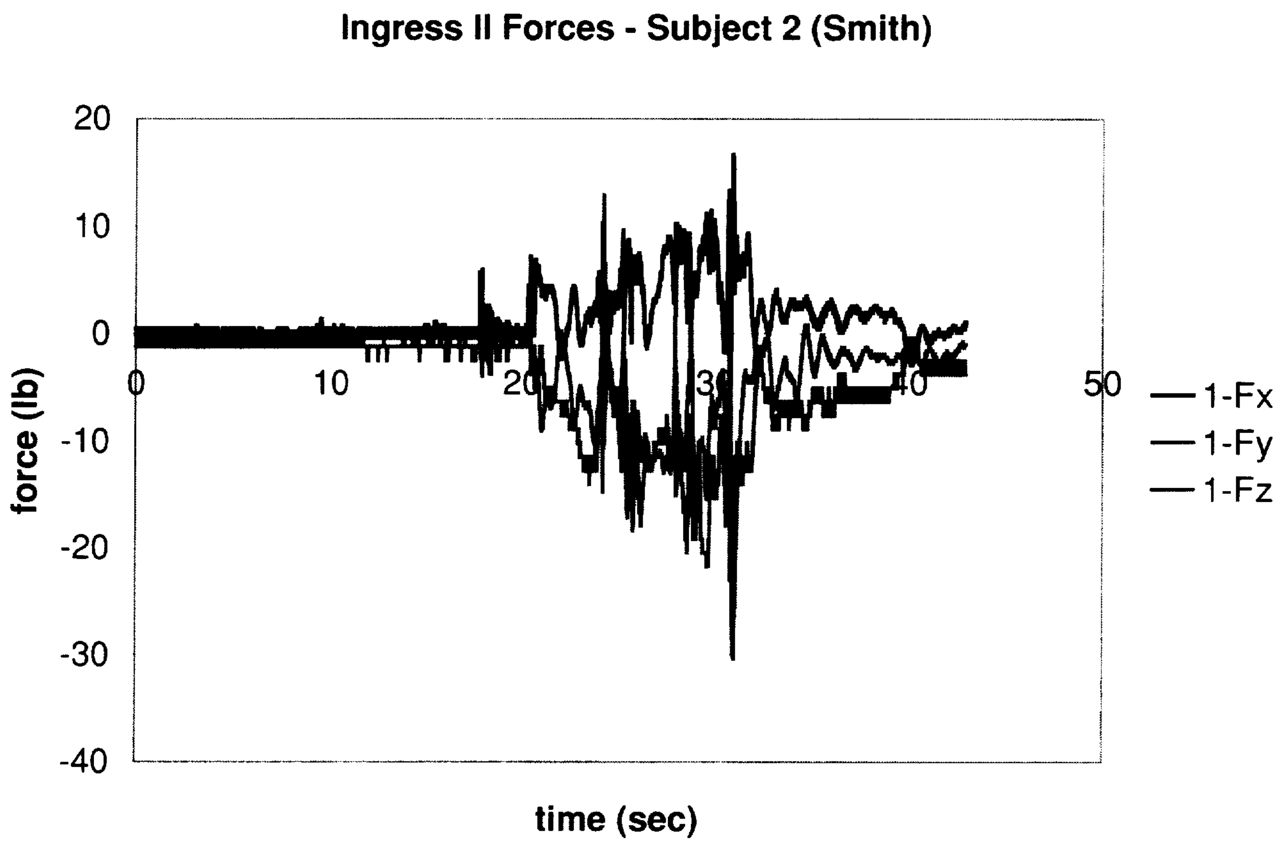


Figure 3: Orientation of Cartesian planes according to the AMTI load cell and its placement on the HST.

