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INERTIAL PROPERTIES OF AN EXTERNAL-FRAME BACKPACK DEVICE

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U.S. Army Soldier and Biological Chemical Command
Soldier Systems Center
Natick, Massachusetts 01760-5020

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14. ABSTRACT
Previously, an external-frame backpack device (35 kg) was fabricated allowing for the placement of a 24.9-kg lead brick load in nine different positions. The purpose of this report was to determine the moment of inertia (MOI) of the backpack for the nine load positions relative to: the backpack's center of mass (COM); reference axes originating on the backpack frame; the COM for the human torso and backpack combined; and the COM for the human body and backpack combined. For the backpack about its COM, the lowest MOI values were found when the COM was located intermediate/central and intermediate/close relative to the load-carrier's trunk. For the backpack relative to the reference axes, the lowest MOI values were found when the COM was located low/central and low/close to the trunk. For the torso and backpack system and for the body and backpack system, the lowest MOI values were found when the COM relative to the trunk was in the intermediate/close or high/close position and the low/close or intermediate/close position, respectively. These data will be used in research examining the effects of manipulations of the COM and the MOI of backpack loads on load carriers' biomechanical and physiological responses.

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Preface and Acknowledgements

The research reported here was conducted during the period from 1 November 2001 to 1 August 2002 under Project Number AH98 and Program Element Number 622786. The work was carried out under a joint program of the Natick Soldier Center (NSC) and the U.S. Army Research Institute of Environmental Medicine (USARIEM), and was entitled "Load Carriage Optimization for Enhanced Warfighter Performance." The program of applied research into the carrying of loads by dismounted troops has been designated a high-priority effort by the Department of Army (DA Science and Technology Objective IV.G.14) and the Department of Defense (DoD Technology Objective M12).

This report is a presentation of the methods and analyses applied to determine the inertial properties of a custom external-frame backpack and the findings from the effort. The work was done at the Center for Military Biomechanics Research, U.S. Army Soldier Systems Center, Natick, MA. The backpack was designed by the Bioengineering Branch at USARIEM to permit a weight to be placed in any of nine specific locations within the pack. The backpack was used in a study to determine the relationship between the sagittal plane location of the center of mass of the loaded pack and the metabolic cost of walking while carrying the load. The reference for the original study is:

Obusek, J. P., Harman, E. A., Frykman, P. N., Palmer, C. J., & Bills, R. K. (1997). The relationship of backpack center of mass location to the metabolic cost of load carriage. *Medicine and Science in Sports and Exercise, 29* (5), S205.

The authors would like to thank COL John P. Obusek and the Bioengineering Branch, USARIEM, for the use of the backpack.

INERTIAL PROPERTIES OF AN EXTERNAL-FRAME BACKPACK DEVICE

Introduction

When considering linear motion, the mass of a body is the inertial property representing the resistance to linear acceleration. However, when rotary motion is involved, mass as well as how that mass is distributed about a particular axis of rotation must be considered (Martin, Hinrichs, Shin, & Nelson, 1982). The moment of inertia (MOI) of a body describes the distribution of mass about a specified axis of rotation and, therefore, is the inertial property that represents a body's resistance to angular acceleration (Hinrichs, Lallemant, & Nelson, 1982; Martin et al.).

In the field, soldiers are required to perform many actions that involve quick changes in angular motion, such as a sudden change of direction while running and "hitting the dirt," as well as prolonged load carriage marches (Hinrichs et al., 1982). The additional mass and moment of inertia of a backpack may affect a soldier's health and ability to perform these actions as intended, quickly and in a controlled manner (Martin et al., 1982). LaFiandra, Holt, Wagenaar, and Obusek (2002b) found that, compared with a condition in which a backpack was not used, carrying a backpack with the load mass close to the body and high on the back, at shoulder height, resulted in an increase in transverse plane upper body torque and net body torque during walking on a horizontal treadmill. Further, in a study in which transverse plane upper body MOI was systematically increased through a backpack device that allowed weights to be manipulated in the transverse plane without an increase in the mass, LaFiandra, Holt, Wagenaar, and Obusek (2002a) found that, as the MOI increased in the transverse plane, upper body torque and net body torque increased. An increase in upper body torque will increase torsional loading of the spine, which in turn is a possible mechanism of injury (White & Panjabi, 1978). In addition, as the mass and moment of inertia of the backpack increase about a given axis, the ability of the soldier to initiate a change in angular motion about that axis becomes more difficult. Similarly, ceasing that movement once started is more difficult. Therefore, a backpack with a reduced mass and a small moment of inertia is desired, and one with a large mass and a large moment of inertia is contraindicated (Hinrichs et al.).

