Astronaut-Induced Disturbances to the Microgravity Environment of the *Mir* Space Station

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In preparation for the International Space Station, the Enhanced Dynamic Load Sensors Space Flight Experiment measured the forces and moments astronauts exerted on the *Mir* Space Station during their daily on-orbit activities to quantify the astronaut-induced disturbances to the microgravity environment during a long-duration space mission. An examination of video recordings of the astronauts moving in the modules and using the instrumented crew restraint and mobility load sensors led to the identification of several typical astronaut motions and the quantification of the associated forces and moments exerted on the spacecraft. For 2806 disturbances recorded by the foot restraints and hand-hold sensor, the highest force magnitude was 137 N. For about 96% of the time, the maximum force magnitude was below 60 N, and for about 99% of the time the maximum force magnitude was below 90 N. For 95% of the astronaut motions, the rms force level was below 9.0 N. It can be concluded that expected astronaut-induced loads from usual intravehicular activity are considerably less than previously thought and will not significantly disturb the microgravity environment.

Nomenclature

F_{mag}	=	force magnitude
$F_{mag,max}$	=	maximum force magnitude
F_{rms}	=	rms force
F_x, F_y, F_z	=	discrete force components
f_k	=	discrete Fourier transform frequency, k/L
$f_{sampling}$	=	sampling frequency
$I_r[f_k]$	=	periodogram
k	=	index variable
L	=	number of samples
M_{mag}	=	moment magnitude
$M_{mag,max}$	=	maximum moment magnitude
M_{rms}	=	rms moment
N_1	=	start index of the event
N_2	=	end index of the event
n	=	index variable
p	=	momentum
r	=	index variable ranging from 1 to R
$S_x[f_k]$	=	power spectral density estimate
U	=	energy in the window
$w[n]$	=	boxcar window function
$X_r[k]$	=	windowed fast Fourier transform
$x[n]$	=	discrete signal
$x_r[n]$	=	subsequences of signal $x[n]$

Introduction

THE first phase of the International Space Station (ISS) Program, known as the Shuttle-Mir Program, provided the United States the opportunity to send astronauts to the Russian space station *Mir* and conduct long-duration space flight experiments. The primary objective was to reduce the technical risk associated with the construction and operation of the ISS. Previous space stations and the shuttle have been used quite extensively for microgravity research, but the ISS is the first human-occupied space vehicle developed with system requirements specifying the microgravity environment. ISS requirements call for microgravity operations for 30-day durations where disturbing accelerations and vibrations are reduced and, if possible, eliminated.[1,2] Within the framework of the Shuttle-Mir Program, the Enhanced Dynamic Load Sensors (EDLS) experiment was conducted on *Mir* to quantify the disturbances to the microgravity environment caused by the presence of astronauts.

In designing the ISS, NASA and its contractors adopted maximum force levels recorded during the T-013 experiment on the *Skylab* orbital station in August of 1973 as the expected disturbance loads from astronaut motion. In this experiment an astronaut executed a set of prescribed activities (console operation, flapping arms, bowing, respiration exercises, etc.) while the reaction forces and moments were measured. The activities included "vigorous soaring" as a worst-case scenario, resulting in maximum loads close to 500 N and a maximum soaring velocity of approximately 1.9 m/s (Refs. 3–6). Exclusive reliance on the limited *Skylab* database was considered questionable for several reasons. The prescribed activities are not representative of routine astronaut motions, and maximum loads arose from vigorous soaring activities that were meant to measure a worst-case scenario. Furthermore, almost the entire data set was recorded in a single session lasting less than 80 min and stemming from a single astronaut subject. Two short additional sessions were conducted to address anomalies found after the first run. While a second astronaut participated in the soaring activities, data were recorded for only the primary subject.[3,4]

As a result, a more comprehensive measurement of astronaut intravehicular activity (IVA) loads was conducted on board the space shuttle during mission STS-62 (4–18 March 1994) under the Dynamic Load Sensors (DLS) investigation. The purpose of DLS was to quantify the forces and moments exerted by the astronauts on the orbiter middeck as they are going about their daily IVA.[7,8] The key hardware component of DLS was a set of three sensors: a touchpad, a foot restraint, and a handhold, similar in appearance to the restraint devices found in the orbiter that assist the crew in moving about the vehicle.[9] Data were recorded over a period of 67 h during flight days 7, 8, and 11 of the 14-day mission. Altogether 301 astronaut motions were found through a correlation with video footage recorded inside the middeck.

