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ACCURACY AND REPEATABILITY OF THE STANDARD AUTOMATED MASS PROPERTIES MEASUREMENT SYSTEM

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FOR THE COMMANDER

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The injury potential to pilots may be significantly affected by the inertial properties of helmet-mounted equipment. In order to accurately assess the effects of such equipment, reliable measurements of mass, center of mass, and mass moments of inertia must be obtained.

The Manikin Testing Laboratory at the Armstrong Laboratory has developed the Standard Automated Mass Properties (STAMP) system to experimentally determine the inertial properties of various objects. It is necessary to quantitatively determine the accuracy and repeatability of measurements obtained by the STAMP system to confidently use these values in analytical models, in correlations between observed empirical response and the inertial properties of head-mounted equipment, and in determining compliance with inertial properties specifications of new helmet-mounted systems.

A reliability assessment of the system was made using rectangular aluminum blocks, an HGU-26/P helmet, and a manikin head. The repeatability of the center of gravity and moment of inertia measurements was obtained by testing the same block

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ten times. The accuracy of the system was analyzed by comparing experimental values of seven blocks of various mass to properties determined analytically. Finally, the repeatability of measuring a helmet and a helmet on a manikin head was examined.

It was determined that the center of gravity of objects such as head encumbrance devices, manikin segments, and cadaver sections can be located accurately to at least 1.7 mm. The mass moments of inertia are accurate to within 1% on a large mass properties instrument, and to within 0.6% on a small mass properties instrument. Measurements of long, slender objects and those under 2 kg may result in slightly larger errors. These results indicate that the inertial values obtained from the STAMP process will introduce negligible error when used for biodynamic applications.

PREFACE

The project was conducted by the Vulnerability Assessment Branch, Biodynamics and Biocommunications Division, Crew Systems Directorate, Armstrong Laboratory (AL/CFBV) and supported by Systems Research Laboratories, Inc. (SRL), 2800 Indian Ripple Road, Dayton, Ohio. The tests were conducted in the Manikin Testing Laboratory (MTL), Building 824, Area B, Wright-Patterson Air Force Base, Ohio.

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INTRODUCTION

The response of the human body to harsh dynamic environments is dependent on the inertial properties of the body and any encumbering equipment. The injury potential for individuals subjected to impact is often determined by the mass, center of gravity, and moments of inertia of the various body segments. Many new helmet-mounted systems are being developed by the Air Force which can drastically alter the net inertial properties of the aircrew member's head. A prior knowledge of the mass, center of gravity, and moments of inertia of added equipment can be used to model human dynamic response, and to help predict the extent of injury potential from the use of such equipment.

A system has been developed at the Manikin Testing Laboratory (MTL) to experimentally determine the inertial properties of any given object. The Standard Automated Mass Properties (STAMP) measurement system utilizes a digital scale, fulcrum balance, and an inverted torsional pendulum to determine mass, center of gravity, and moments of inertia, respectively. These properties are often used to predict human dynamic response by utilizing such tools as the Articulated Total Body (ATB) model (Obergefell et al, 1988) and the Finite Element Head-Spine model (HSM) (Belytschko et al, 1976).

If the predictive model is to be trusted, one must know how accurately the inertial properties have been measured. Although the STAMP process has been largely automated, there is still some dependence on the human operator. Other sources of error may be present in the equipment itself or in the procedures that are used during the STAMP process. These errors must be identified and quantified in order to define the degree of accuracy of the inertial properties determined by the STAMP procedure.

Program Summary

In this investigation, the errors in the STAMP system were analyzed through four test cells. The first two cells measured the properties of rectangular aluminum blocks, the third cell investigated an HGU-26/P helmet, and the fourth cell examined an HGU-26/P helmet on a large Hybrid II manikin head. In Cell A, a 7.081 kg block was measured ten times on the fulcrum balance to determine the center of gravity. Then the moment of inertia about the x-axis was measured ten consecutive times on the mass properties instrument without moving the block on the table. The moments about the y, z, x-y, y-z, and x-z axes were similarly measured. These tests provided a method for determining the repeatability of the system equipment. The second part of Cell A also tested the 7.08 kg block, but in this case the block was repositioned after each measurement. This addressed the variability due to placing the test specimen on the STAMP equipment.

The accuracy of the measuring system was tested in Cell B. The inertial properties of seven rectangular blocks were measured using the STAMP system, and the results were compared to values derived analytically. The differences in the two were compared to the error involved in measuring the geometry of the blocks and to the variability determined in Cell A.

The repeatability of measuring an irregularly shaped object using a mounting box was studied in Cell C. A single HGU-26/P helmet with double visor was placed in the standard helmet mounting box used in the MTL, and the inertial properties were measured. Then the helmet was removed from the mounting box, repositioned, and measured again. This process was performed ten times.

Cell D studied the error involved in positioning the helmet on the manikin head. A "mock-up" consists of a manikin head wearing a helmet and any other head-encumbrance devices. A single mock-up was positioned in the mounting box, and the center of gravity and moments of inertia were measured. Then the helmet was taken off the manikin head, a new mock-up was created, and the inertial properties were measured again. Using this method, a total of ten mock-ups were tested.

The four test cells were used to quantitatively determine the repeatability and accuracy of the STAMP system. The specifics of the STAMP procedures and the equipment it uses must be understood before analyzing its errors. A detailed explanation of the system is given first, followed by a more detailed description of the test series designed to determine the STAMP repeatability and accuracy. A discussion of the results of the experiments is offered, ending with conclusions rendered by the test series.

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THE STAMP MEASUREMENT SYSTEM

The STAMP system consists of a digital scale, a knife-edge fulcrum balance, two torsional pendulum mass properties instruments, several mounting boxes, a three-dimensional digitizer, a microcomputer, and detailed testing procedures. Error may be introduced in any component of this system. The STAMP system and accompanying procedures have been described by Miller, et al. (1991) and by Albery and Lephart (1989).

Equipment

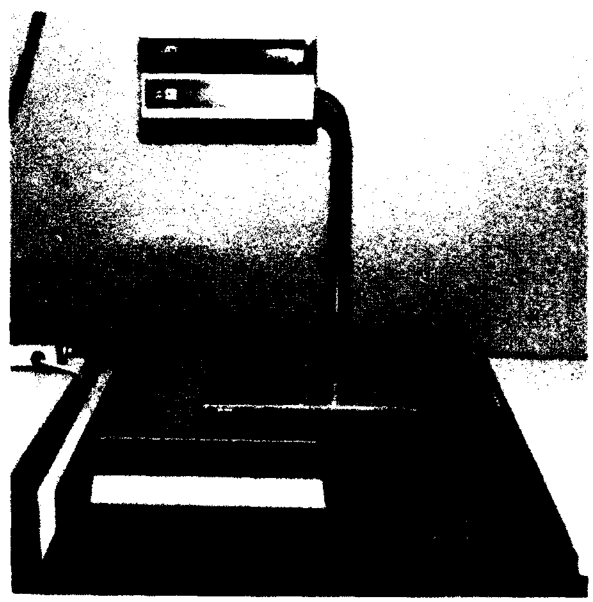

Figure 1. Fulcrum balance and A.N.D. Electronic Scale.

The mass of a test object is measured by an A.N.D. Electronic Scale, Model EP-40KA which is accurate to 0.002 lbs. As shown in Figure 1, a fulcrum balance is used in conjunction with the scale to determine the center of gravity. The MTL utilizes two Space Electronics mass properties instruments to determine the moments of inertia. Model XR-50, or the small mass properties instrument, is shown in Figure 2 and is recommended for weights of 1 to 50 pounds. The large mass properties instrument, Model KGR-9845/8945, is recommended for weights of 10 to 450 pounds and is shown in Figure 3. Each of the mass properties instruments utilizes an internal inverted torsional pendulum to determine the period of rotational oscillation for a given object. The square of this period is directly proportional to the moment of inertia of the test object about the table's central vertical axis.

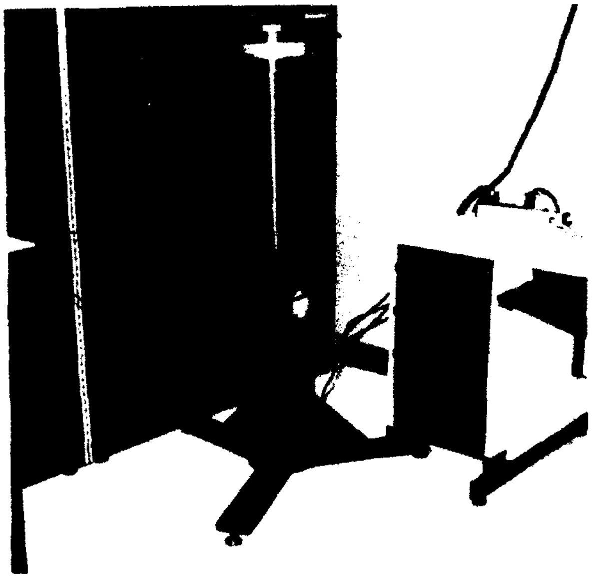

Figure 2. Small Mass Properties Instrument.

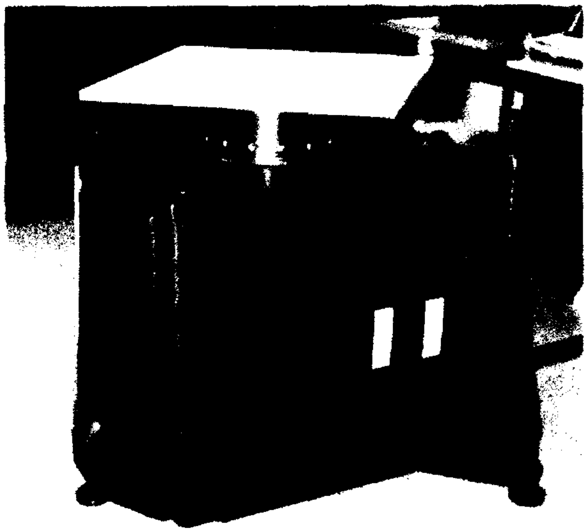

Figure 3. Large Mass Properties Instrument.