The actions that soldiers perform involving quick changes in angular motion typically require angular motion about the soldier's z axis (longitudinal axis), such as a change of direction while running, and about the y axis (medial-lateral axis), such as "hitting the dirt" (Hinrichs et al., 1982). Therefore, having small MOI values about these two principal axes is more critical than about the x axis (anterior-posterior axis). However, it is undesirable for the MOI about either the y or the z axis to be the intermediate moment of inertia, where its magnitude lies between those of the other two principal moments of inertia. When a body rotates about a principal axis that has the minimum or the maximum moment of inertia value, a small disturbance to that rotation will not grow, and the body will continue to rotate about that axis (Greenwood, 1965).

Therefore, the motion is considered to be stable (Greenwood; Wardle, 2001). However, "a small disturbance in angular velocity tends to grow if it is applied to a body which is rotating about the principal axis corresponding to the intermediate moment of inertia" (Greenwood). Therefore, rotation about an axis that has an intermediate MOI value is unstable, and the body will appear to be "out of control" (Greenwood; Wardle). The body will tend to rotate about the other two axes as well, which may make it difficult to control the rotation.

Previously, an external-frame backpack was designed to permit a weight, in the form of a 24.9-kg, lead brick, to be placed in any of nine specific locations within the pack (Obusek, Harman, Frykman, Palmer, & Bills, 1997). Along the x axis, the load could be located in positions close, central, and away from the load-carrier's back and, in the z axis, it could be located high, intermediate, and low relative to the back. The y axis location could not be changed. In this axis, the load was aligned with the approximate center of the load-carrier's back. The mass of the backpack, including the frame, straps, and the lead weight, equaled 35 kg. The backpack was designed to be a testing device for use in studying the effects of the weight carried and the distribution of the weight on the physical performance of soldiers. The backpack was intended to exemplify the possible center of mass (COM) locations of a soldier's backpack load while in the field, and the mass of the pack was intended to mimic the maximum approach load as described in Field Manual 21-18 (Department of the Army, 1990). In a study conducted on 11 male soldiers, Obusek et al. assessed the relationship between the sagittal plane location of the COM of the loaded backpack and the metabolic cost of carrying the load while walking. They found that a high metabolic cost was associated with a low COM position.

Hinrichs et al. (1982) also manipulated backpack COM. However, they used conventional external-frame backpacks, as opposed to a specially fabricated testing device, and investigated the inertial properties of the backpacks when they were loaded in various configurations, as opposed to studying human performance as affected by COM of the load. An Army backpack, the All-Purpose Lightweight Individual Carrying Equipment (ALICE), was one of the backpacks studied by Hinrichs et al. Until August 2001, the ALICE was the Army's standard-issue equipment for the carrying of backpack loads. Using a total of 12 kg of clothing and equipment that soldiers typically carry in their packs, Hinrichs et al. established low, intermediate, and high placements of this basic load within the ALICE pack by making subjective judgments of the densities of the items comprising the load. Hinrichs et al. found that moving the basic load from a low to a high position in the ALICE backpack raised the COM in the z axis by approximately 0.04 m, but had little effect on the MOI about the x, y, or z axis. With the basic load in the intermediate position, adding two lead weights totaling 9.12 kg to either the bottom or the top of the pack produced relatively large increases in the MOIs about the x and the y axes and relatively small increases in the MOI about the z axis, compared with the MOI values for the basic load alone. Placing the lead weights on the top of the backpack raised the COM in the z axis by about 0.18 m, compared with the placement of the weights on the bottom surface of the pack. The top placement also resulted in slightly lower MOIs about both the x and the y axes than the bottom placement did.

Data comparable to those generated for the ALICE backpack by Hinrichs et al. (1982) are not available for the backpack device used by Obusek et al. (1997). At the time that the Obusek et al. study was conducted, the moment of inertia of the custom external-frame backpack was not determined for any of the nine different load positions. Since the inertial characteristics of a loaded backpack may have an effect on the soldier's health and ability to perform physical activities, we thought it important to measure the MOI of the backpack device in the nine different positions. In the work reported here, we determined MOI values relative to the COM locations of the backpack device and relative to reference axes originating on the backpack frame, toward its bottom edge. Establishing reference axes on the frame served to keep the origin the same for the nine load positions, making differences among the inertial properties of the positions easy to identify. These two sets of measurements involve the backpack only and do not capture the inertial characteristics of the human-backpack system. Therefore, we generated two additional sets of data, one for the human torso and backpack system (torso & backpack) and one for the full human body and backpack system (body & backpack).