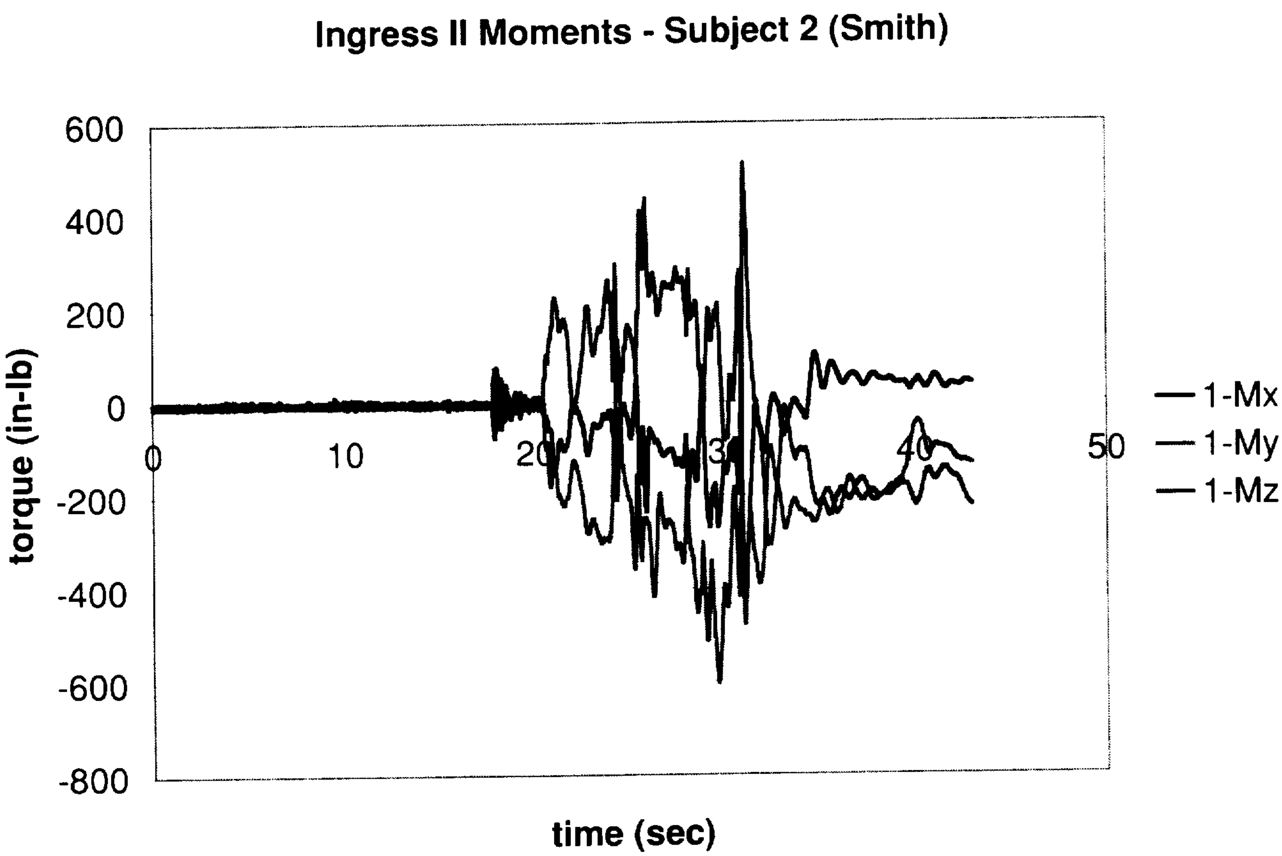
We calculated the spike force—defined as the maximum force exerted during the given trial in a given direction—in both the positive and negative direction for each of the Cartesian planes. We also calculated resultant forces for each time interval, and determined the resultant spike force. We performed similar analyses to calculate a resultant spike moment.

In addition, both force and moment graphs made of each trial compare input loads versus time. Graph 1 shows an example of a force versus time graph.



Graph 1: Force versus time graph – ingress (example).

Similar graphs generated show torque versus time, or moment data.



Graph 2: Torque versus time graph – ingress (example).

3.0 Results

3.1 Sustained Force and Moment Analysis

We performed the sustained force and moment analysis for every trial the four test subjects completed. We then performed a percentage comparison between the nominal and subsequent reduced-load trials for the forces and moments in each direction. See Appendix A for this comparison.

The charts below present a comparison between the nominal load and the most efficient, or lowest reduced load. The nominal sustained resultant force (Nom. Rf) is the average resultant force measured during the crewmembers' first attempt at ingress or egress. The lowest, or most efficient, reduced load (Min Rf) is the smallest sustained resultant force measured during one of the trials. We compare these two values below for ingress and egress and make a similar comparison between the nominal sustained resultant moment (Nom. Rm) and the lowest reduced-load (Min Rm) moment.

Table 1: Percent Difference Comparison Between Sustained Nominal and Most Efficient (Lowest Reduced-Load) Forces and Moments – Ingress

	Reduced-Load Force			Reduced-Load Moment		
Subject	**Nominal**	**Minimum**	**Diff.**	**Nominal**	**Minimum**	**Diff.**
1	15.1	12.0	20%	391.3	258.1	34%
2	7.9	8.4	-7%	231.8	201.6	13%
3	20.6	12.8	38%	547.9	354.9	35%
4	9.7	6.6	33%	242.9	180.4	26%
AVG.	**13.3**	**10.0**	**21%**	**353.5**	**248.8**	**27%**

Table 2: Percent Difference Comparison Between Sustained Nominal and Most Efficient (Lowest Reduced-Load) Forces and Moments – Egress

	Reduced-Load Force			Reduced-Load Moment		
Subject	**Nominal**	**Minimum**	**Diff.**	**Nominal**	**Minimum**	**Diff.**
1	8.7	6.5	26%	184.7	161.6	12%
2	7.7	11.1	-45%	216.7	313.5	-45%
3	15.2	15.5	-2%	279.3	388.9	-39%
4	10.5	8.6	18%	213.0	167.5	21%
AVG.	**10.5**	**10.4**	**-1%**	**223.4**	**257.9**	**-12%**

Note from these tables that the nominal loads during ingress were significantly higher than those during nominal egress. As a result of this training exercise, however, crewmembers were able to decrease their sustained resultant force and moment much more significantly during ingress than egress. During ingress, they were able to achieve a 21% decrease in force, and a 27% decrease in moment. During egress, however, two of the subjects were not able to decrease their forces or moments in any of their reduced-load trials from their nominal trial. This greatly affected the average percent difference for the four subjects. Although Subject 1 and Subject 4 were able to decrease their egress sustained resultant force through this training, the overall difference between the nominal and reduced-load force trials for egress was nearly zero. Moment data produced similar patterns, with the average reduced-load moment data actually greater than the average nominal moment data.