The EDLS experiment was proposed as a follow-on to DLS to expand the shuttle database by collecting astronaut reaction forces and moments on Russia's *Mir* space station. The limited volume of the space shuttle middeck coupled with the constant activity of

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numerous crewmembers limits the applicability of the data to IVA operations during a long-duration space flight. In addition, shuttle missions normally last about two weeks, and as a result there is insufficient time to observe long-term astronaut adaptation to weightlessness. A general-purpose acceleration measurement system, Space Acceleration Measurement System (SAMS),[10,11] flew on *Mir*, which provided the opportunity to correlate the astronaut-induced forces and moments with the accelerations experienced by a *Mir* module or the entire complex[12–14] and establish transfer functions.[15]

Historically, early investigations of astronaut-spacecraft interaction focused on how the spacecraft attitude would be perturbed by the astronauts and how to account for this disturbance source in the design of the vehicle attitude control system. This issue was first raised in 1962.[16] The question of astronaut motion potentially disturbing the microgravity environment specified for scientific experiments became a primary concern with the beginning of the space shuttle program and the launch of the Russian space station *Mir* in the 1980s.[8]

The low-frequency acceleration level experienced by a spacecraft in low Earth orbit is approximately 10^{-6} g. A level of $10^{-7} g$ can be achieved over a very small region near the center of mass. The accelerations experienced by the spacecraft are classified fundamentally as quasi-steady, oscillatory, or transient.[17]

Quasi-steady accelerations below 0.01 Hz are produced by external forces and kinematics.[1] Oscillatory accelerations (so-called "g-jitter") are generated within the spacecraft in the region 0.01 to 300 Hz. Sources of oscillatory disturbances are the mechanical motions of reciprocating pumps, fans, motors, gyros, and other devices, as well as the acoustic noise from fans, duct inlets/outlets, pumps, blowers, etc. Astronaut exercise activity on a treadmill or ergometer can also produce a strong periodic perturbation to the microgravity environment. Reaction forces and moments caused by astronaut motion are transient accelerations (i.e., spikes) and have typically a duration of less than a second and are nonperiodic. The energy in the disturbance is usually spread across a broad frequency range. The structural modes of the spacecraft are often excited by transient accelerations, and thus the dynamic response can last much longer than the actual perturbation.[17]

The sensitivity to the acceleration level and frequency varies greatly by type of experiment conducted in orbit. Although an overall acceleration level of less than $10^{-3} g$ is sufficient for some experiments, $10^{-8} g$ may be specified for others. To put the magnitude of disturbances produced by the astronauts into perspective, the Space Shuttle Orbiter's acceleratory environment shifts from microgravity to as much as $10^{-4} g$ during the firing of the vernier thrusters used for fine attitude control, resulting in a $10^{-2} g$ environment.[17] [The Space Shuttle Orbiter is equipped with six vernier thrusters (2 forward and 4 aft), which are used for fine attitude control. Each thruster is rated at 107 N (24 lb) of thrust.]

Methods

The EDLS experiment measured daily astronaut IVA activities and prescribed motions. In a daily IVA session data acquisition was activated, and the astronauts went about their scientific or operational activities. Whenever the EDLS sensors detected loads exceeding a specified minimum threshold level, data were recorded on the storage medium. One such recording is known as an *event*, which is understood as either a specific astronaut motion lasting from a few seconds to several minutes or several motions together without an interruption in the loading to a sensor. If a distinction of individual motions in the latter case is needed, they are referred to as *subevents*. In prescribed motion sessions the astronaut subjects used one or more foot restraint sensors while throwing a small ball of approximately 2 cm in diameter at a target 1.5–2 m away for repeated trials with their eyes either open or closed. The purpose of the throwing activity was to quantify the adaptation of human motor control in microgravity, and results are published elsewhere.[18]