Martin et al. (1982), extending the Hinrichs et al. (1982) effort on measuring the inertial properties of external-frame backpacks, developed a mathematical model of the inertial characteristics of a human-backpack system. Martin et al. treated the human as a rigid body and constructed both male and female human body models. They derived COM and MOI values for the body from data presented by Hanavan (1964), who devised a human model that incorporated simple, symmetrical, geometric forms. Four designs of backpack systems were tested by Martin et al., with the weights and the locations of the loads in the packs being varied. A basic load of military clothing and equipment weighing 9.07 kg was placed in the pack and the location of additional weights of up to 13.6 kg was manipulated. The ALICE pack and frame was one of the systems included in the study. The heaviest load tested in the ALICE was 26.11 kg, which included the 3.44-kg weight of the pack and frame. The findings for the male body model and the heaviest load in the ALICE indicated that centering the added load relative to the y and the z axes and placing it close to the trunk along the x axis resulted in lower MOIs about the y and the z axes than did placing the added load away from the trunk along the x axis. Similarly, when the added load was centered with respect to the x and the y axes and located low in the pack relative to the z axis, MOIs about the x and the y axes were lower than they were when the added load was placed high in the pack.

In this work, we used a different human model than the geometric model used by Martin et al. (1982). The one used here was based on a study by Chandler, Clauser, McConville, Reynolds, and Young (1975) of the mass distribution properties of six male cadavers. There is a paucity of data on the inertial characteristics of humans and the data that are available are based on small sample sizes. However, it has been suggested that better estimates of mass distribution properties are obtained from cadaver data than from presently available geometric models, such as that used by Martin et al. (Reynolds, 1978). In addition to measuring the inertial properties of intact cadavers, Chandler et al. took measurements on body segments. The availability of the segment data allowed us to extend our work to include investigation of the inertial properties of the torso and backpack system.

The data we generated in this study of the inertial characteristics of the backpack device designed for manipulating COM location complement the data from the study by Obusek et al. (1997) in which energy expenditure was assessed among soldiers carrying the device. The measurements we report here will be used in future work to analyze the data obtained by Obusek et al. for effects of MOI, as well as for effects of COM. Also, the methods we exercised for quantifying inertial properties of backpack loads serve as the foundation for planned research into the biomechanical and physiological effects of manipulating load COM and MOI independently. The specific purposes of undertaking the testing of the backpack device were:

1. To determine the backpack COM locations for the nine different load positions and the MOI values about the COMs;

2. To establish the backpack MOIs for the nine different load positions relative to reference axes originating at the lower left corner of the backpack frame;

3. To estimate the MOIs of the torso & backpack system and the body & backpack system about each system's COMs for the nine different load positions, using data obtained from measurements of the mass properties of human cadavers.

Method

Backpack System

The backpack used in this study was a custom external-frame backpack, designed by the Bioengineering Branch of USARIEM. The pack was secured to an Army-issue frame, the frame of the ALICE. The ALICE frame was made of aluminum tubing and had metal loops to which straps were attached. The straps for the custom backpack system were standard Army items that are worn as part of the ALICE. The shoulder straps and a lower back strap were made of cloth spacer material covered with nylon duck, and the waist strap was made of narrow webbing. The custom backpack itself was made of metal. Within it, a 24.9-kg lead brick load could be placed in three positions along the x axis relative to the load-carrier's trunk: close, central, and away from the back. In addition, the backpack was adjustable along the z axis allowing for high, intermediate, and low positions relative to the load-carrier's trunk. The result is a total of nine different load positions. Load position was fixed along the y axis, with the load being placed symmetrically relative to the midline of the pack. The mass of the backpack with the lead weight, frame, and straps was 35 kg. The nine different load positions are graphically displayed in Figure 1, where position 1 represents high and away and position 9 represents low and close relative to the load-carrier's back. Figure 2 shows the backpack from a side and from an angled view. Some dimensions of the pack and frame are also included in the figure. Figure 3 shows the inside of the pack, in load position 7 (low and away), with the lead brick load placed symmetrically about the midline.