3.2 Spike Force and Moment Analysis

We also performed spike force and moment analysis for every trial the four test subjects completed. We then performed a percentage comparison between the nominal and reduced-load trials for the forces and moments in each direction. See Appendix A for this comparison.

The charts below show a comparison between the nominal load and the most efficient, or lowest reduced load. The nominal spike resultant force (Nom. Rf) is the maximum resultant force measured during the crewmembers' first attempt at ingress or egress. The lowest, or most efficient, reduced load (Min Rf) is the smallest maximum resultant force measured during one of the trials. For the Min Rf, we calculated the maximum resultant for each of the ingress and egress trials. The trial with the smallest maximum value provided the Min Rf. We compare the Nom Rf and Min Rf values for ingress and egress below, as well as the nominal sustained resultant moment (Nom. Rm) and the lowest reduced-load (Min Rm) moment.

Table 3: Percent Difference Comparison Between Spike Nominal and Most Efficient (Lowest Reduced-Load) Forces and Moments – Ingress

	Reduced-Load Force			Reduced-Load Moment		
Subject	**Nominal**	**Minimum**	**Diff.**	**Nominal**	**Minimum**	**Diff.**
1	68.0	38.9	43%	1580.3	928.6	41%
2	42.1	31.0	26%	840.9	544.3	35%
3	92.2	37.8	59%	2177.0	1170.6	46%
4	68.3	30.7	55%	1056.9	546.0	48%
AVG.	**67.6**	**34.6**	**46%**	**1413.8**	**797.4**	**43%**

Table 4: Percent Difference Comparison Between Spike Nominal and Most Efficient (Lowest Reduced-Load) Forces and Moments – Egress

	Reduced-Load Force			Reduced-Load Moment		
Subject	**Nominal**	**Minimum**	**Diff.**	**Nominal**	**Minimum**	**Diff.**
1	28.3	16.6	41%	611.8	334.1	45%
2	25.2	19.7	22%	756.7	590.6	22%
3	67.5	48.8	28%	1405.4	1288.8	8%
4	26.4	35.0	-33%	659.1	749.2	-14%
AVG.	**36.8**	**30.0**	**15%**	**858.3**	**740.6**	**15%**

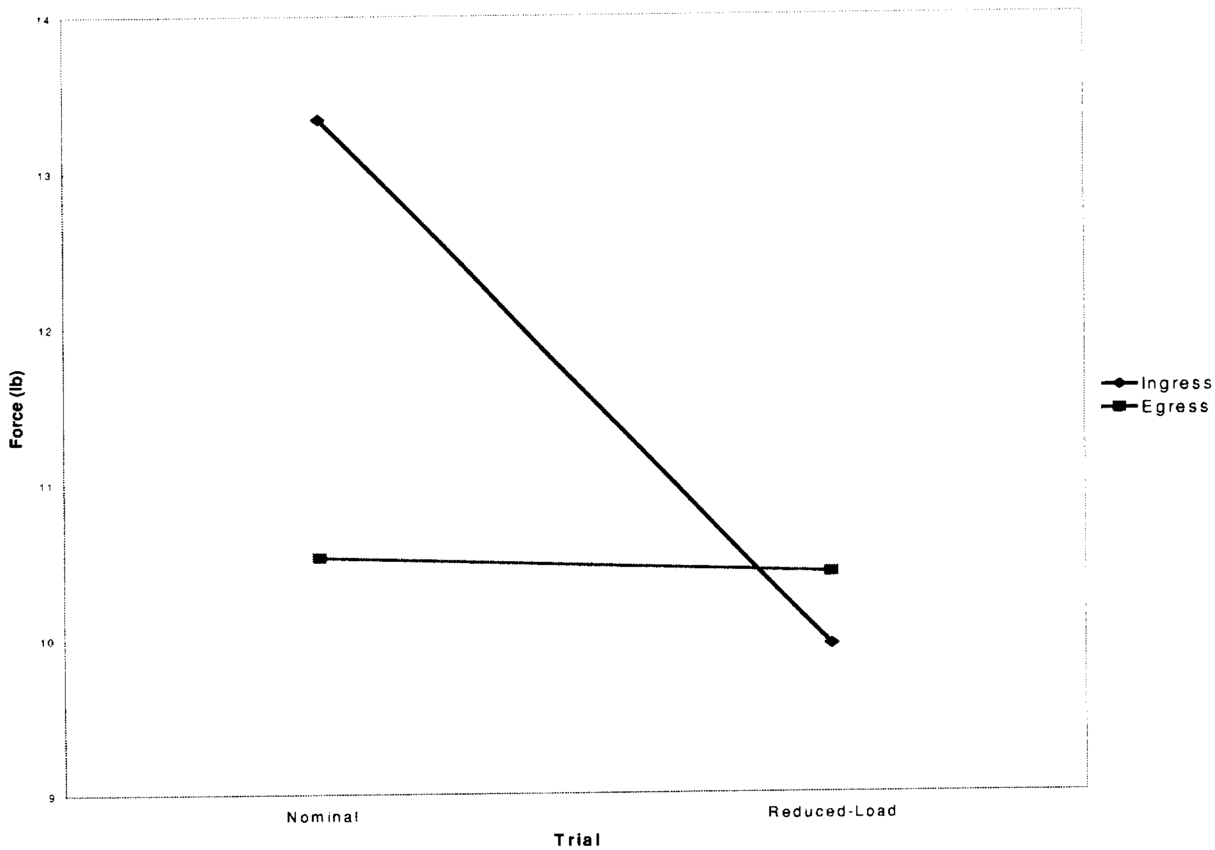
Similar to the sustained forces and moments, note that the nominal ingress loads were significantly greater than the nominal egress loads. However, this study provided training that enabled the crewmembers to decrease their spike resultant force and moment much more significantly during ingress than egress. During ingress, they were able to achieve a 46% decrease in force, and a 43% decrease in moment. Different from the sustained load analysis, most of the subjects were able to decrease their resultant input forces and moments through reduced-load trials during egress. Subject 4, however, continuously had higher resultant force and moment data for each of the reduced-load trials after his nominal trial during egress. The overall average percent difference for both spike resultant forces and moments was 15%.