As shown in Figure 4, the test object is secured to a three-sided, orthogonal balsa wood box. This mounting box is used to define a known, constant coordinate system. A second balsa wood fixture called a jig is used to place the composite object on a 45 degree angle from the horizontal table surface. This provides the off-axis, or cross product moments of inertia. A manikin head in a mounting box and in the jig is shown in Figure 5.

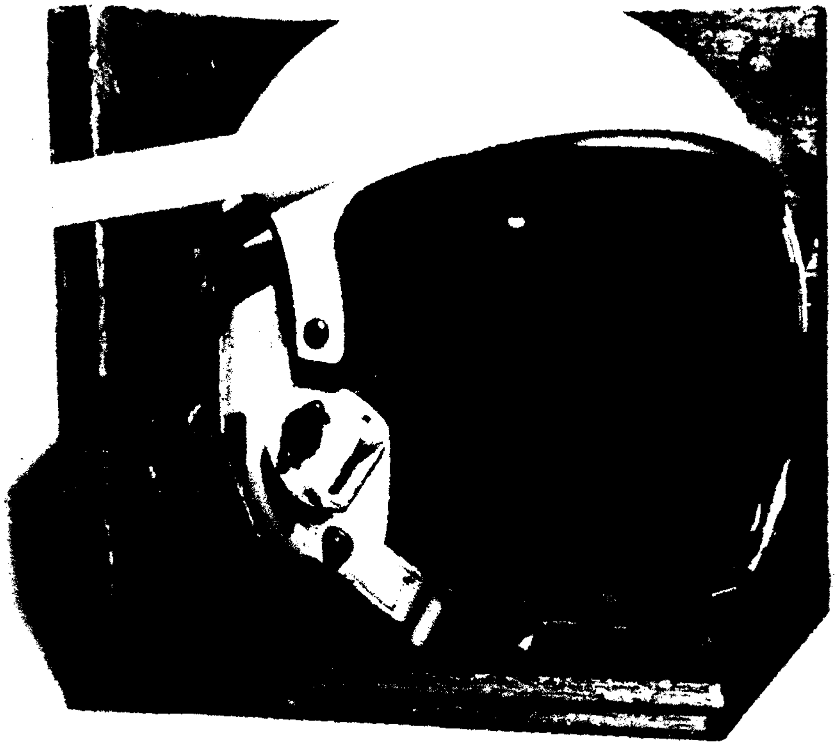

Figure 4. Helmet in mounting box.

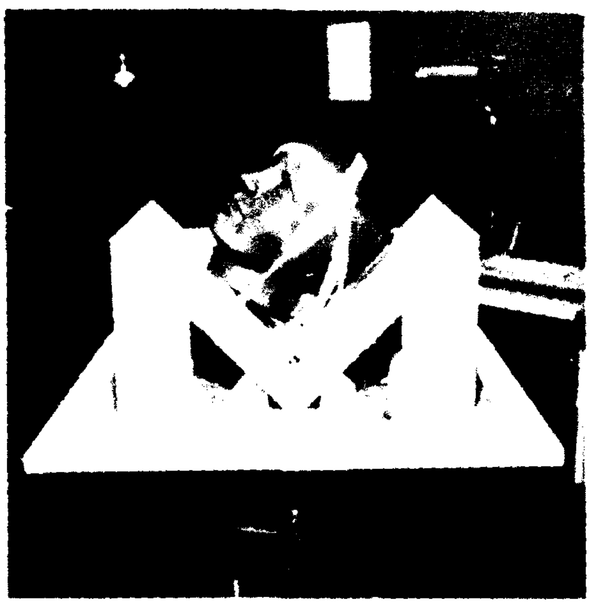

Figure 5. Manikin head and mounting box placed in jig.

Several pieces of equipment serve to analyze the data obtained from the scale, balance, and mass properties instruments. The Faro Medical Technologies system, shown in Figure 6, is a three dimensional digitizer which can locate any point in space to within 0.1 mm. It is used to establish coordinate systems for the box and for the test object. A microcomputer and in-house software are used to analyze the data obtained from the tests.

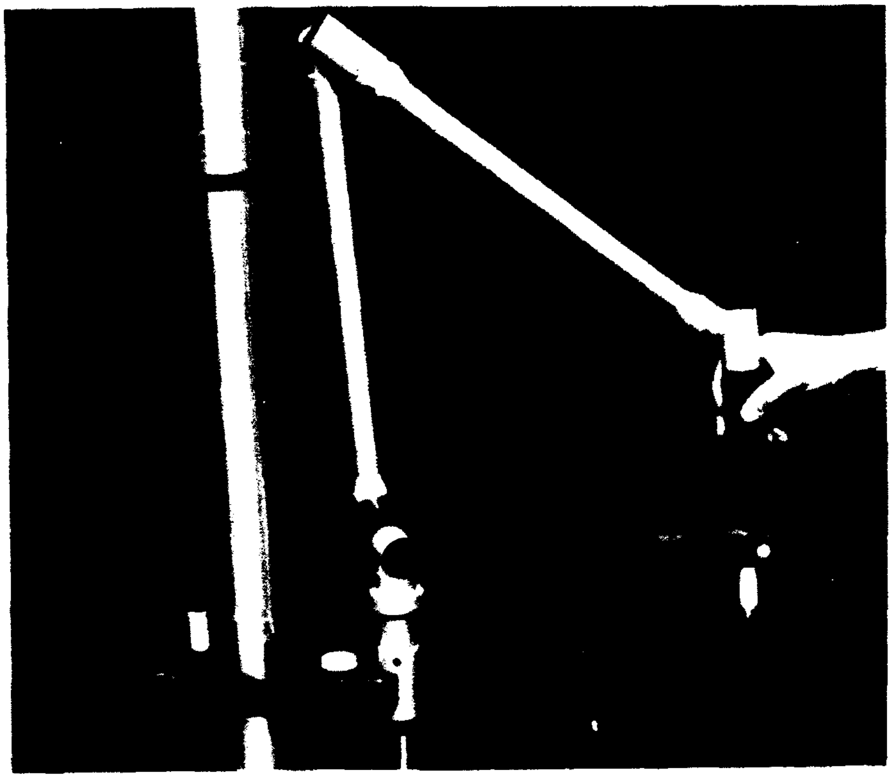

Figure 6. Faro Medical Technologies System.

STAMP Procedures

Typically, test objects are irregular in shape and must be secured in the mounting box using velcro straps and/or masking tape. Each edge of the box is assigned an axis direction, establishing an orthogonal box coordinate system. The inertial properties of the balsa wood fixtures have been determined previously, and are subtracted from those of the composite specimen. This yields the properties of the test object alone.

The mass of the composite is measured using the A.N.D. Electronic Scale. Then the center of gravity is found by placing the edge of the box against the chock of the fulcrum balance, as shown in Figure 7. By performing this procedure with all three edges of the mounting box, it is possible to determine the three-dimensional center of gravity of the composite object. The STAMP software then subtracts the contribution of the mounting box and determines the center of gravity of the test object, measured in the box coordinate system.

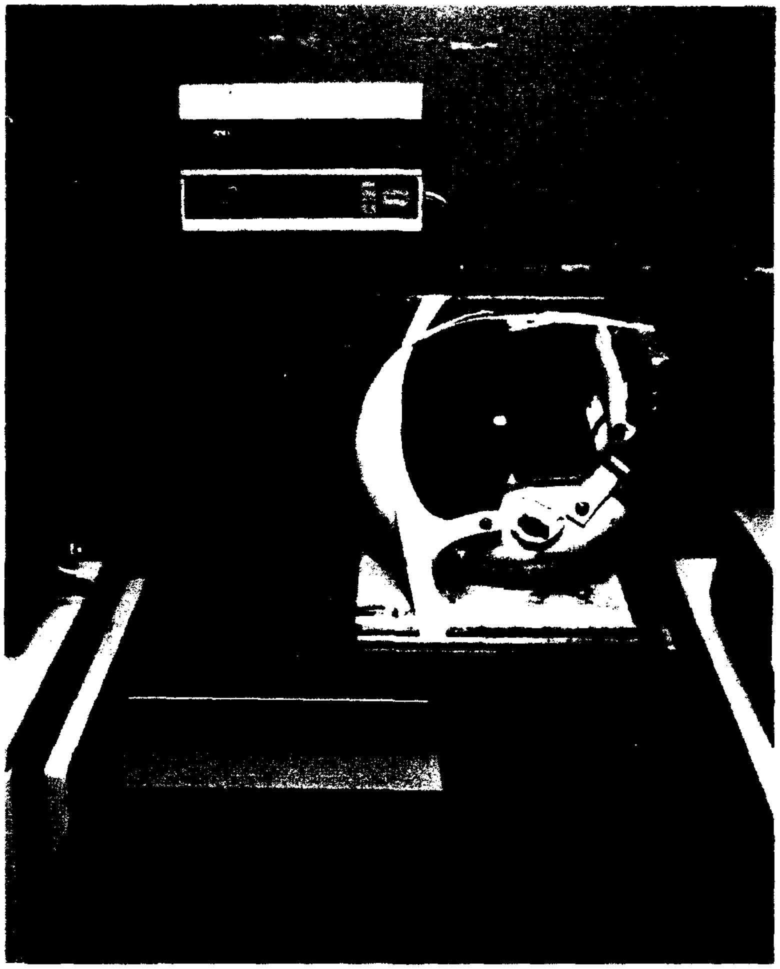

Figure 7. Helmet in mounting box on the fulcrum balance.

The mass moments of inertia are then determined. The mass properties instruments measure the moments about the center of the tables, thus it is important to place the center of gravity of the composite object over this location. The STAMP software calculates the proper location of the origin of the mounting box with respect to a grid system on the top of the moment table. The grid system on the large mass properties instrument is marked in 0.5 inch increments, while the small mass properties instrument grids are marked in 0.1 inch increments. The three moments about the cardinal axes are determined by placing each face of the box down on the table, in the location specified by the STAMP software. In Figure 8, one of the moments of inertia for the HGU-26/P helmet is shown being measured on the large mass properties table. In order to determine the full inertial matrix, it is also necessary to find off-axis moments. A balsa wood jig is used for this purpose, and has two sides which are at 45 degree angles to the horizontal axis of the table. The mounting box is placed into the jig, the jig is placed on the mass properties table, and off-axis moments are obtained. Again, the STAMP software calculates the proper location for the position of the jig, mounting box, and test object configuration with respect to the table grid system.