EDLS data recording began during the NASA 2/Mir 21 mission and between 24 May and 30 August 1996; 33 EDLS data recording sessions were conducted of which 31 recorded daily activity and two recorded throwing activity of the three crew members. Because of an on-orbit failure of the data acquisition computer,[19] it was not
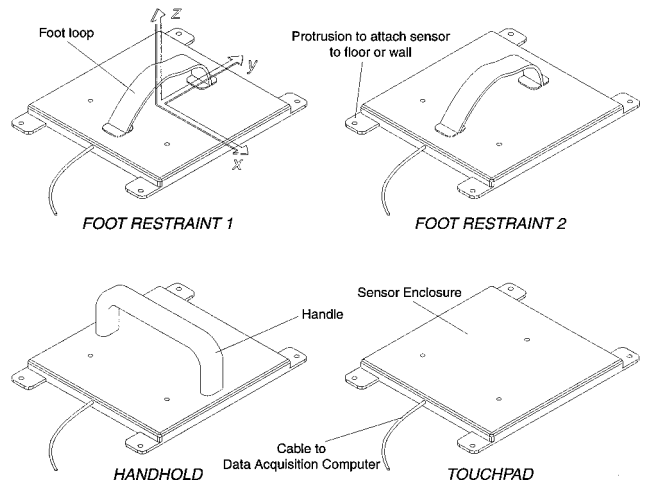

Fig. 1   Four EDLS sensors used onboard the Russian space station *Mir* to measure the reaction forces and moments produced by the astronauts.

possible to record EDLS data during the NASA 3/Mir 22 mission. A similar computer system on *Mir* for another experiment[20] was modified to act as a substitute data acquisition system with EDLS sessions resuming during the NASA 4/Mir 22/Mir 23 mission from 25 February to 9 May 1997. During this mission, 17 total sessions were conducted including 11 daily IVA activity sessions and six throwing sessions in which all *Mir* crew members participated. During each EDLS session, numerous crew members exerted IVA loads through the sensors. Following the collision of a *Progress* resupply vehicle with the *Spektr* module of *Mir* in June 1997 and the resulting difficulties on the station, astronauts were not available to perform additional EDLS sessions. The overall data recording time was 133 h during the 13 months EDLS was operating on *Mir*.

The key hardware component of the experiment was a set of four six-degree-of-freedom load sensors consisting of an instrumented handhold, touchpad, and two foot restraints. The sensors, shown in Fig. 1, were designed to provide the same functionality as the foot loops and hand rails built into the Space Shuttle Orbiter and the *Mir* orbital complex for astronaut use. The sensors are interchangeable. The touchpad's functionality was envisioned to be that of a flat surface the astronauts would use to push themselves off using either their hands or feet.

Each sensor, with dimensions of $24 \times 24 \times 2$ cm (without attachments), measures forces and torques with three custom-designed load cells (so-called flexures) in a circular arrangement placed 120 deg apart. Each load cell is equipped with two full Wheatstone strain gauge bridges consisting of four foil strain gauges. The sensor feeds the data acquisition computer with six signals that measure the deflection of the load cells. However, only three of the six signals from the touchpad sensor were actually sampled because of the limited number of channels on the A/D converter, so that only translational load information is available for that unit. The sensor enclosure and the flexures were designed for a microgravity full scale load of 400 N of force and 50 N · m of torque.[9] The unit housing the experiment computer, the signal conditioning system, the storage mechanism, and related components, is referred to as the Experiment Support Module (ESM). Because only 15 data acquisition channels were available, at any given time at most three sensors could be used resulting in two possible sensor configurations: 1) two foot restraint sensors and a touchpad sensor; and 2) a foot restraint sensor, a handhold sensor, and a touchpad sensor. In the case of the original ESM (used during NASA 2/Mir 21), sensor signals were sampled with a 13-bit A/D converter at a rate of 250 Hz. To avoid aliasing of the data, the signals were passed through an eighth-order low-pass Bessel filter with a corner frequency of 125 Hz. For the substitute ESM (used during NASA 4/Mir 22/Mir 23) A/D conversion was performed with 16-bit resolution and filtered with a fourth-order Bessel filter. The filter corner frequency and the sampling rate were the same for both systems.