Although the training was not able to substantially affect the crewmembers' ability to decrease input loads during egress, the overall forces and moments applied to the HST during egress were still lower than those applied during ingress.

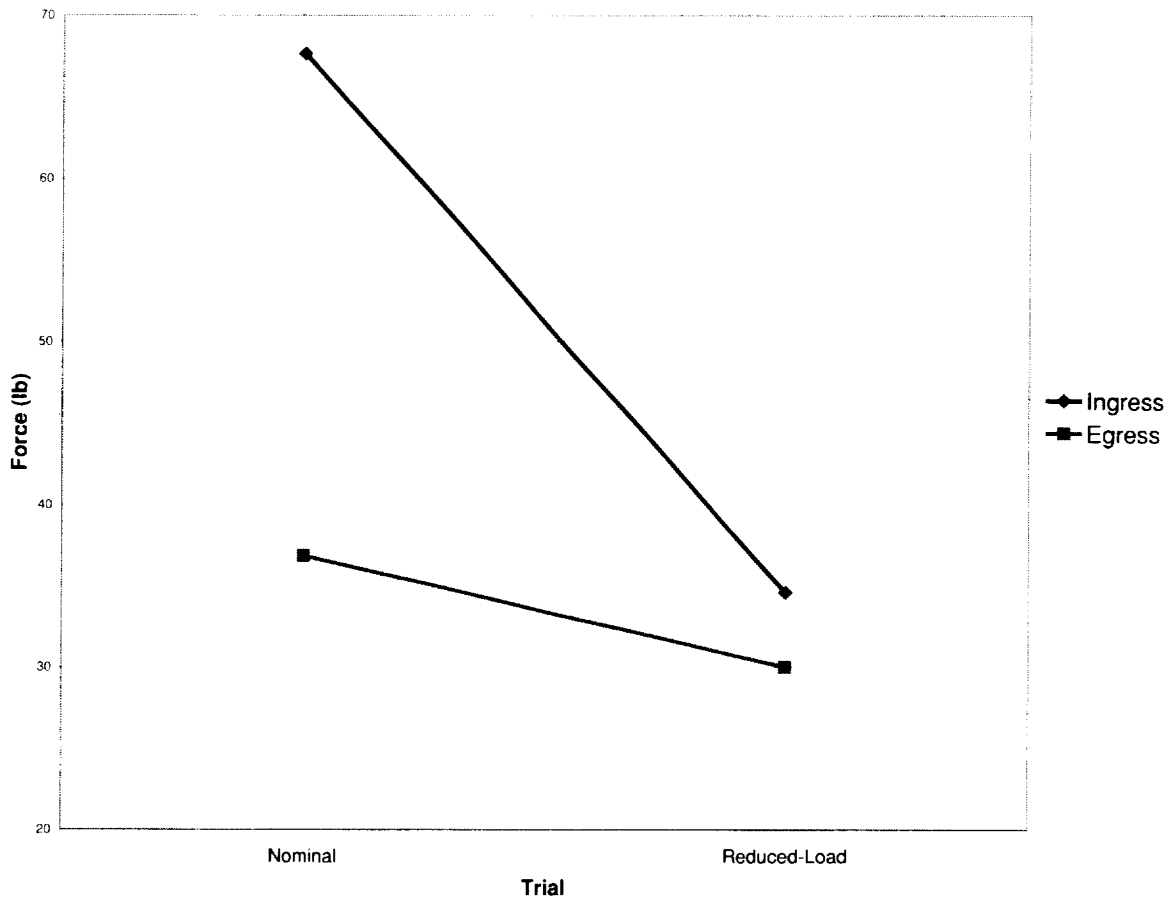
4.0 Discussion

The purpose of this study was to provide real-time training feedback for the crewmembers of STS-103 in an effort to decrease the loads applied to the HST during an EVA. As shown in both the sustained and spike data, the ingress loads were substantially higher than the egress loads during the nominal trial; therefore, it was more important during this exercise for the crewmembers to focus on decreasing ingress loads. This training was highly successful in providing information to the crewmembers that allowed them to adjust their ingress procedure and decrease their input loads. Surprisingly, the training was not nearly as effective during egress, as there was not a significant decrease in the either the forces or moments created during these trials. Despite the varying effectiveness of the training, however, the end spike forces and moments applied during egress remained lower than the end spike forces and moments applied during ingress. This was due, in part, to the constant trend of egress loads to be significantly lower than ingress loads, particularly during the nominal trial.

The graphs below show the decrease in force values between the nominal and reduced-load trials for ingress and egress. Graph 3 shows the values for sustained force, and Graph 4 shows the values for spike force. As displayed visually on these graphs, the decrease in force for ingress is much more significant than for egress, but the final values for both ingress and egress are similar.



Graph 3: Sustained forces: nominal versus reduced loads.



Graph 4: Spike forces: nominal versus reduced load.

5.0 Conclusion and Application

During their EVAs, the crew of STS-103 were required to ingress and egress the PFR on the HST. Through the verbal real-time feedback given during this test, the crew could now feel more comfortable and familiar with the loads applied to the HST during different body positions and scenarios. Analysis of the data gathered during this testing proves that the subjects were able to significantly reduce the loads that they were originally applying to the HST. Overall the training was substantially more successful for decreasing ingress loads, but the egress loads were relatively low even during the nominal trials. The end result ingress and egress loads for each of the subjects were very similar to one another.