Figure 8. Helmet in mounting box on large mass properties instrument.

The STAMP procedure determines the center of gravity and six moments of inertia, all measured with respect to the box axis system. Information referenced to the box axis system is of little significance, since altering the position of the test object could significantly alter the data that are collected. It is necessary to establish a body-fixed coordinate system for the test object - axes that are independent of placement in the mounting box.

This axis system is established using the three-dimensional digitizer. At least three non-colinear points are required to establish an orthogonal body axis system. These points may be arbitrarily chosen, but they are generally mechanical landmarks such as indentations, holes, bolts, or possibly anthropometric landmarks when measuring manikin or cadaver segments. The digitizer is used to measure the locations of the box origin and points in the x, y, and z directions. This establishes the reference box coordinate system in which the inertial properties have been measured. Then the body landmarks are digitized and the points are used to calculate a transformation matrix between the box coordinate system and the body coordinate system. The STAMP software uses the transformation matrix to calculate the inertial properties with respect to the body coordinate system, which is independent of the position of the test object in the mounting box.

The locations of various landmarks are given in the box coordinate system as well as in the body system. Other coordinate systems may also be specified and used, as established by other components of the STAMP software. The moments of inertia are reported in the principal coordinate system of the body. The origin of this system is the center of gravity of the body, while the orientation of the axes is found by diagonalizing the full inertia matrix with respect to this origin.

Although much of the STAMP procedure has been automated, there is still a good deal of dependence on the skill and experience of the operator. It is a simple and efficient process, yet there are a large number of steps in the test procedure. Error may be introduced at any one of these steps. To analyze the magnitude of this error, it is necessary to perform a series of accuracy and repeatability experiments.

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EXPERIMENTAL PROCEDURES

Each of the test cells was performed on both the large and the small mass properties instruments. For the test cells involving the aluminum blocks, center of gravity (CG) measurements were conducted during test sequences on both the large and the small mass properties instruments. The measurement of the centers of gravity did not depend on the measurements of the moments of inertia, therefore there is no significance for a CG measurement being reported for a test on a particular mass properties instrument. The measurements of the moments of inertia did, however, depend on the center of gravity measurements since this affected the placement of the test object CG on the mass properties table. In Cells C and D, the center of gravity of the composite test object was only measured once for each composite set-up. This CG location was used in the moment of inertia measurements on the large mass properties instrument, and then the same setup and the same CG location were used for the small mass properties instrument. The results from the two instruments were examined separately, then the accuracies of the two instruments were compared.

Cell A addressed the repeatability of the equipment used in the STAMP system. A 7.08 kg rectangular block served as the test object for this cell. The mass and center of gravity were first measured, then the block was placed on the large mass properties table. Since the block was rectangular, there was no need for it to be placed in the mounting box. A new box data set was established which had no effective inertial properties. This was necessary to match the STAMP software protocol. As shown in Figure 9, an axis system was devised where the x-axis corresponded to the shortest edge of the block, the z-axis to the longest, and the y-axis to the intermediate edge. It was also unnecessary to digitize the rectangular block, since the coordinate system of the imaginary box was parallel to the coordinate system of the block. Ten different periods of oscillation were taken about the x-axis of the composite, without moving it on the mass properties table. Ten periods were then measured for the y and z axes. The block was repositioned in the jig to provide ten period measurements about the xy, yz, and xz axes.

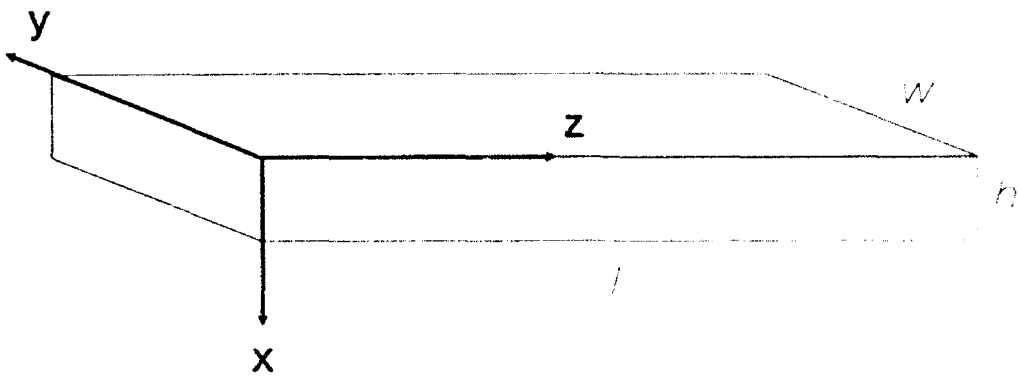

Figure 9. Block axis system.

The second portion of Cell A also tested the 7.08 kg aluminum block. The entire sequence of measurements was performed once on the small mass properties instrument, and then again on the large mass properties instrument. For the tests on each instrument, the center of gravity was found, then the moments of inertia about each of the six axes were measured. The entire process was repeated, for a total of ten tests on each instrument. Thus, in Cell A a total of twenty measurements of the center of gravity and of the moments of inertia were obtained. These measurements revealed the amount of variability in positioning the test object on the table.

Six additional blocks of mass 0.512, 1.268, 2.832, 5.436, 10.714, and 17.373 kg were used in Cell B. The protocol was similar to that of Cell A: there was no mounting box and data points were not digitized. The center of gravity of each of the blocks was measured, then the moments of inertia were determined on the small mass properties table. This process was repeated three different times for each block, and the average center of gravity and principal moments of inertia were compared to values determined analytically. The entire procedure was then repeated on the large mass properties instrument. Due to the large lengths of their z axes, the 10.714 and 17.373 kg blocks did not fit on the small mass properties table. Therefore, these blocks were not tested on the small mass properties instrument.

An HGU-26/P helmet with double visor was used in Cell C. The tests were conducted with the outermost, tinted visor down. The helmet was first secured to the mounting box, with the front of the helmet facing out at approximately 45 degrees (see Figure 4). The mass and center of gravity were measured on the scale and fulcrum balance, and the six moments of inertia were obtained. In order to determine the inertial properties of the helmet in a body-fixed axis system, a helmet axis system was defined. The points used to establish the helmet system were located using the three-dimensional digitizer.

As shown in Figure 10, three points located on the HGU-26/P were chosen to define the helmet axis system. These points were easily accessible when the helmet was placed in the mounting box, and were spaced at sufficient intervals to minimize error. The box axis system was first defined, then the helmet landmarks were digitized. Finally, a transformation matrix from the box axis system to the helmet axis system was used to transform the data into the helmet system. The entire process was repeated - the helmet was removed from the mounting box, then repositioned and secured, the mass and center of gravity were determined, the moments measured, and the landmarks digitized. A total of ten tests were conducted to assess the variability of placi. ' the test object in the mounting box.

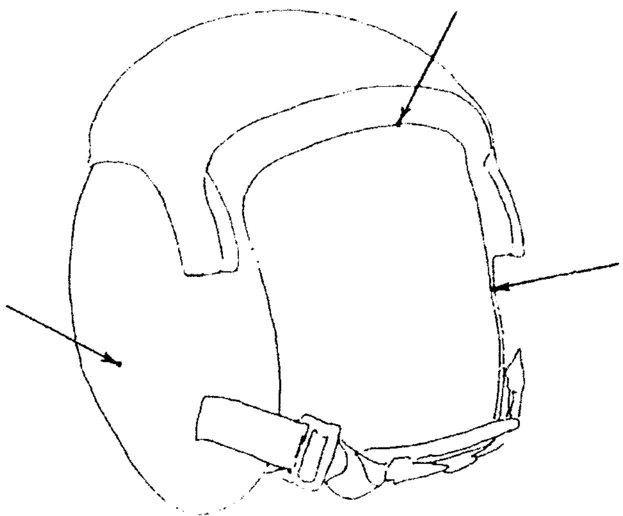

Figure 10. Defining points of the helmet axis system.

The HGU-26/P was placed on a modified large Hybrid II manikin head in Cell D. Due to the variability in helmets and in the size and shape of human heads, there is no official criterion for fitting a helmet on a head. The test conductor generally determined a comfortable fit on a human subject, and then placed the helmet on the manikin head in a similar fashion. The chin and nape straps were tightened snugly, and the helmet was placed symmetrically on the head.

It is possible to devise a technique to repeatedly place a given helmet in the same place on a given manikin head. This might be done by marking the helmet contour directly on the manikin head, or by specifying particular distances between anatomical landmarks and points on the helmet (i.e. the brow of the helmet must be 2.5 cm above the sellion). In Cell D, there was no repeatability technique used for fitting the helmet. There was, however, an inherent reproducibility mechanism in the sense that the operator repeated this placement a total of ten times, and probably became more skillful and efficient at the task.

The helmet was placed on the head with the outer visor down, creating what is called a mock-up. The inertial properties of the mock-up were then measured in a similar fashion to that of Cell C. The mass and center of gravity were obtained for the mock-up, and the mass moments of inertia were measured on the small mass properties instrument. Using the same center of gravity location and the same mock-up, moments of inertia were obtained on the large mass properties table. A total of ten different mock-ups were tested.

When the data from Cell D were analyzed, there were actually two different body axis systems. The first was the helmet axis system of Cell C, while the second was the anatomical axis system of the manikin head. Each of these axis systems can be defined using the three dimensional digitizer. The anatomical system of the head was defined by four anatomical landmarks: the sellion, the left and right tragions, and the right infraorbitale (McConville, et al, 1980). Unfortunately, these points were often covered when the helmet was placed on the head. Thus three additional points were used which were accessible for the digitizer and served to define an intermediate head axis system. This intermediate axis system could then be related back to the anatomical axis system once the helmet was removed from the head and the desired anatomical landmarks were digitized.

Once the process was complete, the mock-up was removed from the mounting box and the helmet was taken off the manikin head. The entire procedure was then repeated for a total of ten different mock-ups. The output of the STAMP software includes the locations of various landmarks as well as the transformations between coordinate systems. Data were provided in the box, head, and helmet axis systems. The principal moments of inertia were calculated with respect to the center of gravity of the combined head and helmet mock-up.