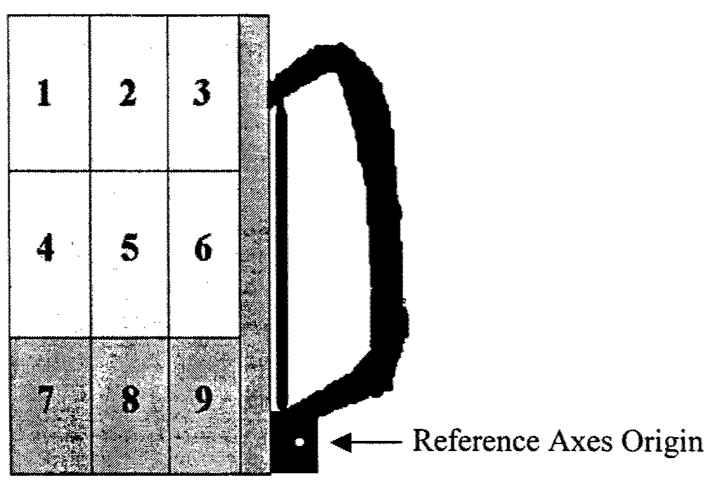

Figure 1. Schematic diagram of the nine load positions from a left lateral view, where position 1 represents high and away and position 9 represents low and close relative to the wearer's back. The backpack reference axes origin located on the lower left corner of the backpack frame is shown.

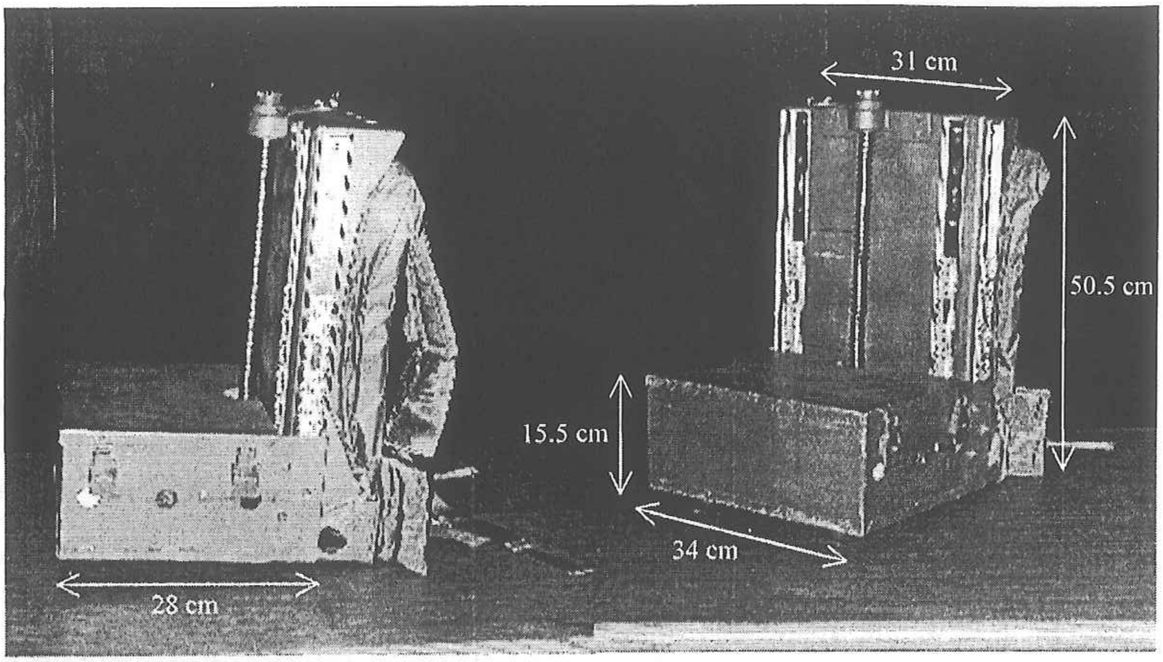

Figure 2. Side and angled views of the custom backpack with the dimensions of the pack and frame shown.

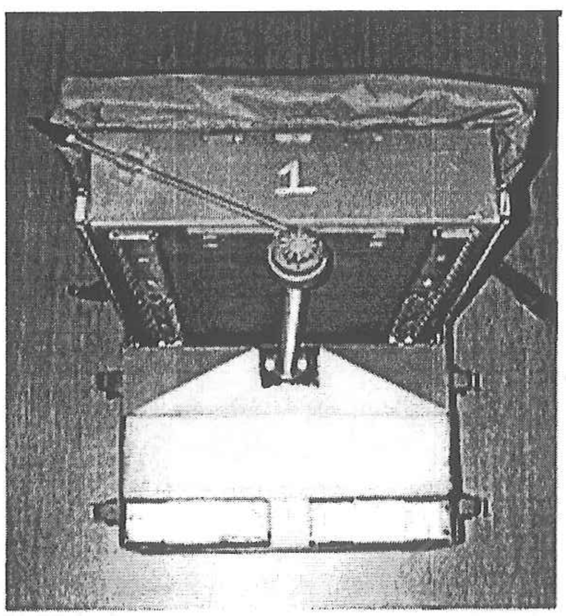

Figure 3. Overhead view of the inside of the pack, in load position 7 (low and away), with the lead brick load placed symmetrically about the midline.