The Mission Operations Directorate counterparts working with the crew of STS-103 felt that the reduced loads the crewmembers achieved were sufficient for the safe completion of each EVA during this HST repair mission. The data were transferred to another analysis group at Goddard

Space Flight Center for further analysis of the exact loads being put on the solar arrays of the HST during the crewmembers' ingress and egress.

Overall, this study was successful in providing real-time training feedback to the crewmembers, and well as producing data which showed the crewmembers' ability to adjust their input loads during ingress and egress of a PFR. Mission planners can use these data in future missions when concerned about the input loads to an object during EVA.

Appendix A: Comparison of Nominal Versus Reduced-Load Trials

Table 5: Overall Sustained Force Values – Ingress

This chart displays the directional and resultant sustained force (lb) values for each of the four test subjects during each of their trials ingressing the PFR.

Subject	Trial	Fx	Fy	Fz	R	Fx Diff	Fy Diff	Fz Diff	R Diff
1	Nominal	7.7	7.7	7.4	13.14	0%	0%	0%	0%
	Ingress II	6.2	7.1	7.4	12.00	19%	8%	-1%	9%
	Ingress III	5.1	6.8	6.9	10.98	34%	12%	6%	16%
	Ingress IV	6.0	7.5	7.3	12.10	21%	3%	0%	8%
2	Nominal	3.5	4.2	4.5	7.06	0%	0%	0%	0%
	Ingress II	2.9	4.9	7.0	9.03	19%	-17%	-57%	-28%
	Ingress III	3.4	4.4	5.3	7.66	3%	-4%	-18%	-9%
	Ingress IV	4.9	6.9	7.0	10.98	-39%	-65%	-57%	-56%
3	Nominal	7.9	10.8	12.9	18.58	0%	0%	0%	0%
	Ingress II	5.2	8.2	9.9	13.88	34%	24%	23%	25%
	Ingress III	4.7	6.1	8.9	11.77	41%	43%	31%	37%
	Ingress IV	5.5	7.3	10.8	14.16	30%	33%	16%	24%
	Ingress V	5.0	6.1	11.9	14.30	36%	43%	8%	23%
4	Nominal	4.0	5.3	5.5	8.64	0%	0%	0%	0%
	Ingress II	4.9	5.8	5.2	9.22	-24%	-9%	6%	-7%
	Ingress III	3.3	3.1	3.6	5.73	18%	42%	35%	34%
	Ingress IV	4.1	4.6	3.8	7.28	-4%	14%	31%	16%

Table 6: Overall Sustained Force Values – Egress

This chart displays the directional and resultant sustained force (lb) values for each of the four test subjects during each of their trials egressing the PFR.