To convert the load cell deflection signals measured by a sensor into an applied load, a 6×6 calibration matrix is required, which

converts the six measured voltages into three applied force and three applied moment components reflecting various properties of a sensor's specific enclosure, load cells, strain gauges, etc.[9] Following the 24 months on *Mir*, the sensors were recalibrated postflight with the substitute ESM once the hardware returned to the ground laboratory. The accuracy was within ±1.6% of the full-scale load for all four sensors.[19] Transformation into forces and moments was made with the preflight calibration matrix for the data recorded during the NASA 2/Mir 21 mission (with the original ESM) and the postflight calibration matrix for the data recorded during the NASA 4/Mir 22/Mir 23 mission (with the substitute ESM). All data were low-pass filtered with a digital three-pole elliptical filter with a cutoff frequency of 30 Hz.

Analysis

From the entire data set collected, individual events (i.e., individual astronaut motions) were identified. The force traces for a typical event recorded by the handhold sensor are shown in Fig. 2. In this example the event lasts from time index 0.4 s to time index 3.8 s. Each event was verified manually. Although this approach was time consuming, it ensured high-fidelity data analysis without the omission of "interesting" but valid data. Overall, 4819 events were identified with the breakdown by mission and sensor type provided in Table 1. These events are contained in 1257 data files and represent a total contact time of the astronauts with the sensors of 19.3 h. The data from the touchpad sensor are not considered further because it was used (unintended) as a foot restraint in a location underneath a standard *Mir* hand rail affixed to the floor. Forces were recorded from the EDLS touchpad, but no measure of the load applied to the *Mir* hand rail were possible in this configuration. The EDLS handhold

Table 1   Number of astronaut motions recorded

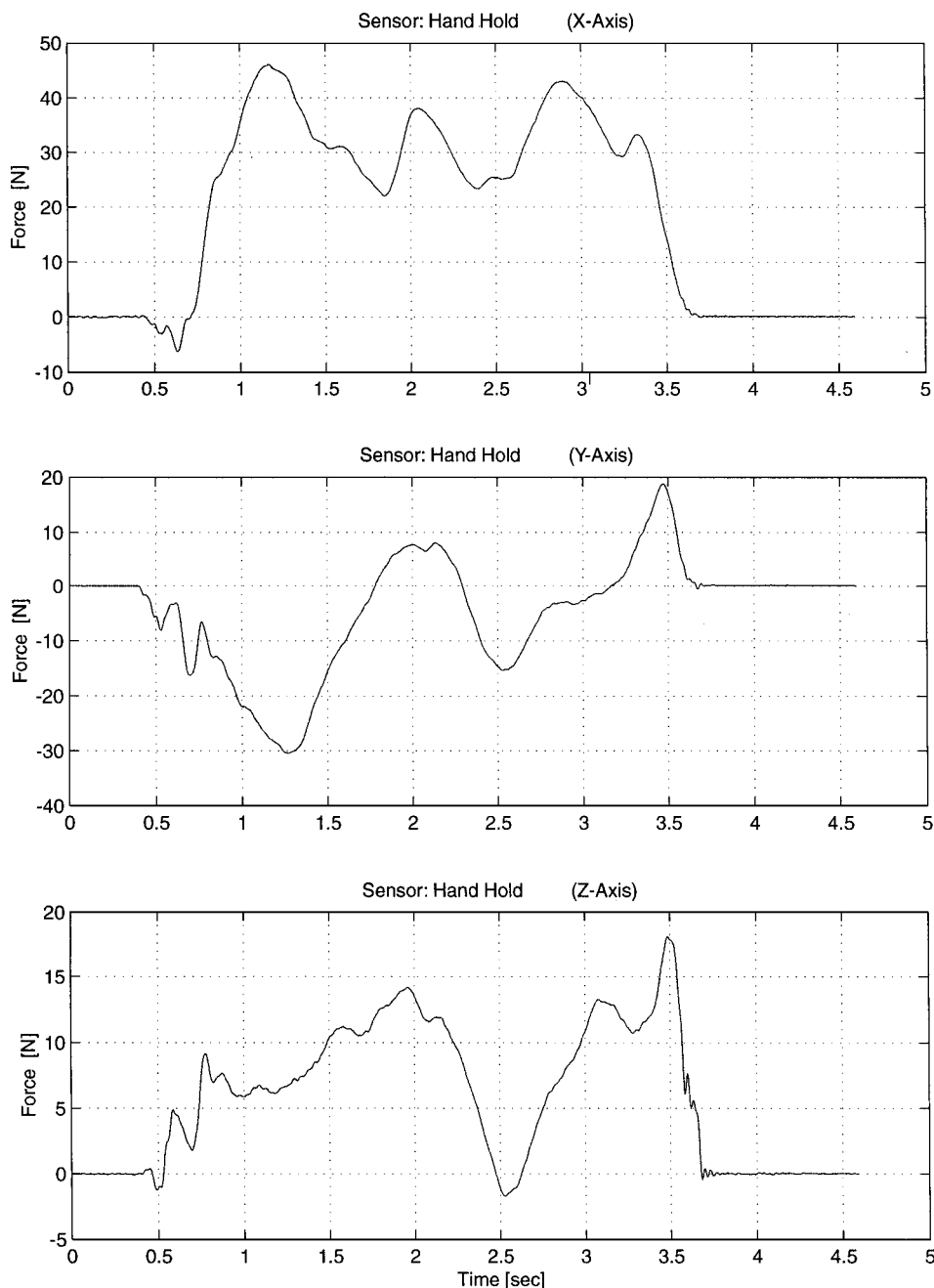| Type of sensor	NASA 2 mission	NASA 4 mission	Total
Foot restraint sensor 1	1817	326	2143
Foot restraint sensor 2	362	0	362
Handhold sensor	230	71	301
Touchpad sensor	1089	585	1674
Total	3498	982	4480