Backpack Holder

A rigid, aluminum holder was designed to stabilize the backpack while the mass distribution measurements were being taken. The holder was based on a previously designed aluminum holder that was used to stabilize an ALICE pack and frame (Hinrichs et al., 1982). The backpack was firmly fixed to the rear end of the holder for all testing. Figure 4 shows the backpack inside its aluminum holder. The rear left corner of the holder was defined as the reference corner, and a set of three orthogonal coordinate axes was defined relative to that corner, as illustrated in Figure 5. The x axis was oriented from front to back, the y axis from left to right, and the z axis from bottom to top. The dimensions of the holder were 0.412 m, 0.470 m, and 0.456 m along the x, y, and z axes, respectively.

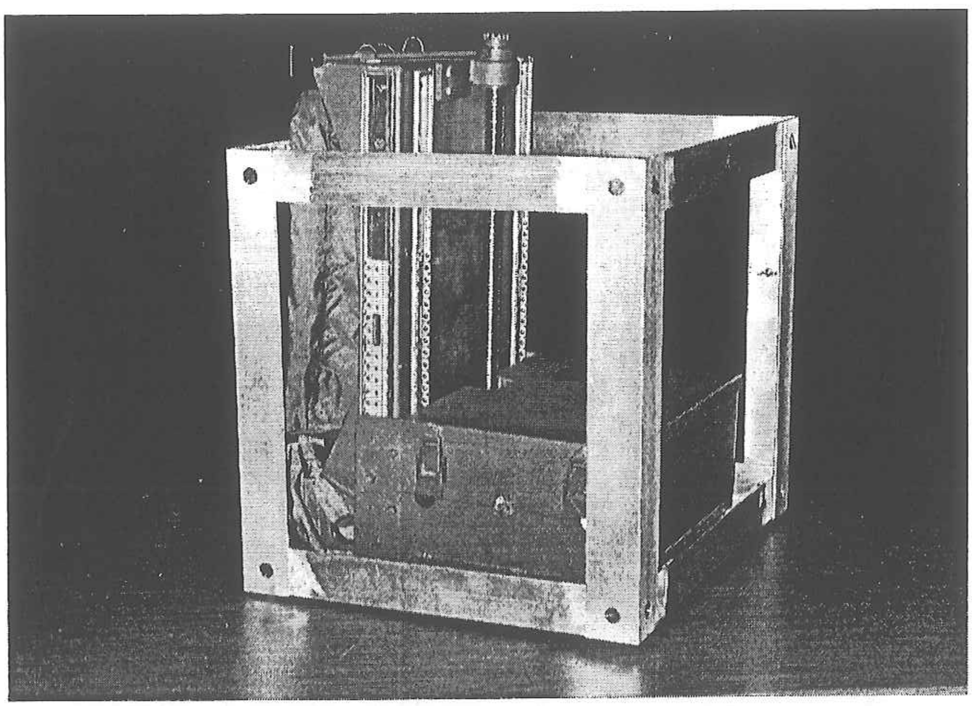

Figure 4. Backpack firmly fixed to the rear edge of the holder.

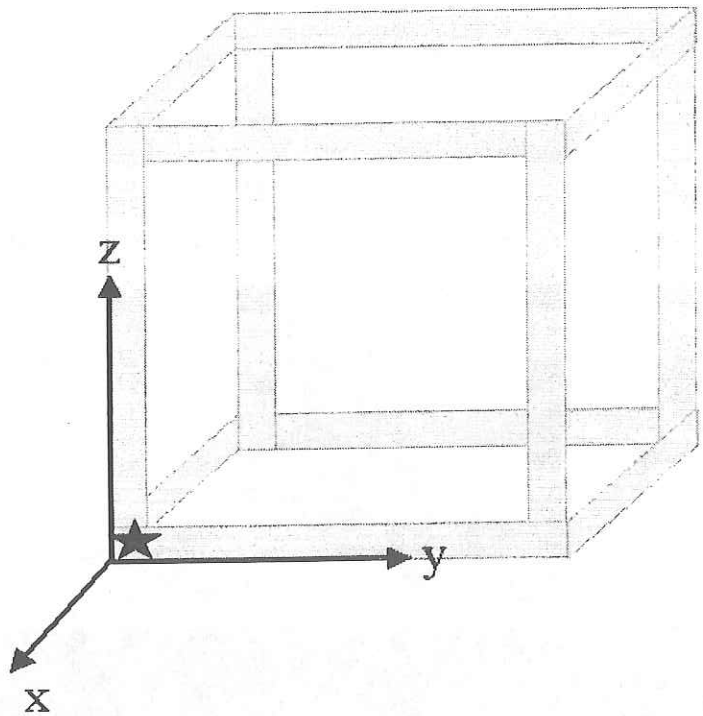

Figure 5. Schematic diagram of the holder from a rear view showing reference corner of the holder (rear left corner).