Subject	Trial	Fx	Fy	Fz	R	Fx Diff	Fy Diff	Fz Diff	R Diff
1	Nominal	4.1	5.0	4.2	7.76	0%	0%	0%	0%
	Egress II	4.0	4.4	2.9	6.64	3%	12%	31%	14%
	Egress III	3.0	3.3	3.6	5.72	28%	34%	14%	26%
	Egress IV	3.4	4.6	3.8	6.85	19%	8%	11%	12%
2	Nominal	4.1	4.3	3.2	6.76	0%	0%	0%	0%
	Egress II	5.9	9.8	7.5	13.65	-44%	-129%	-131%	-102%
	Egress III	3.3	7.4	6.5	10.42	21%	-74%	-102%	-54%
	Egress IV	4.8	8.9	5.8	11.68	-16%	-109%	-79%	-73%
3	Nominal	8.4	8.6	5.7	13.24	0%	0%	0%	0%
	Egress II	5.6	8.2	10.6	14.54	33%	4%	-88%	-10%
	Egress III	7.2	11.9	13.5	19.38	14%	-39%	-139%	-46%
	Egress IV	4.9	11.7	13.4	18.44	41%	-36%	-137%	-39%
	Egress V	8.1	11.9	15.1	20.84	3%	-38%	-167%	-57%
4	Nominal	4.4	5.3	6.2	9.25	0%	0%	0%	0%
	Egress II	5.7	8.6	5.4	11.63	-28%	-63%	13%	-26%
	Egress III	6.2	6.5	5.8	10.69	-41%	-22%	6%	-16%
	Egress IV	4.1	5.0	4.2	7.73	6%	5%	32%	16%

Table 7: Overall Sustained Moment Values – Ingress

This chart displays the directional and resultant sustained moment (in-lb) values for each of the four test subjects during each of their trials ingressing the PFR.

Subject	Trial	Mx	My	Mz	R	Mx Diff	My Diff	Mz Diff	R Diff
1	Nominal	164.4	219.5	199.0	338.88	0%	0%	0%	0%
	Ingress II	149.9	215.6	131.9	293.89	9%	2%	34%	13%
	Ingress III	137.2	173.3	129.0	255.93	17%	21%	35%	24%
	Ingress IV	139.1	155.2	116.7	238.91	15%	29%	41%	30%
2	Nominal	60.9	144.2	145.2	213.50	0%	0%	0%	0%
	Ingress II	67.4	205.2	154.8	265.77	-11%	-42%	-7%	-24%
	Ingress III	54.8	133.0	113.8	183.41	10%	8%	22%	14%
	Ingress IV	95.1	199.3	152.1	268.16	-56%	-38%	-5%	-26%
3	Nominal	306.9	328.4	234.3	506.87	0%	0%	0%	0%
	Ingress II	218.9	265.3	146.6	373.90	29%	19%	37%	26%
	Ingress III	199.8	251.8	101.7	337.12	35%	23%	57%	33%
	Ingress IV	241.3	292.5	143.2	405.35	21%	11%	39%	20%
	Ingress V	129.5	412.9	169.2	464.59	58%	-26%	28%	8%
4	Nominal	146.7	102.1	120.8	215.70	0%	0%	0%	0%
	Ingress II	121.2	112.3	145.5	220.19	17%	-10%	-20%	-2%
	Ingress III	102.7	78.9	90.4	158.00	30%	23%	25%	27%
	Ingress IV	112.8	105.5	137.9	207.00	23%	-3%	-14%	4%

Table 8: Overall Sustained Moment Values – Egress

This chart displays the directional and resultant sustained moment (in-lb) values for each of the four test subjects during each of their trials egressing the PFR.

Subject	Trial	Mx	My	Mz	R	Mx Diff	My Diff	Mz Diff	R Diff
1	Nominal	70.0	94.9	115.5	165.10	0%	0%	0%	0%
	Egress II	56.0	98.5	81.8	139.73	20%	-4%	29%	15%
	Egress III	60.1	134.8	74.1	165.15	14%	-42%	36%	0%
	Egress IV	96.3	107.9	144.5	204.43	-38%	-14%	-25%	-24%
2	Nominal	100.6	113.1	134.0	202.19	0%	0%	0%	0%
	Egress II	168.8	217.3	208.3	345.07	-68%	-92%	-55%	-71%
	Egress III	61.5	205.9	191.5	287.89	39%	-82%	-43%	-42%
	Egress IV	74.0	183.0	291.2	351.77	27%	-62%	-117%	-74%
3	Nominal	138.3	145.0	159.7	256.24	0%	0%	0%	0%
	Egress II	181.5	231.6	222.0	368.63	-31%	-60%	-39%	-44%
	Egress III	237.3	335.8	291.3	503.98	-72%	-132%	-82%	-97%
	Egress IV	246.8	334.6	304.6	515.39	-78%	-131%	-91%	-101%
	Egress V	289.1	361.1	264.3	532.77	-109%	-149%	-66%	-108%
4	Nominal	124.0	121.9	63.5	185.10	0%	0%	0%	0%
	Egress II	207.3	160.9	189.2	323.50	-67%	-32%	-198%	-75%
	Egress III	174.9	312.2	215.0	417.49	-41%	-156%	-238%	-126%
	Egress IV	98.6	81.5	78.4	150.05	20%	33%	-23%	19%

Table 9: Overall Spike Force Values – Ingress

This chart displays the directional and resultant spike force (lb) values for each of the four test subjects during each of their trials ingressing the PFR.