RESULTS

The four test cells provided a means for measuring the accuracy and repeatability of the STAMP system. Results from the study are presented in terms of the mean (X_n), the standard error (S_n), and the adjusted standard deviation (σ). The adjusted standard deviation is defined by:

$$\sigma^2 = \frac{[(\delta_1)^2 + (\delta_2)^2 + \ldots + (\delta_n)^2]}{n-1} \tag{1}$$

where there are n data points and each δ_i represents the difference between the ith value and the mean. The adjusted standard deviation addresses the amount of dispersion present in the data. The standard error describes the certainty of the mean and more closely involves the number of data points collected. It represents how closely the mean value obtained in the tests approximates the "true mean" of the measured quantity. This "true mean" is the value that would be obtained for the mean if you could perform an infinite number of tests. The standard error is valuable in determining if enough data were collected. As the number of data points collected increases, the standard error generally decreases. It is calculated as:

$$S_n = \frac{\sigma}{\sqrt{n}} \tag{2}$$

Most of the data are reported in terms of $X_n \pm S_n$.

Finally, the coefficient of variation is a useful tool for measuring the relative amounts of dispersion in a set of data. It is calculated by dividing the standard deviation by the mean and is generally expressed in percentages. This value will be used in examining the moment of inertia data.

The results from each test cell are listed below. Data for the mass and center of gravity measurements are discussed first, followed by results from the small mass properties instrument and the large mass properties instrument. A comparison between the two instruments will be made in the discussion section. The raw data from each individual test are given in Appendix A.

Cell A

The tests conducted in Cell A were very consistent. The center of gravity for the 7.081 kg block was repeatable to the nearest tenth of a millimeter when successive measurements were taken without moving the block on the fulcrum balance. No error is assumed to be introduced due to imprecision in the center of gravity measurements.

The moments of inertia were also very repeatable. Ten successive measurements were recorded for each of the six moment axes. The means, standard errors, and standard deviations for the six measured moments from the small and large mass properties instruments are listed in Table 1.

For the small mass properties instrument, the largest

Table 1. Precision of moment measurements, Cell A.

	Small Mass Prop Instrument ($kg\text{-}cm^2$)		Large Mass Prop Instrument ($kg\text{-}cm^2$)	
	$X_n \pm S_n$	σ	$X_n \pm S_n$	σ
I_x	541.283 ± 0.007	0.022	541.381 ± 0.006	0.019
I_y	525.921 ± 0.007	0.023	526.156 ± 0.006	0.018
I_z	26.278 ± 0.002	0.005	26.156 ± 0.000	0.000
I_{xy}	641.360 ± 0.016	0.050	642.150 ± 0.021	0.067
I_{yz}	479.239 ± 0.025	0.079	484.958 ± 0.057	0.180
I_{xz}	485.035 ± 0.021	0.067	486.078 ± 0.038	0.119

standard deviation for any of the six axes was 0.079 $kg\text{-}cm^2$. This is extremely low, since the mean for this measurement is 479.239 $kg\text{-}cm^2$. The coefficient of variation for the measurement is on the order of one-hundredth of one percent.

The large mass properties table has a maximum standard of deviation of 0.180 kg-cm^2, where the mean is 484.958 kg-cm^2. This also provides a coefficient of variation on the order of one-hundredth of one percent.

The second section of Cell A investigated the repeatability of measurements when replacing the test specimen on the STAMP equipment. The entire test sequence was performed using the 7.08 kg block. This sequence consisted of measuring the mass, locating the center of gravity, and determining the six moments of inertia. The process was then repeated for a total of ten different tests.

The means, standard errors, and standard deviations are listed for the center of gravity measurements and for the moments of inertia in Table 2. Again, the results are very consistent. For the small mass properties instrument tests, the largest standard deviation for the center of gravity locations is 0.005 cm, while the largest standard deviation for the moments of inertia is 0.744 kg-cm^2. The respective values for the large mass properties tests are 0.010 cm and 4.363 kg-cm^2. As noted previously, the CG measurements were independent of which mass properties instrument was used. The CGs were simply recorded during the large or small mass properties measurement sequence.

Table 2. Placement repeatability for Is and CGs, Cell A.

	Small Mass Prop Instrument			Large Mass Prop Instrument		
	[a] Xn	Sn	σ	Xn	Sn	σ
CGx	2.567	0.002	0.005	2.521	0.003	0.010
CGy	5.062	0.001	0.004	5.060	0.000	0.000
CGz	25.360	0.000	0.000	25.360	0.000	0.000
Ix	1584.268	0.226	0.713	1590.798	0.808	2.554
Iy	1538.201	0.235	0.744	1535.925	1.380	4.363
Iz	75.350	0.065	0.205	74.706	0.094	0.296

[a]*CGs* are given in cm, *Is* in kg-cm^2.

Cell B

The accuracy of the STAMP system was studied in Cell B. Seven rectangular aluminum blocks were each tested three different times. The mass and dimensions of each block, including the 7.081 kg block used in Cell A, are listed in Table 3.

Table 3. Dimensions of the aluminum test blocks.

Block ID#	mass (kg)	length [z] (cm)	width [y] (cm)	height [x] (cm)
1	0.512	9.599	7.981	2.494
2	1.268	15.314	11.389	2.611
3	2.832	20.325	10.173	5.075
4	5.436	20.460	12.845	7.661
5	7.081	50.828	10.173	5.067
6	10.714	51.336	10.160	7.620
7	17.373	66.286	12.690	7.856

The centers of gravity for each block in the x, y, and z directions are calculated by halving the height, width, and length, respectively (see Figure 9). The moments of inertia about the centroidal axes of a rectangular block are calculated using the equations

$$I_x = \frac{1}{12} m(l^2 + w^2) \qquad I_y = \frac{1}{12} m(l^2 + h^2) \qquad I_z = \frac{1}{12} m(w^2 + h^2) \quad \textbf{(3)}$$

where l, w, and h correspond to the length, width, and height of the block, respectively. The calculated values for the centers of gravity and for the moments of inertia are listed in Table 4.

The lengths of the 10.7 and 17.4 kg blocks were too large for testing on the small mass properties table, and were not included in the test cell. The means of the centers of gravity and moments of inertia measured during the small mass properties instrument tests are listed in Table 5. All seven blocks were tested on the large mass properties instrument, and the moments of inertia and centers of gravity are listed in Table 6.

Table 4. Analytical values for mass properties of test blocks.

mass (kg)	CGx (cm)	CGy (cm)	CGz (cm)	Ix ($kg-cm^2$)	Iy ($kg-cm^2$)	Iz ($kg-cm^2$)
0.5	1.247	3.991	4.800	6.654	4.200	2.985
1.3	1.306	5.695	7.657	38.499	25.509	14.431
2.8	2.538	5.087	10.163	121.917	103.571	30.502
5.4	3.831	6.423	10.230	264.373	216.218	101.329
7.1	2.534	5.087	25.414	1585.584	1539.665	76.220
10.7	3.810	5.080	25.668	2445.032	2404.712	144.000
17.4	3.928	6.345	33.143	6594.541	6450.746	322.502

Table 5. Properties of blocks found on small instrument, Cell B.

mass (kg)	CG_x (cm)	CG_y (cm)	CG_z (cm)	I_x ($kg-cm^2$)	I_y ($kg-cm^2$)	I_z ($kg-cm^2$)
0.5	1.20	3.98	4.74	7.401	5.687	0.641
1.3	1.28	5.64	7.61	38.061	25.810	13.507
2.8	2.51	5.05	10.12	121.025	102.820	30.142
5.4	3.82	6.39	10.17	264.287	216.117	100.431
7.1	2.57	5.06	25.36	1584.268	1538.201	75.350

instrument, and the moments of inertia and centers of gravity are listed in Table 6.

The experimental values obtained on both mass properties instruments (Tables 5 and 6) can now be compared to the calculated inertial properties (Table 4). This is done using a percent error or percent difference calculation, where:

$$\%err = \frac{|experimental - analytical|}{analytical} x100 \qquad (4)$$

Table 6. Properties found on large instrument, Cell B.

mass (kg)	CGx (cm)	CGy (cm)	CGz (cm)	Ix ($kg-cm^2$)	Iy ($kg-cm^2$)	Iz ($kg-cm^2$)
0.5	1.20	3.98	4.74	7.443	5.835	0.839
1.3	1.28	5.64	7.61	37.887	25.545	13.768
2.8	2.50	5.05	10.12	120.884	103.074	29.964
5.4	3.82	6.38	10.17	264.781	216.929	100.658
7.1	2.52	5.06	25.36	1590.798	1535.925	74.706
10.7	3.75	5.06	25.60	2450.935	2394.652	142.194
17.4	3.88	6.41	33.12	6607.063	6433.434	311.124

Table 7. Percent errors in *CG*s, experimental vs. analytic, Cell B.

Block (kg)	Small Mass Prop Instrument (% error)			Large Mass Prop Instrument (% error)		
	CGx	CGy	CGz	CGx	CGy	CGz
0.5	3.77	0.26	1.24	3.77	0.26	1.24
1.3	1.95	0.96	0.61	1.95	0.96	0.61
2.8	1.08	0.72	0.42	1.48	0.72	0.45
5.4	0.27	0.51	0.59	0.27	0.66	0.59
7.1[a]	1.30	0.49	0.21	0.51	0.53	0.21
10.7	*	*	*	1.58	0.39	0.27
17.4	*	*	*	1.22	1.02	0.07

* Not measured on small mass properties instrument.
[a] Measured during Cell A.

As mentioned previously, separate CG measurements were taken in Cells A and B before measuring the moments of inertia on the large and on the small mass properties tables. The average percent errors in the measurements of the centers of gravity for the large and small mass properties tests are

Table 8. Percent error in *Is*, experimental vs. analytic, Cell B.