Fig. 2   Three force components for an event recorded by the handhold sensor on 10 July 1996 during the NASA 2/Mir 21 mission to *Mir*.

and foot restraints encompass restraint design slated for the ISS, and all data were analyzed.

The analysis was conducted in both the time and the frequency domain. As part of the former, the maximum force magnitude (i.e., the magnitude of the force vector) occurring in each event is computed:

$$F_{\mathrm{mag, max}} = \max_{N_1 \leq n \leq N_2} \left(\sqrt{F_x^2[n] + F_y^2[n] + F_z^2[n]} \right) \qquad (1)$$

The rms force is a measure of the average load:

$$F_{\mathrm{rms}} = \sqrt{\left(\sum_{n=N_1}^{N_2} \left(F_x^2[n] + F_y^2[n] + F_z^2[n] \right) \right) \Big/ N} \qquad (2)$$

Similarly, the maximum moment magnitude $M_{\mathrm{mag, max}}$ and rms moment M_{rms} are determined for each event. For some applications the largest force component rather than the force magnitude is of interest, and therefore the largest of three force components is determined and its axis noted. The total momentum transferred in each event is the force magnitude integrated over time, which was approximated with a trapezoidal rule so that the momentum p is determined by the formula

$$p = \frac{1}{f_{\mathrm{sampling}}} \sum_{n=N_1}^{N_2} F_{\mathrm{mag}}[n] \qquad (3)$$

In the frequency domain analysis the distribution of power in the astronaut-induced disturbance was computed. The power spectral density (PSD) was used to calculate the frequency below which 95% (two standard deviations) of the signal's energy in the event was contained. For the discrete signal $x[n]$ recorded by the sensors, the PSD was estimated using Welch's Method of Modified Periodograms.[21] The signal $x[n]$ is decomposed into subsequences $x_r[n]$ of length L samples such that r ranges from 1 to R. For each of the subsequences $x_r[n]$, the windowed fast Fourier transform $X_r[k]$ was computed as follows:

$$X_r[k] = \sum_{n=0}^{L-1} x_r[n] w[n] \exp\left(\frac{-j2\pi nk}{L} \right) \qquad (4)$$