Subject	Trial	Fx	Fy	Fz	R	Fx Diff	Fy Diff	Fz Diff	R Diff
1	Nominal	37.4	42.7	45.1	72.45	0%	0%	0%	0%
	Ingress II	34.3	31.3	42.1	62.67	8%	27%	7%	13%
	Ingress III	22.7	31.3	29.3	48.49	39%	27%	35%	33%
	Ingress IV	30.0	37.0	28.0	55.25	20%	13%	38%	24%
2	Nominal	25.3	20.8	39.8	51.52	0%	0%	0%	0%
	Ingress II	16.7	30.4	23.0	41.58	34%	-46%	42%	19%
	Ingress III	19.8	16.0	24.3	35.17	22%	23%	39%	32%
	Ingress IV	19.7	31.3	21.7	42.88	22%	-50%	45%	17%
3	Nominal	54.5	89.3	66.2	123.79	0%	0%	0%	0%
	Ingress II	33.4	31.7	35.5	58.13	39%	64%	46%	53%
	Ingress III	30.6	29.6	44.4	61.57	44%	67%	33%	50%
	Ingress IV	41.9	23.9	43.2	64.78	23%	73%	35%	48%
	Ingress V	24.8	26.1	30.3	47.07	55%	71%	54%	62%
4	Nominal	24.1	41.9	66.4	82.14	0%	0%	0%	0%
	Ingress II	25.2	21.6	52.3	61.92	-4%	48%	21%	25%
	Ingress III	20.9	15.9	29.7	39.65	13%	62%	55%	52%
	Ingress IV	15.7	28.1	29.2	43.49	35%	33%	56%	47%

Table 10: Overall Spike Force Values – Egress

This chart displays the directional and resultant spike force (lb) values for each of the four test subjects during each of their trials egressing the PFR.

Subject	Trial	Fx	Fy	Fz	R	Fx Diff	Fy Diff	Fz Diff	R Diff
1	Nominal	19.6	25.6	15.6	35.83	0%	0%	0%	0%
	Egress II	14.1	15.4	9.2	22.82	28%	40%	41%	36%
	Egress III	17.5	18.7	18.1	31.38	11%	27%	-16%	12%
	Egress IV	17.1	18.4	11.3	27.60	13%	28%	27%	23%
2	Nominal	12.7	22.6	16.6	30.76	0%	0%	0%	0%
	Egress II	27.4	28.3	24.3	46.28	-116%	-25%	-46%	-50%
	Egress III	9.9	15.4	14.0	23.07	22%	32%	15%	25%
	Egress IV	15.4	25.0	20.5	35.78	-22%	-11%	-23%	-16%
3	Nominal	54.5	57.8	26.5	83.75	0%	0%	0%	0%
	Egress II	27.6	32.6	34.2	54.71	49%	44%	-29%	35%
	Egress III	37.4	38.6	43.2	68.92	31%	33%	-63%	18%
	Egress IV	20.8	35.0	29.1	50.05	62%	39%	-10%	40%
	Egress V	25.1	45.5	34.2	62.22	54%	21%	-29%	26%
4	Nominal	18.6	24.5	22.0	37.88	0%	0%	0%	0%
	Egress II	24.4	41.0	40.0	62.28	-31%	-67%	-81%	-64%
	Egress III	34.2	35.0	39.5	62.91	-84%	-43%	-79%	-66%
	Egress IV	16.0	30.2	16.9	38.16	14%	-23%	23%	-1%

Table 11: Overall Spike Moment Values – Ingress

This chart displays the directional and resultant spike moment (in-lb) values for each of the four test subjects during each of their trials ingressing the PFR.

Subject	Trial	Mx	My	Mz	R	Mx Diff	My Diff	Mz Diff	R Diff
1	Nominal	1174.3	1293.3	787.2	1916.00	0%	0%	0%	0%
	Ingress II	635.1	916.6	541.4	1239.57	46%	29%	31%	35%
	Ingress III	517.0	829.4	477.1	1087.57	56%	36%	39%	43%
	Ingress IV	687.1	525.9	696.5	1110.78	41%	59%	12%	42%
2	Nominal	366.6	687.1	611.6	990.26	0%	0%	0%	0%
	Ingress II	475.4	603.3	512.6	923.48	-30%	12%	16%	7%
	Ingress III	223.2	394.1	541.5	705.88	39%	43%	11%	29%
	Ingress IV	433.7	516.1	562.1	877.79	-18%	25%	8%	11%
3	Nominal	1319.8	1600.9	1602.3	2621.51	0%	0%	0%	0%
	Ingress II	951.8	788.3	695.0	1417.92	28%	51%	57%	46%
	Ingress III	830.4	915.6	523.5	1342.33	37%	43%	67%	49%
	Ingress IV	614.0	1079.5	839.1	1498.80	53%	33%	48%	43%
	Ingress V	657.6	1019.7	743.4	1423.02	50%	36%	54%	46%
4	Nominal	1052.9	458.6	545.8	1271.52	0%	0%	0%	0%
	Ingress II	440.8	606.8	405.5	852.66	58%	-32%	26%	33%
	Ingress III	496.4	327.8	428.6	733.18	53%	29%	21%	42%
	Ingress IV	517.6	456.9	486.4	844.48	51%	0%	11%	34%

Table 12: Overall Spike Moment Values – Egress

This chart displays the directional and resultant spike moment (in-lb) values for each of the four test subjects during each of their trials egressing the PFR.