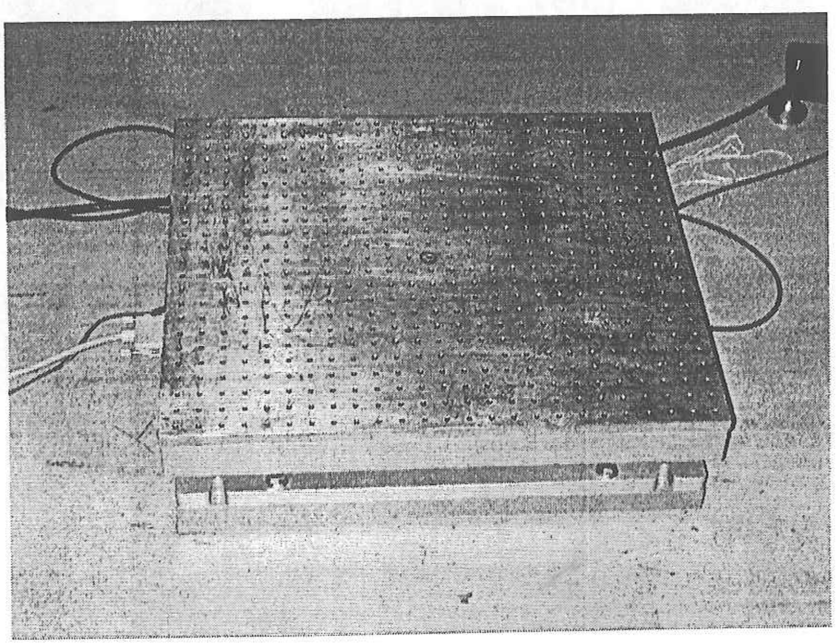

Figure 6. Force plate used to measure mass and COM of holder, backpack, and composite.

Mass

A force plate (Model OR6-5, AMTI, Watertown, MA) was used to measure the mass of the holder (6.077 kg), the backpack (35 kg), and the composite (41.077 kg). The composite was comprised of the holder with the backpack in place. The dimensions of the force plate were 0.508 meters along the y axis and 0.464 meters along the x axis. Mass was measured to the nearest 0.001 kg. Figure 6 shows the AMTI force plate.

Center of Mass

Force and moment data were measured and collected using the AMTI force plate interfaced with a computer-based data acquisition system. The data acquisition system consisted of a microcomputer with LabVIEW Version 6*i* (National Instruments, Austin, TX) and a 16-bit 64 channel data acquisition board (National Instruments). The voltage output from the force plate was sampled at 1000 Hz. LabVIEW was used to collect, display, and analyze the force plate data.

For each measurement, the test object was placed on the plate and raw data were collected for one second (1000 ms). Center of pressure (COP) for both x and y coordinates was computed from the raw force and moment data at each millisecond interval and then averaged across the 1000 ms. Averaging the data over the 1000-ms window aided in reducing the noise on the COP measurement. The average standard deviation for the one-second sample (1000 readings) was 0.00009 m and 0.00012 m for the x and y coordinates, respectively. For static objects, on a horizontal surface, the line of gravity (COP) passes through the center of mass of the object. Hence, we refer to the COP of the object as the center of mass of the test part.

A custom aluminum interface plate, which consisted of a matrix of precision-drilled holes 2 cm on center, was placed on the force plate to allow for the accurate measurement of the COM locations, as illustrated in Figure 6. The dimensions of the interface plate were the same as those of the force plate, 0.508 meters along the y axis and 0.464 meters along the x axis, and the mass of the interface plate was 8.12 kg.