The periodogram $I_r[f_k]$ is computed with the following expression:

$$I_r[f_k] = (1/U)|X_r[k]|^2 \qquad (5)$$

where U is calculated as follows:

$$U = \sum_{n=0}^{L-1} (w[n])^2 \qquad (6)$$

The PSD estimate $S_x[f_x]$ is then the weighted sum of the periodograms of each of the individual subsequences:

$$S_x[f_k] = \frac{1}{R} \sum_{r=1}^{R} I_r[f_k] \qquad (7)$$

With the PSD distribution known the trapezoidal method was used to estimate the area underneath the PSD curve and a second-order interpolation to obtain the frequency below which 95% of the energy content lies for the frequency analysis.

The EDLS experiment measured the disturbances to the microgravity environment caused by the astronauts for a wide variety of typical astronaut motions. For example, at the low end of the disturbance spectrum is the contact of the astronaut's toes with the sensors during a position/posture adjustment while using the foot restraint sensors. On the other end of the spectrum is a forceful push-off away from the sensors as the astronaut has completed the work and wants to move to another module. The number of occurrences of the first mentioned event is far larger than that of the second. For this reason the mean force/moment/momentum measurement is fairly low, but the standard deviation for all events is large given the wide magnitude range of events measured.

Results

The characteristic motions observed during EDLS were very similar to those seen during DLS, which have been described.[8] Figure 3 shows a histogram of the maximum force magnitudes recorded by the two foot restraint sensors and the handhold sensor in the EDLS experiment. For these 2806 events 96% of the time the maximum force magnitude was below 60 N, and about 99% of the time the maximum force magnitude was below 90 N. For each force magnitude interval the frequency of occurrence is provided. For example, about 17.4% of all events have a maximum force magnitude between 20 and 30 N. The highest force magnitude measured by the two foot restraint sensors was 137 N and for the handhold sensor 124 N. Assuming a total mass of 400 metric tons for the ISS at assembly complete, an applied force of 137 N would result in an acceleration of about $3.5 \times 10^{-5} g$ excluding dynamic effects of the
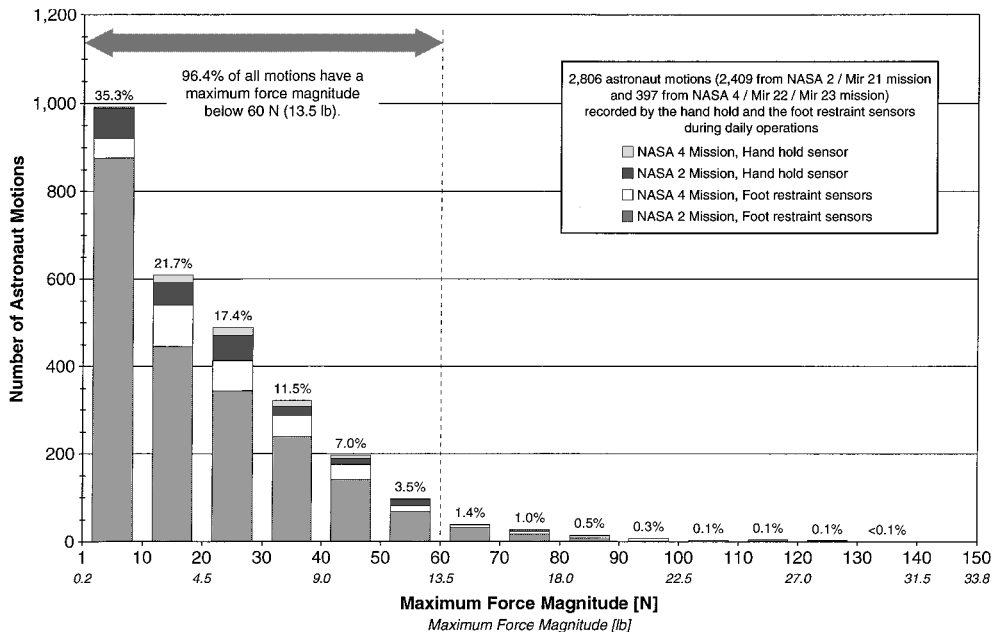