Subject	Trial	Mx	My	Mz	R	Mx Diff	My Diff	Mz Diff	R Diff
1	Nominal	403.7	398.6	451.7	725.16	0%	0%	0%	0%
	Egress II	187.6	271.0	293.3	441.20	54%	32%	35%	39%
	Egress III	217.7	572.7	354.3	707.75	46%	-44%	22%	2%
	Egress IV	387.5	307.6	450.0	668.77	4%	23%	0%	8%
2	Nominal	353.9	352.2	575.3	761.77	0%	0%	0%	0%
	Egress II	574.9	737.6	644.6	1135.82	-62%	-109%	-12%	-49%
	Egress III	182.7	418.5	459.8	648.04	48%	-19%	20%	15%
	Egress IV	283.3	453.4	753.5	923.87	20%	-29%	-31%	-21%
3	Nominal	875.5	601.6	992.0	1453.39	0%	0%	0%	0%
	Egress II	767.9	770.9	833.6	1370.68	12%	-28%	16%	6%
	Egress III	777.1	1044.6	916.1	1591.99	11%	-74%	8%	-10%
	Egress IV	668.4	814.5	912.8	1394.00	24%	-35%	8%	4%
	Egress V	845.4	859.8	912.8	1512.33	3%	-43%	8%	-4%
4	Nominal	557.7	451.7	262.0	764.00	0%	0%	0%	0%
	Egress II	1074.9	545.8	420.4	1276.72	-93%	-21%	-60%	-67%
	Egress III	916.4	905.0	601.8	1421.63	-64%	-100%	-130%	-86%
	Egress IV	624.8	327.8	285.6	761.20	-12%	27%	-9%	0%

Appendix B: Additional Force and Moment Data

Table 13: Sustained Force and Moment Values Collected in Addition to Ingress/Egress Values

Subj.	Description	Fx	Fy	Fz	Mx	My	Mz
1	Standing in PFR (quiescent forces)	1.1	0.8	2.1	15.8	26.2	136.7
	Working on connector	2.3	2.6	3.3	93.9	74.9	106.4
2	Standing in PFR (quiescent forces)	1.4	2.2	1.1	107.2	55.0	52.9
3	Standing in PFR (quiescent forces)	0.5	2.4	3.0	55.7	94.9	

Table 14: Spike Force and Moment Values Collected in Addition to Ingress/Egress Values

Subj.	Description	Fx	Fy	Fz	Mx	My	Mz
1	Standing in PFR (quiescent forces)	3.7	3.7	6.2	55.7	94.9	217.4
	Working on connector	14.7	14.2	16.5	341.2	491.1	372.5
2	Standing in PFR (quiescent forces)	5.7	7.9	5.1	192.2	176.1	130.7
3	Standing in PFR (quiescent forces)	2.8	5.4	4.7	192.2	176.1	130.7

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13. ABSTRACT *(Maximum 200 words)*
The Hubble Space Telescope (HST) was deployed from the Space Shuttle Discovery on April 25, 1990. It is capable of performing observations in the visible, near-ultraviolet, and near-infrared (1150 A to 1 mm). The HST weighs 12 tons, and collects light with an 8-ft-diameter mirror. The attitude control and maneuvering is performed by four of six gyroscopes, or reaction wheels. The HST contains fine guidance sensors that lock onto guide stars to reduce the spacecraft drift and increase the pointing accuracy.
The HST was designed to last 15 years, with crewed service missions approximately every three years. The first service mission, STS-61, took place in 1993. The second service mission took place in 1997. In 1999, the STS-103 crew performed the third service mission to the HST. This mission's purpose was to replace the right sensor units and make improvements on the fine guidance sensors. To perform these tasks on the HST, the STS-103 crewmembers used a portable foot restraint to anchor themselves to the HST in the zero-gravity environment. The solar arrays currently used on the telescope are second-generation, and therefore susceptible to loads placed on the telescope. The crew and Mission Operations Directorate worried about the damage that the crew could possibly cause during ingress and egress of the PFR and by transferring loads to the solar arrays. The purpose of this study is to inform the crewmembers of the loads they are imparting on the HST, and train them to decrease these loads to a safer level. Minimizing these loads will significantly decrease the chance of crewmembers causing damage to the solar arrays while repairing the HST.

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