The COMs of the holder and of the composite (i.e., the holder and the backpack) relative to the reference corner of the holder were determined, which then allowed for the calculation of the COM of the backpack relative to the reference corner. The origin of the force plate was located in the geometric center of the plate. The reference corner of the holder was always placed in the lower left quadrant of the force plate when determining the COM position in the xy, xz, and yz planes of the holder and the composite. The following three equations from Serway (1990) were used to determine the x, y, and z components of the backpack COM with respect to the reference corner of the holder:

$$x_p = (M_c x_c - M_h x_h) / M_p \qquad (1)$$

$$y_p = (M_c y_c - M_h y_h) / M_p \quad (2)$$

$$z_p = (M_c z_c - M_h z_h) / M_p \quad (3)$$

where M_c, M_h, M_p are the mass of the composite, holder, and backpack, respectively, and x_c, y_c, and z_c are the distances (x, y, and z component) the composite COM was from the reference corner of the holder, and x_h, y_h, and z_h are the distances (x, y, and z component) the holder COM was from the reference corner of the holder.

The sensitivity of the force plate for the vertical force (F_z) channel has been reported by the manufacturer to be 0.08 micro-volt/volt/N (AMTI, 1991). With the amplifier gain set at 4000 and the excitation voltage equal to 10 volts, the output level for a 60-kg load would equal 1.88 volts and, with a 7-kg load, the output level would equal 0.22 volts. The accuracy of the force plate was factory tested at a low limit of 60 pounds, which yielded a 1-mm error in center of pressure measurement (AMTI, Personal Communication, June, 2001). In addition to the testing by the manufacturer, we tested the error of the COP measurement with objects weighing 7 kg and found a maximum 8-mm error in COP measurements. Placing the 7-kg object in different marked positions in different quadrants of the force plate and measuring the COP yielded values that had a range of differences from 2 mm to 8 mm. These differences are due to the low output level of the plate.

Based on the testing, an 8-mm error in COP measurements was assumed, and this error was found to be acceptable in the determination of the COM of test parts and in the determination of MOI values. As an example of the impact of the error, assuming the COM of a 7-kg test part had an error of 8 mm, the MOI would change by only $\pm 0.000448\ kg\cdot m^2$.

Moment of Inertia

Relative to backpack COM. The x, y, and z axes passing through the COM of the backpack and parallel to the coordinate axes of the reference corner of the holder were chosen as the coordinate axes for this measurement. If the chosen axes correspond to the "principal axes of inertia", the products of inertia (I_{xy}, I_{xz}, and I_{yz}) vanish, and the terms describing the MOI about the x, y, and z axes (I_{xx}, I_{yy}, and I_{zz}) are the only terms that need to be considered. For more information on these six parameters, known as the "inertia tensor", the reader should refer to such texts as Synge and Griffith (1942) and Greenwood (1965).

A Moment of Inertia Instrument (Model XR250, Space Electronics, Inc., Berlin, CT) was used to determine the MOI of the backpack about the x, y, and z axes passing through the backpack's COM. The MOI accuracy as listed in the manual specifications is 0.25% of reading plus $2.926 \times 10^{-7}\ kg\cdot m^2$ (Space Electronics, Inc., n.d.). This MOI instrument, shown in Figure 7, consisted of an inverted torsion pendulum that oscillated in a rotational manner. The measuring of the exact period of oscillation of the torsion pendulum was accomplished through a counter that interpreted the outputted TTL signal from the device. LabVIEW Version 6*i* (National Instruments, Austin, TX) was used to develop the program to compute the inertial properties of the backpack using the equations described below.

A custom aluminum interface platform was designed for mounting on the pendulum. The interface platform was fixed to the MOI device to allow for the most efficient placement of the composite. The MOI platform interface and dimensions and the force plate interface and dimensions were identical. This allowed for the identical alignments of the holder/composite on the force plate and on the MOI device. Once the COM position was determined on the force plate for each plane (xy, xz, yz), the composite was placed in the same position on the interface platform fixed to the MOI device. The placement of the composite was such that the axis of rotation of the MOI device passed through the COM of the composite in each plane, permitting the acquisition of the MOI about the x, y, and z axes, as illustrated in Figure 7. Manufacturer-supplied instructions were then followed to operate the device to obtain the MOI (Space Electronics, Inc., n.d.).

The total time for one complete cycle is the period of the oscillation. The tofal system MOI can be given by:

$$I_T = CT^2 \quad (4)$$

where I_T is the total system MOI, C is the calibration constant of the instrument, and T is the mean period of three consecutive oscillations, in seconds (Space Electronics, Inc., n.d.). The average standard deviation of the three consecutive oscillations was 0.00114 seconds. To test the accuracy of the measurement, the average standard deviation of three mean periods was taken and found to be 0.00087 seconds.