Fig. 3 Histogram of the maximum force magnitudes recorded by the two foot restraint sensors and the handhold sensor.

structure. The average force magnitude recorded was 21 ± 18 N, and the median force magnitude was 16 N. The normal or z component of the applied force was the largest of the three components 59% of the time. The duration of events ranged from 0.1 to 557.2 s with an average of 15.0 ± 36.1 and a median value of 3.7. The distribution of the rms force values for the events is shown in Fig. 4. The largest rms force was 35.6 N, the average value was 2.4 ± 3.1 N, and the median value 1.3 N. For 96% of the astronaut motions, the rms force value was below 9.0 N.

A histogram of the maximum moment magnitudes is shown in Fig. 5. The largest moment was measured by foot restraint 1 with a value of 18.3 N · m. The average moment was 1.9 ± 2.2 N · m. The distribution of the moment magnitude for the 2806 events was such that 96% of all events had a maximum moment magnitude below 7 N · m. The average momentum imparted by the astronauts on the station was 83.1 ± 228.2 kg · m/s in the 2806 events. An analysis of the power spectral density distribution in the events showed that on average 95% of the power was contained below a frequency of 2.6 ± 2.4 Hz. The results of the statistical analysis of the astronaut motions are summarized in Table 2.

Table 2 Summary of the results from the statistical analysis of the astronaut motions