Mass (kg)	Small Mass Prop Instrument (% error)			Large Mass Prop Instrument (% error)		
	Ix	Iy	Iz	Ix	Iy	Iz
0.5	11.23	35.40	78.53	11.86	38.94	71.84
1.3	1.14	1.18	6.40	1.59	0.32	4.59
2.8	0.73	0.73	1.18	0.85	0.48	1.76
5.4	0.03	0.05	0.89	0.15	0.33	0.66
7.1[a]	0.08	0.10	1.14	0.33	0.24	1.99
10.7	*	*	*	0.24	0.42	1.25
17.4	*	*	*	0.19	0.27	3.53

* Not measured on small mass properties instrument.
[a] Measured during Cell A.

The measurements of the centers of gravity are very accurate, although some significant errors are found in the CGx measurements. The x-direction corresponds to the height dimension, which is the smallest measurement on the block. While the percentages are somewhat large, the absolute difference is no more than 0.05 cm.

As can be seen, the moments of inertia are unreliable for the 0.5 kg block. Again, the percentage error can be deceptive. As shown in Tables A-5 and A-6, most of the absolute differences between the experimental and the analytical values are less than 1 kg-cm^2. Error is introduced because the weights of the mass properties tables are simply too large when compared to the test object. The manufacturer of the instruments only recommends testing weights as low as one pound (0.373 kg) for the small mass properties instrument. As the masses increase, the accuracy of the measurements improves considerably, to less than one percent for most of the moments.

Cell C

The third cell involves testing an irregularly-shaped object placed in the mounting box. An HGU-26/P helmet without headform is tested a total of ten times. The test object is secured in the mounting box, the center of gravity is determined, the moments of inertia are measured on the small and then the large mass properties instrument, and the box and helmet landmarks are digitized. The helmet is removed from the box, and the process is repeated.

In addition to the helmet axis system, the data are given in the head anatomical coordinate system. To do this, it is necessary to utilize the first test from Cell D. When a helmet is placed on a headform, it is possible to determine the three dimensional locations of the helmet landmarks and the head landmarks. An offset and transformation between the head axis system and helmet axis system are determined, which can be used to establish the head anatomical coordinate system with respect to the existing helmet axis system. The location of the head axis system is stored, and can be used for the helmet even after the head is removed. This technique is shown schematically in Figure 11. Using these methods, the helmet data can be reported in the head anatomical system.

The center of gravity in the x, y, and z directions determined in the large and the small mass properties tests are listed in Table 9. Table 10 lists the moments of inertia. The data are presented as the mean plus or minus the standard error, followed by the standard deviation.

Table 9. CG location of helmet, measured in Cell C.

	Head Anatomical System (cm)		Helmet System (cm)	
	X ± S	σ	X ± S	σ
CG_x	1.162 ± 0.019	0.062	4.671 ± 0.042	0.072
CG_y	-0.013 ± 0.017	0.054	-0.014 ± 0.035	0.061
CG_z	4.308 ± 0.015	0.048	3.240 ± 0.029	0.051

The data show that the measurement of the center of gravity is repeatable to well within 1 mm for this test cell.

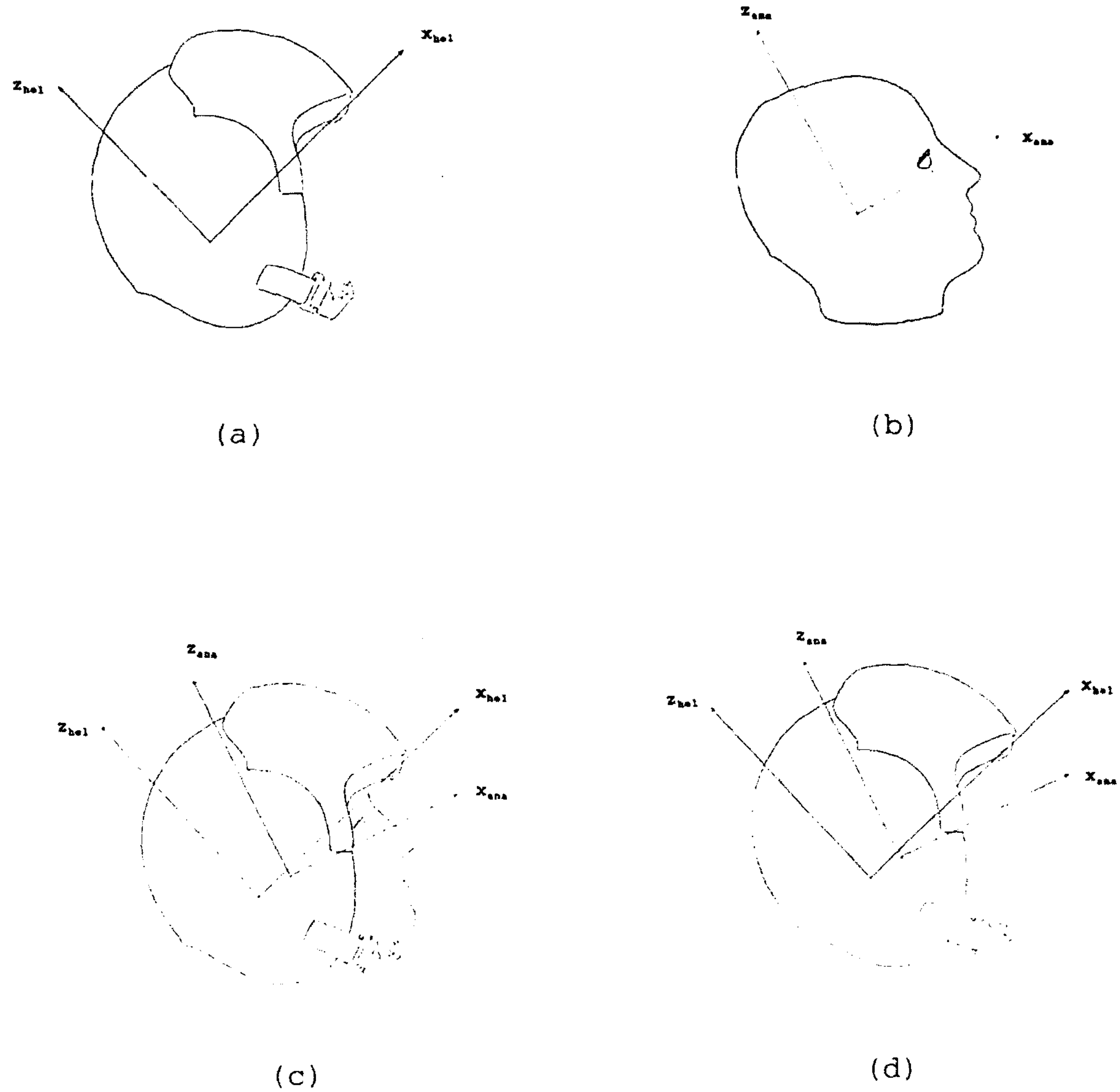

Figure 11. Axis systems of (a) helmet, (b) head, (c) head and helmet, and (d) helmet with head removed.

Cell D

The repeatability of mounting a helmet on a manikin head is examined in Cell D. The helmet is placed on the head, the center of gravity is determined, the moments of inertia are measured, relevant landmarks are digitized, and the data are analyzed by the STAMP software. This process is repeated

Table 10. Principal moments of inertia for helmet, Cell C.

	Small Mass Prop Instrument ($kg\text{-}cm^2$)		Large Mass Prop Instrument ($kg\text{-}cm^2$)	
	X ± S	σ	X ± S	σ
Ix	135.572 ± 0.087	0.274	137.337 ± 0.162	0.513
Iy	114.893 ± 0.221	0.700	115.967 ± 0.454	1.437
Iz	158.730 ± 0.152	0.481	160.542 ± 0.184	0.581

ten times. The means, standard errors, and standard deviations of the center of gravity measurements are listed in Table 11, while the same variables for moments of inertia on the large and small mass properties instruments are listed in Table 12.

Table 11. CG of combined head and helmet, measured in Cell D.

	Head Anatomical System (cm)		Helmet System (cm)	
	X ± S	σ	X ± S	σ
CGx	-0.768 ± 0.011	0.035	2.533 ± 0.021	0.036
CGy	0.075 ± 0.017	0.053	0.048 ± 0.037	0.064
CGz	3.324 ± 0.016	0.052	2.890 ± 0.038	0.066

Table 12. Principal *Is* for combined head and helmet, Cell D.

	Small Mass Prop Instrument ($kg\text{-}cm^2$)		Large Mass Prop Instrument ($kg\text{-}cm^2$)	
	X ± S	σ	X ± S	σ
Ix	358.536 ± 0.298	0.942	362.610 ± 0.402	1.271
Iy	367.084 ± 0.325	1.028	379.218 ± 0.730	2.309
Iz	315.375 ± 0.537	1.699	321.184 ± 0.370	1.172

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DISCUSSION

The major sources of error in the STAMP system were addressed in this test series. Variables which were not analyzed for error include test conductor dependence, the precision and skill in using the digitizer, environmental effects such as air currents, temperature and humidity, and numerical round-off errors in the STAMP software. The test environment was fairly constant, however, as the temperature was controlled within 69-71°F, the relative humidity within 10-40%, and airflow was uniform throughout the test series. Each of the test cells analyzed a particular aspect of the STAMP procedure.

Precision of the STAMP Equipment

The precision of the equipment is of paramount interest when evaluating a measuring device. In the first part of Cell A, the test block was placed on each piece of equipment and measured ten consecutive times without repositioning the block. Tests were performed on the scale, on the fulcrum balance, and on the mass properties tables. The precision of the equipment proved to be excellent, being within one-tenth of one percent.

Cell A then addressed the variability in placing a test object on the measuring equipment. The center of gravity was first determined. Using this information, the STAMP software calculated the proper location for the composite test object CG to be placed on the mass properties table. The small mass properties table has a grid spacing of 0.1 inches, while the large mass properties table spacing is 0.5 inches. The test conductor should be able to place the test object on the large table to within 0.125 inches (i.e., he can visually approximate quarter divisions of the grid spacing). Using this spacing, it is possible to predict the amount of error which may be introduced in the placement of the object center of gravity. The parallel axis theorem states that

$$I_{xx} = \overline{I} + md^2 \quad (5)$$

where I_{xx} is the moment of inertia about a given axis, $\overline{I}$ is the moment about the object's center of gravity, and d is the perpendicular distance between the two axes. The 0.125 inch accuracy is equivalent to 0.318 cm. If we then square this distance, we obtain 0.1 cm^2. To examine the effects of the center of gravity placement, we examined the 7.1 kg block. This object has a moment of inertia about the z-axis of 74.71 kg-cm^2. If the placement of the block is off by 0.318 cm, then the measured moment would become 75.424 kg-cm^2, which is a difference of 0.95 percent. The possible error on the small mass properties instrument is even less.