| Measurement	Foot restraint 1 and 2 sensors	Handhold sensor	Foot restraint 1, foot restraint 2, handhold sensors
Force magnitude			
Maximum value, N	136.6	124.0	136.6
Average value, N	20.7 ± 18.1	25.1 ± 20.5	21.1 ± 18.4
Median value, N	15.6	21.7	16.2
Moment magnitude			
Maximum value, N · m	18.31	14.24	18.31
Average value, N · m	1.83 ± 2.10	2.56 ± 2.47	1.91 ± 2.15
Median value, N · m	1.08	1.82	1.13
Rms force			
Maximum value, N	35.6	33.5	35.6
Average value, N	2.3 ± 2.9	3.8 ± 4.5	2.4 ± 3.1
Median value, N	1.2	2.7	1.3
Average duration, s	16.3	4.9	15.0
Average momentum transfer, kg · m/s	87.3	47.5	83.1
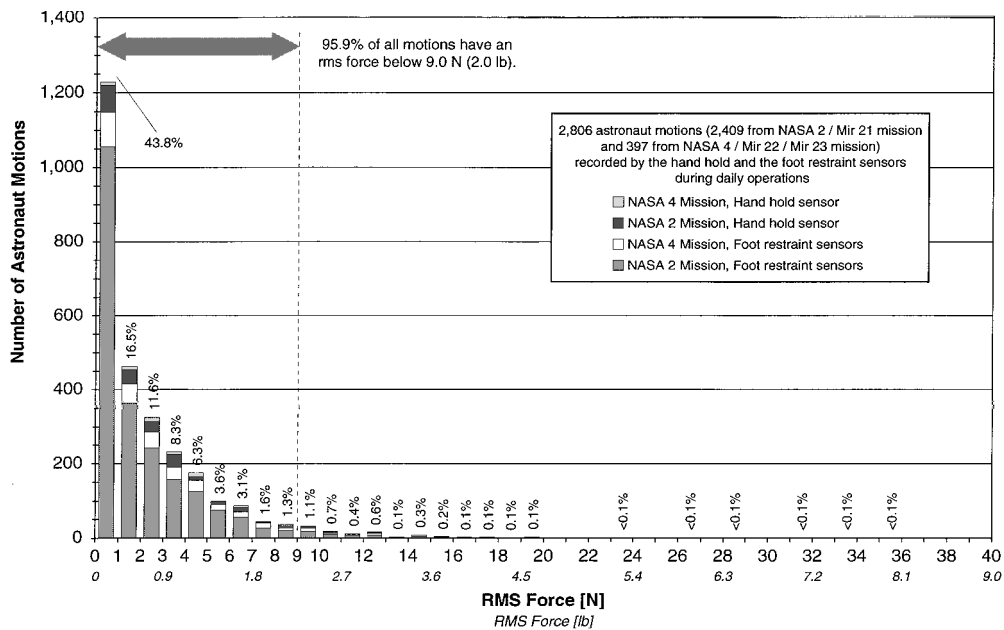
Fig. 4 Histogram of the rms forces recorded by the two foot restraint sensors and the handhold sensor.
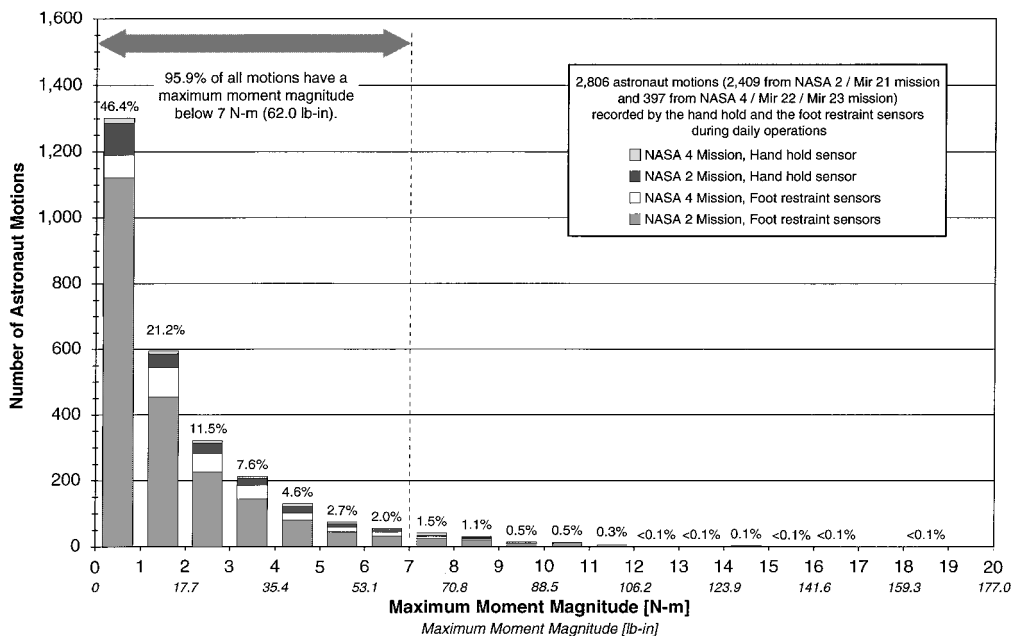

Fig. 5 Histogram of the maximum moment magnitudes recorded by the two foot restraint sensors and the handhold sensor.

As the astronauts adapt to the microgravity environment in orbit during the first several weeks in space, it is expected that their motions decrease in velocity and magnitude. Because of the high operational demand on the crew during the spacecraft hand-over time and shortly thereafter, the astronauts recorded EDLS sessions after the first three weeks in space. Overall, the EDLS experiment did not observe any significant change in the average force level observed.

Conclusions

The EDLS experiment produced the first comprehensive description of IVA astronaut motions and quantified astronaut-induced loads in microgravity for long-duration space flight. Living on orbit, astronauts adapt to microgravity resulting in finely controlled motions, slow velocities, and low force levels. Astronaut-induced loads expected on the ISS from usual IVA are considerably smaller than previously thought and will not significantly disturb the ISS microgravity environment.

Current specifications for ISS microgravity operations do not include detailed effects of crew activity, but do include effects caused by usage of crew equipment, such as the operation of exercise devices and latched or hinged enclosures. The specifications state only that "crew effects will be mitigated to the extent possible."[2] The magnitude of astronaut-induced loads is difficult to infer from visual observation but active sensing with real-time feedback of the applied force and torque levels could be a valuable tool for the astronauts during microgravity operations.

Acknowledgments

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