A second source of error in the system is the placement of the fulcrum balance on the digital scale. Presently the balance is stored when not in use, and the placement of the knife-edge may vary when the center of gravity is measured. This is evident when comparing the CG_x values for the large and small mass properties instrument tests in Table 2. Although the standard deviations for both instruments are very small, the means differ by 0.046 cm. The two tests (on large and small instruments) were conducted on different days, and the placement of the knife-edge may have varied somewhat. Furthermore, the CG_x measurement has the greatest susceptibility to these errors. The surface of the y-z face is the smallest of the three, which results in more mass being concentrated away from the scale (see Figure 12). Even small differences in positioning the specimen can significantly affect the measurements in this direction.

The means for CG_y and CG_z on the two instruments are much closer: the CG_y means varied by 0.002 cm and the CG_z means were exactly the same. As the area of the surface placed on the scale increases and the measured length becomes greater, the error decreases. The lengths in the y and z directions are more indicative of the types of tests generally performed in the MTL: the lengths of helmets and manikin segments are generally on the order of 20 cm rather than 2 cm.

Currently steps are being taken to correct the variance caused by the placement of the fulcrum balance. A small groove has been machined into the support leg of the balance so that the knife-edge is placed consistently. This should minimize the amount of error introduced in this section of the STAMP procedure.

Examining Table 2, it is seen that the largest standard deviation measured for the center of gravity location is

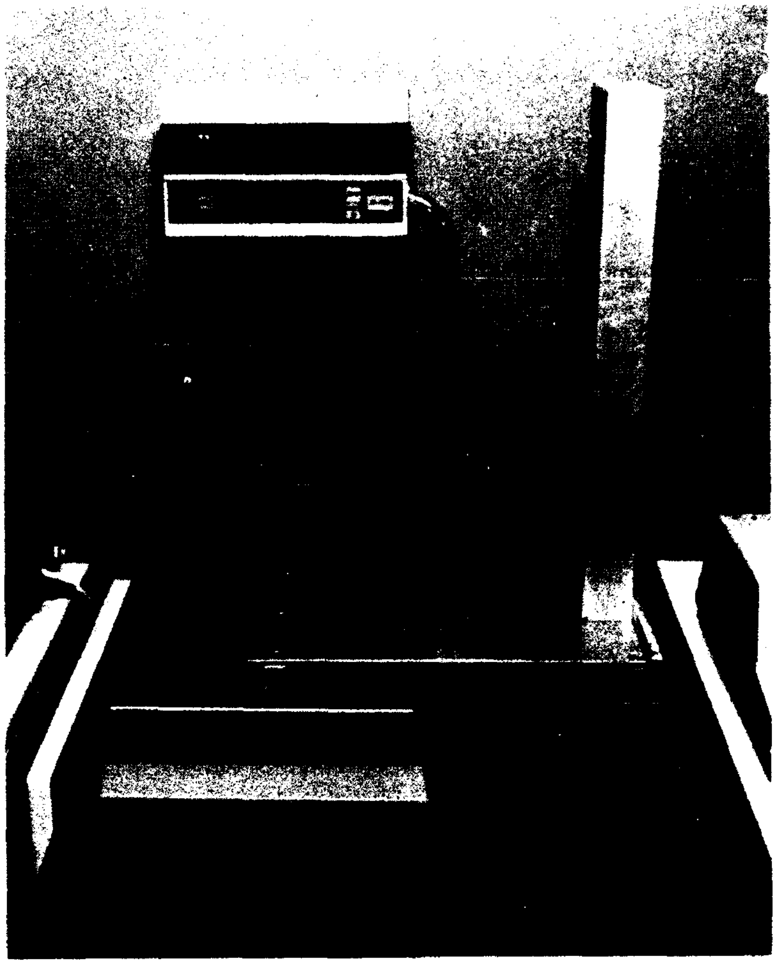

Figure 12. Measurement of CGx on fulcrum balance.

0.005 cm on the small instrument and 0.010 cm on the large instrument, both in the x-direction. The maximum standard deviations for the moments of inertia are 0.744 kg-cm^2 for the small mass properties instrument and 4.363 kg-cm^2 for the large mass properties instrument. These standard deviations are 0.05% and 0.3% of the means for the moment of inertia measurements.

Accuracy of the Equipment

Cell B compares the results obtained in the STAMP procedures to properties determined analytically. The analytic values are calculated using measurements obtained from calipers, which are accurate to one-thousandth of an inch. Some assumptions are made in these calculations that may alter the percentage differences obtained in Cell B. We assume that the blocks are perfectly rectangular, when in fact the lengths of some of the similar edges differ by as much as 0.005 inch. The blocks are also assumed to have constant density throughout. Finally, some human error may have been introduced when measuring the lengths of the blocks.

The STAMP CG measurements matched the analytical results very closely. As noted in Table 7, the largest difference in these measurements is for the CG in the x direction of the smallest block. While the difference is 3.7%, the actual value by which the two differ is only 0.05 cm. As noted previously, the smaller edges usually provide the greatest relative errors in measurements. From these results, it is concluded that the accuracy of the equipment for CG measurements is good to at least 0.05 cm.

The moment of inertia measurements also match the analytical results well. For masses of 2.8 kg and above, all of the I_x and I_y measurements are under 1% (with values as low as 0.03%). However, the results for the 0.5 kg block are less reliable, especially in the z-direction. Tables A-5 and A-6 reveal that while the percentage differences may be quite large, the actual values generally differ by less than 1 kg-cm^2 for the 1.3 kg block and by less than 2.5 kg-cm^2 for the 0.5 kg-cm^2 block. The object mass threshold for obtaining moment of inertia data accurate to 1% appears to be somewhere between 1.3 and 2.8 kg.

The largest errors are present in the I_z moments. This is the smallest moment that is measured for the blocks, and differences in these values result in larger percentage differences than for larger moments. In practical applications, the z-axis moments do not as significant influence predictive analyses or injury mechanisms as moments about the other axes. Lower moment of inertia values result in lower generated torques and moments. Furthermore, human response to impact is generally in roll and pitching motions rather than yaw, and injuries are usually obtained from the former two angular responses rather than the latter. Therefore the larger percentage differences for the z-axis moments (which are still only about 1%) do not cause significant problems.

Repeatability of Placing the Helmet in the Mounting Box

The repeatability of placing an HGU-26/P helmet in the mounting box was determined in Cell C. In the anatomical coordinate system, the largest standard deviation for the center of gravity was 0.062 cm in the x-direction (refer to Table 9). Values in the y and z directions were 0.054 and 0.048 cm, respectively. When measuring the same helmet, 96% of all measurements will be within twice the largest standard deviation (i.e., ±0.125 cm) of the mean. This error may become even lower once the improvement to the fulcrum balance placement is made.

The moment of inertia data are also very repeatable. One must realize, however, that the principal moments are with respect to an axis system which is determined by the test measurements. This principal axis system is defined with respect to the anatomical coordinate system, which is constant for each mock-up or test configuration. Referring to Table A-13 of the appendix, it can be seen that some of the yaw angles are considerably different. The axes are all relatively equivalent, however, thus comparisons are made with the understanding that the small differences in axis orientation may add to the error present in the measurements.

In Table 10, the maximum standard deviation for the small mass properties instrument is 0.700 kg-cm^2. The coefficient of variation for this measurement is 0.6%. The large mass properties instrument produces measurements which vary by a standard deviation 1.437 kg-cm^2, or a coefficient of variation slightly less than 1%. Both of these errors are quite small.

Repeatability of Placing the Helmet on the Manikin Head

Cell D actually includes the error present in Cell C. The helmet is taken out of the mounting box in both cells, then repositioned for each successive test. To only test the variability in placing the helmet on the head, one would have to leave the helmet in the mounting box and somehow reposition the head inside the helmet for each test. This is not practical, and is not the standard procedure for testing a head/helmet mock-up.

The variability of helmet placements for the ten mock-ups can be examined by determining the distance between the helmet CG and the head CG. As evident in Table A-11, the largest discrepancy between any two tests in a given direction was 0.21 inches. This would alter the moment of inertia measurements by 0.04 multiplied by the mass of the test object. Another measure of repeatability of placing the helmet on the manikin head is the amount of angular displacement between the anatomical and helmet axis systems. These angular displacement were all very close, to within one tenth of a degree for all measurements. Therefore, the variability in placing the helmet on the manikin head should not greatly affect the measurements of the center of gravity or of the mass moments of inertia.

The repeatability of the center of gravity measurements for Cell D is even better than for Cell C. This is somewhat surprising, since the error introduced during Cell C (maximum standard deviation of 0.062 cm) is also introduced during Cell D (maximum standard deviation of 0.053 cm). The primary reason for this disparity is the overwhelming contribution of the head mass to the overall center of gravity of the mock-up. The large Hybrid II head has a mass of 4.14 kg while the helmet is only 1.34 kg. The center of gravity for a composite object tends to be closer to the CG of the article of greater mass. Furthermore, as seen in Cell B, the center of gravity measurements tend to become more accurate as the weight and size of the test object increase.

The moment of inertia measurements of the combined head/helmet mock-up all have coefficients of variation less than 0.7%. As in Cell C, one must remember that the principal axes for each test are not perfectly aligned. This causes additional error in the moment of inertia measurements.

CONCLUSIONS

The STAMP system provides highly accurate measurements of the center of gravity and moments of inertia of a given test object. The overall accuracy of the center of gravity measurements are discussed first, followed by an analysis of the moment of inertia data.

Center of Gravity Accuracy

The fulcrum balance is a very simple piece of equipment with very little room for error. The precision of the center of gravity measurements is excellent, being within one-hundredth of one-percent. No error is assumed to be introduced due to the precision of the equipment.

Placing the test object on the testing surfaces does, however, cause variability in the measurements. As demonstrated by the difference in CGx means in Table 2, the center of gravity measurements may differ by as much as 0.05 cm, due mostly to variability in placement of the fulcrum knife-edge. This problem is being rectified by developing an improved means of consistently placing the fulcrum on the balance.

Since the CG measurements do not depend on which instrument measures the moments of inertia, we can combine the small and large mass properties data for a given CG measurement on the block. To obtain an overall standard deviation for the CGx measurements shown in Table 2, we combined the CGx data from Tables A-3 and A-4. The standard deviation of this set of twenty CGx measurements is 0.067 cm.

In order to obtain an overall standard deviation for CG measurements, the standard deviations from the three directions were averaged. This average was 0.023 cm, therefore a conservative standard deviation of 0.030 cm is used for the center of gravity measurements.

The mass properties of a rectangular block can be calculated, yet the error of the analytical assumptions may be greater than that of the measuring equipment. In Cell B, the center of gravity measurements differed from the analytical values by no more than 0.05 cm. The accuracy of the center of gravity measurements is assumed to be at this maximum error level of 0.05 cm.

This accuracy value is similar to the standard error discussed earlier - if the true center of gravity of an object is 2.0 cm, then the mean of measurements taken by the STAMP procedure will fall within 0.05 cm of that value (i.e., between 1.95 and 2.05 cm). We assume the error to be distributed normally about the true value, with a standard deviation of 0.025 cm of the true value (i.e, one-half the maximum error). An example of this type of frequency distribution is shown in Figure 13a.

Once this mean is determined, one must add to it the distribution from the tests used to determine this mean. Assuming that placement repeatability is equivalent for different sized blocks, we can utilize the standard deviation from Cell A. Therefore the mean for a number of CG tests will be within 0.05 cm of the true CG value, and these tests will have a standard deviation of 0.03 cm about that mean. A frequency distribution with a standard deviation of 0.03 cm about an experimental mean of 2.05 cm is shown in Figure 13b.

To put this in perspective, assume that we take one thousand CG measurements per day for one hundred consecutive days. The tests from each day provide a mean and a standard deviation. Since 96% of all mean values lie within two standard deviations of the true value (see Figure 13a), a total of four of the days' means lie outside 0.05 cm of the true value (2% are 0.05 cm less than the true value, 2% are 0.05 cm greater than the true value). As shown in Figure 13b, data from each of these four days have a standard deviation of 0.03 cm about their experimental mean. Therefore 96% of the one thousand measurements during each day are within 0.06 cm (or two standard deviations) of the day's experimental mean. The remaining 4% lie in the outer extremes of the measurements; twenty are 0.06 cm less than the mean, twenty are 0.06 cm greater than the mean. Four days produced means beyond the 0.05 cm limit and twenty tests from each day are an additional 0.06 cm away from the true value. Therefore eighty tests out of the total 100,000 measurements (0.08%) lie outside 0.11 cm of the true value. A representative probability distribution for measurements about the true value of 2.0 cm is shown in Figure 13d.

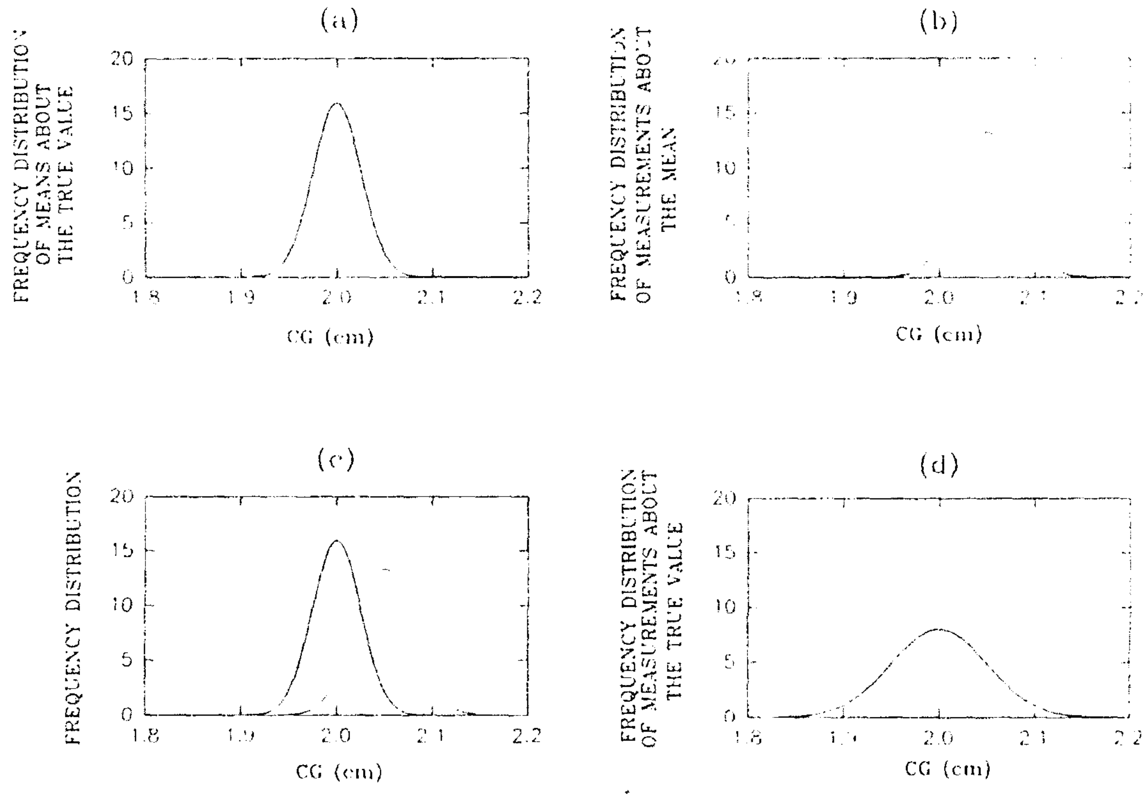

Figure 13. Frequency distributions of CG measurements.

Helmet and Head Measurements

Two practical applications are studied in Cells C and D. For these test objects, there were no "correct" values to compare to the experimental STAMP measurements. We must assume that the system accuracy is as good for these test objects as it is for the aluminum blocks, or within 0.05 cm. From Table 9, the largest standard deviation in the anatomical coordinate system is 0.062 cm. If we apply the same reasoning as for the standard deviations of the rectangular blocks, the mean of the measurements should lie within 0.05 cm of the true value, with a standard deviation of 0.062 cm about this mean. Therefore virtually all measurements will lie within 0.174 cm of the true value.

Applying the same technique to the combined head and helmet, we obtain an accuracy to within 0.05 cm of the true value and a standard deviation of 0.05 cm about the experimental mean. This yields a maximum error of 0.15 cm from the true value of the center of gravity. As explained previously, the increased accuracy for Cell D is due to the added mass of the headform. There is less repeatability in fitting the helmet on the manikin head than in placing the helmet in the mounting box, but the additional mass of the head overwhelms this error.

Moments of Inertia

The mass moment of inertia measurements were also very reliable. From Cell A, we see that the precision of the instruments is extremely high, to within 0.01%. As evident in Table 2, the repeatability of specimen placement is demonstrated by coefficients of variance of under 0.28% for all measurements on the small mass properties instrument and under 0.40% on the large mass properties instrument. The coefficients of variation are even lower if the I_z measurements are excluded, at 0.05% and 0.35% for the small and large instruments, respectively.

The accuracies of the instruments are shown in Table 8. For the small mass properties instrument, the overall average percent error for the 2.8, 5.4, and 7.1 kg blocks is 0.55%. The corresponding measurement on the large mass properties instrument is 0.75%, and increases to 0.85% if the 10.7 and 17.4 kg blocks are included in the sample. If only the I_x and I_y values are included, the overall average errors are 0.29% and 0.39% for the small and large instruments, respectively. For both instruments, smaller masses (i.e., 0.5-1.3 kg) may be measured accurately to within one or two kg-cm^2. Measurements of long, slender objects, however, may be less accurate (particularly for moments about the long axis).

In a worse case scenario, the accuracy error and the repeatability error would add together. For blocks of 2.8 kg and above, this results in a 0.83% error for the small mass properties instrument and a 1.25% error for the large mass properties instrument. These are maximum errors that are indicative of values that would be obtained for the long axis measurements of slender objects. As explained in the center of gravity analysis, these maximum errors very rarely occur; most of the error would be concentrated closer to the true value of the moment of inertia.

If the I_z measurements are not included, the error becomes substantially less. The average overall error for the small mass properties instrument drops to 0.34%, while the large instrument error becomes 0.74%. These values indicate that the moment of inertia measurements of the rectangular blocks show a high degree of accuracy and repeatability for masses above 2.8 kg and reasonable reliability (within 2.5 kg-cm^2) for smaller masses.

The moments of inertia for the helmet and for the combined head and helmet are also very repeatable. The average coefficients of variance for the helmet only are 0.34% and 0.66% for the small and large mass properties instruments, respectively. The corresponding values for the combined head and helmet are 0.36% and 0.44%. Assuming the accuracy error is equal to that for the I_x and I_y value described above (i.e., 0.29% and 0.39%), combined error values of 0.62% and 1.05% are obtained for the helmet only tests, while the combined head and helmet measurements produce errors of 0.65% and 0.83% for the small and large instruments, respectively.

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SUMMARY

The STAMP system is a very accurate, time-efficient means for measuring the mass properties of test objects. The system can locate the center of gravity of a test object to within 1.75 mm, and can determine the moments of inertia for typical helmet systems to within 0.6% using the small mass properties instrument and to within 1% using the large mass properties instrument. The accuracy of the moment of inertia measurements depends on the type of object being tested. Accuracy is reduced to an error of 1.0-2.5 kg-cm^2 when measuring masses below 2 kg. If objects with small masses are long and slender, additional error may be present in the moment measured about the long axis of the object. Most moment of inertia measurements, however, are more accurate than the maximum values quoted above, as are the center of gravity measurements. It is concluded that the errors introduced during the STAMP procedures are not significant when the mass properties measurements are used for analytical modeling, for applying injury criteria, for assessing biodynamic response, or for determining compliance with inertial specifications of helmet-mounted systems.

APPENDIX

Tables of Raw Data

Table A-1. Moments of inertia (kg-cm^2).
Cell A: Precision of small instrument.

Test	Ix	Iy	Iz	Ixy	Iyz	Ixz
1	541.246	525.917	26.276	641.342	479.189	485.006
2	541.255	525.934	26.278	641.305	479.262	485.051
3	541.284	525.883	26.277	641.319	479.185	485.095
4	541.284	525.909	26.269	641.342	479.338	484.986
5	541.310	525.938	26.279	641.333	479.306	485.144
6	541.310	525.947	26.283	641.435	479.133	485.018
7	541.259	525.934	26.272	641.435	479.286	484.953
8	541.297	525.904	26.285	641.323	479.117	484.969
9	541.293	525.892	26.283	641.421	479.254	485.128
10	541.289	525.951	26.278	641.347	479.322	484.998

Table A-2. Moments of inertia (kg-cm^2).
Cell A: Precision of large instrument.

	Ix	Iy	Iz	Ixy	Iyz	Ixz
1	541.369	526.183	26.156	641.998	484.639	485.842
2	541.369	526.183	26.156	642.118	484.789	485.992
3	541.369	526.183	26.156	642.118	484.752	486.067
4	541.369	526.145	26.156	642.158	484.902	486.067
5	541.369	526.145	26.156	642.158	485.015	486.067
6	541.369	526.145	26.156	642.198	485.052	486.030
7	541.369	526.145	26.156	642.118	485.015	486.142
8	541.408	526.145	26.156	642.198	485.127	486.105
9	541.408	526.145	26.156	642.198	485.127	486.180
10	541.408	526.145	26.156	642.238	485.165	486.293

Table A-3. Center of gravity (cm) and moments of inertia (kg-cm2) Cell A: Placement repeatability for small instrument test series.

Test	CGx	CGy	CGz	Ix	Iy	Iz
1	2.57	5.06	25.36	1583.773	1538.231	75.418
2	2.56	5.07	25.36	1584.595	1538.766	75.480
3	2.56	5.07	25.36	1585.193	1538.830	75.516
4	2.57	5.06	25.36	1584.728	1538.955	75.369
5	2.56	5.06	25.36	1584.840	1538.662	75.696
6	2.57	5.06	25.36	1582.847	1537.492	74.980
7	2.57	5.06	25.36	1583.583	1537.529	75.108
8	2.57	5.06	25.36	1584.187	1536.648	75.231
9	2.57	5.06	25.36	1584.108	1538.438	75.346
10	2.57	5.06	25.36	1584.825	1538.457	75.360

Table A-4. Center of gravity (cm) and moments of inertia (kg-cm^2) Cell A: Placement repeatability for large instrument test series.

Test	CGx	CGy	CGz	Ix	Iy	Iz
1	2.53	5.06	25.36	1587.859	1539.234	75.123
2	2.52	5.06	25.36	1591.325	1538.654	74.551
3	2.53	5.06	25.36	1588.744	1541.951	74.224
4	2.53	5.06	25.36	1589.780	1540.804	75.161
5	2.53	5.06	25.36	1589.300	1534.339	74.459
6	2.50	5.06	25.36	1591.994	1531.173	74.689
7	2.51	5.06	25.36	1588.655	1536.906	74.713
8	2.52	5.06	25.36	1593.691	1530.680	74.479
9	2.52	5.06	25.36	1590.553	1535.845	74.775
10	2.52	5.06	25.36	1596.075	1529.663	74.887

Table A-5. Center of gravity (cm) and moments of inertia ($kg\text{-}cm^2$) Cell B: Accuracy study of small instrument test series.

Block	CGx	CGy	CGz	Ix	Iy	Iz
0.5 kg	1.20	3.98	4.74	7.402	5.652	0.684
	1.20	3.98	4.74	7.402	5.711	0.608
	1.20	3.98	4.74	7.400	5.697	0.631
1.3 kg	1.28	5.64	7.61	38.057	25.806	13.515
	1.28	5.64	7.61	38.068	25.816	13.502
	1.28	5.64	7.61	38.057	25.809	13.504
2.8 kg	2.51	5.05	10.12	121.025	102.823	30.152
	2.51	5.05	10.12	121.029	102.822	30.132
	2.51	5.05	10.12	121.020	102.815	30.143
5.4 kg	3.82	6.39	10.17	264.304	216.119	100.412
	3.82	6.39	10.17	264.274	216.118	100.474
	3.82	6.39	10.17	264.282	216.115	100.408

Table A-6. Center of gravity (cm) and moments of inertia ($kg-cm^2$) Cell B: Accuracy study of large instrument.

Block	CGx	CGy	CGz	Ix	Iy	Iz
0.5 kg	1.20	3.98	4.74	7.329	5.758	0.803
	1.20	3.98	4.74	7.812	5.927	1.075
	1.20	3.98	4.74	7.189	5.821	0.639
1.3 kg	1.28	5.64	7.61	38.022	25.439	13.911
	1.28	5.64	7.61	37.792	25.593	13.563
	1.28	5.64	7.61	37.847	25.603	13.831
2.8 kg	2.50	5.05	10.12	120.823	102.673	30.188
	2.50	5.05	10.11	121.008	102.974	30.157
	2.50	5.05	10.12	120.821	103.575	29.548
5.4 kg	3.82	6.39	10.17	264.490	216.756	100.720
	3.82	6.39	10.17	264.773	217.014	100.748
	3.82	6.36	10.17	265.080	217.018	100.506
10.7 kg	3.75	5.06	25.60	2457.154	2388.753	142.490
	3.75	5.06	25.60	2446.639	2399.870	141.826
	3.75	5.06	25.60	2449.013	2395.334	142.265
17.4 kg	3.88	6.41	33.12	6605.090	6432.882	310.368
	3.88	6.41	33.12	6615.926	6433.617	307.990
	3.88	6.41	33.12	6600.172	6433.802	315.013

Table A-7. Center of gravity (cm) and moments of inertia ($kg\text{-}cm^2$). Cell C: Helmet on small instrument.

Test	CGx	CGy	CGz	Ix	Iy	Iz
1	1.04	-0.03	4.33	135.953	115.368	159.545
2	1.15	0.00	4.30	135.905	115.868	158.652
3	1.14	-0.11	4.27	135.651	115.258	158.402
4	1.13	0.03	4.32	135.756	115.800	158.960
5	1.13	0.02	4.26	135.571	114.801	159.222
6	1.17	0.07	4.23	135.515	115.059	158.753
7	1.19	0.03	4.31	135.305	114.335	158.745
8	1.26	-0.03	4.39	135.434	113.816	157.999
9	1.24	-0.03	4.30	135.036	114.098	158.074
10	1.17	-0.08	4.37	135.598	114.525	158.948

Table A-8. Center of gravity (cm) and moments of inertia ($kg\text{-}cm^2$). Cell C: Helmet on large instrument.

Test	CGx	CGy	CGz	Ix	Iy	Iz
1	1.04	-0.03	4.33	137.532	115.479	161.521
2	1.15	0.00	4.30	137.618	113.466	161.088
3	1.14	-0.11	4.27	137.150	116.473	160.426
4	1.13	0.03	4.32	137.768	116.760	160.475
5	1.13	0.02	4.26	136.822	116.663	160.316
6	1.17	0.07	4.23	137.205	118.426	160.800
7	1.19	0.03	4.31	137.080	116.517	161.036
8	1.26	-0.03	4.39	138.440	116.461	159.938
9	1.24	-0.03	4.30	136.733	114.013	159.566
10	1.17	-0.08	4.37	137.019	115.407	160.249

Table A-9. Center of gravity (cm) and moments of inertia ($kg\text{-}cm^2$). Cell D: Helmet and head on small instrument.

Test	CGx	CGy	CGz	Ix	Iy	Iz
1	-0.76	0.13	3.28	359.090	366.425	313.325
2	-0.79	0.17	3.27	357.747	369.495	318.301
3	-0.74	0.05	3.33	358.776	367.086	316.766
4	-0.79	0.09	3.37	357.034	366.671	317.000
5	-0.79	0.08	3.31	358.283	368.345	315.470
6	-0.84	0.08	3.41	359.925	366.321	314.790
7	-0.73	0.01	3.36	359.481	366.792	314.567
8	-0.74	-0.01	3.26	358.787	366.706	314.691
9	-0.73	0.09	3.28	358.970	366.601	312.784
10	-0.77	0.06	3.37	357.268	366.401	316.059

Table A-10. Center of gravity (cm) and moments of inertia ($kg\text{-}cm^2$). Cell D: Helmet and head on large instrument.

Test	CGx	CGy	CGz	Ix	Iy	Iz
1	-0.76	0.13	3.28	362.806	377.461	319.801
2	-0.79	0.17	3.27	361.941	379.775	322.514
3	-0.74	0.05	3.33	364.634	377.520	318.679
4	-0.79	0.09	3.37	360.994	378.125	321.274
5	-0.79	0.08	3.31	362.473	379.188	321.326
6	-0.84	0.08	3.41	360.661	384.116	322.541
7	-0.73	0.01	3.36	363.660	380.836	321.059
8	-0.74	-0.01	3.26	363.846	381.103	321.374
9	-0.73	0.09	3.28	363.207	377.655	321.448
10	-0.77	0.06	3.37	361.880	376.406	321.821

Table A-11. Helmet fit on manikin head: distance from head CG to helmet CG; yaw, pitch and roll angles from anatomical to helmet system.

Test	CG Distances (inches)			Angular Displacement (degrees)		
	x	y	z	yaw	pitch	roll
1	1.00	17.58	0.77	0.00	0.25	1.11
2	0.98	17.60	0.76	-0.04	0.33	1.11
3	1.01	17.64	0.76	0.04	0.12	1.19
4	0.98	17.61	0.78	-0.04	0.21	1.27
5	0.99	17.55	0.78	-0.04	0.16	1.15
6	0.99	17.62	0.78	-0.12	0.16	1.31
7	0.98	17.64	0.77	0.04	0.04	1.23
8	1.01	17.58	0.78	0.04	0.04	1.07
9	0.99	17.58	0.78	0.04	0.16	1.07
10	1.01	17.64	0.80	-0.30	0.02	1.33

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