The calibration constant was determined by using a calibration weight provided by the manufacturer of the MOI device. The exact MOI of the calibration weight was engraved on the weight and allowed for the calculation of the calibration constant from the following equation:

$$C = I_{cw}/(T_c^2 - T_o^2) \quad (5)$$

where I_{cw} is the calibration weight MOI, T_c is the period with the calibration weight mounted on the instrument, and T_o is the period with the weight removed (Space Electronics, Inc., n.d.). The procedure to determine the calibration constant was completed before the start of the study.

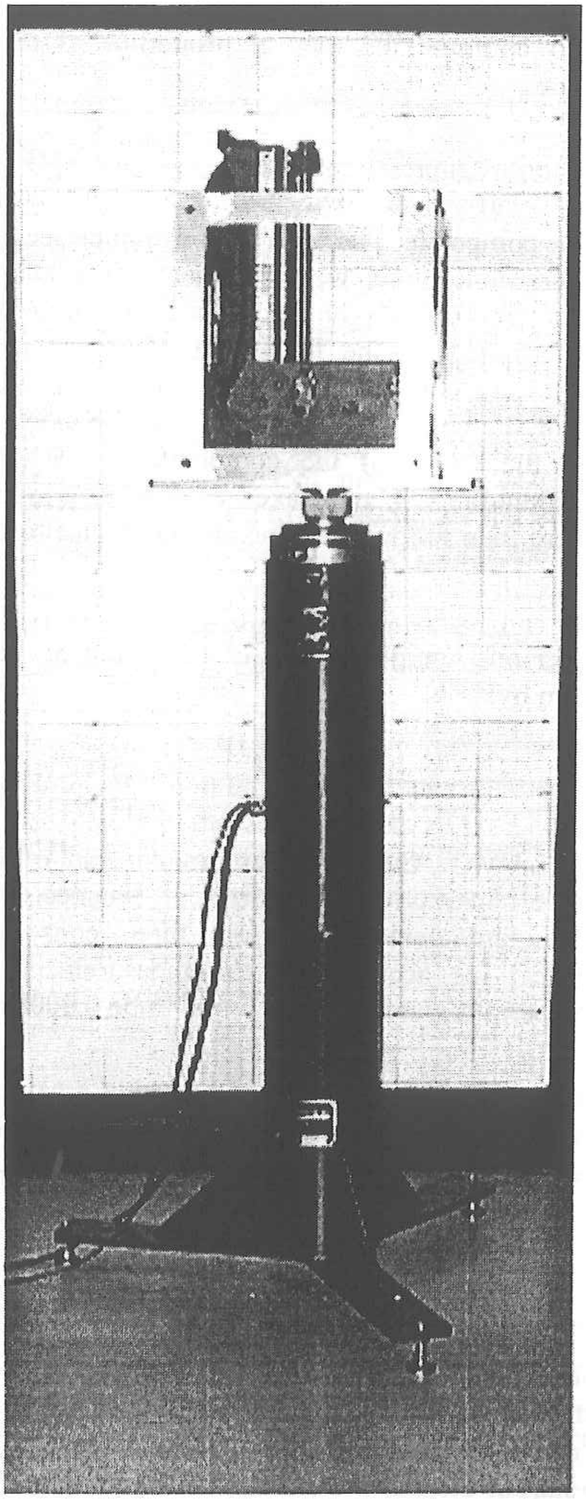

Figure 7. Moment of Inertia Instrument used to determine the MOI of the backpack.

With the calculation of the calibration constant, the total system MOI (I_T) could be determined and could be expressed as the combination of the platform MOI (I_{pl}), the holder MOI (I_h), and the backpack MOI (I_p):

$$I_T = I_{pl} + I_h + I_p \tag{6}$$

In order to determine the components that make up the total MOI and specifically the MOI of the backpack about the axis that runs through its center of mass, the parallel-axis theorem was utilized. Serway (1990) provided the following equation, which then allowed for the calculation of the MOI of the backpack about its COM. The parallel-axis theorem states that the moment of inertia about any axis (I) that is parallel to and a distance d away from the axis that passes through the center of mass is given by:

$$I = I_{CM} + Md^2 \tag{7}$$

where I_{CM} is the MOI about the COM and M is the mass (Serway, 1990).

Since the platform was symmetrical, the COM of the platform was located in the geometric center of the plate directly over the axis of rotation of the MOI device. Therefore, the d^2 term in the parallel-axis theorem is zero and

$$I_{pl} = I_{CMpl} \tag{8}$$

The MOI of the holder (I_h) is given by

$$I_h = I_{CMh} + M_h d_h^2 \tag{9}$$

where I_{CMh} is the MOI of the holder about the axis that passes through the COM of the holder, M_h is the mass of the holder, and d_h is the distance the COM of the holder was displaced when the COM of the composite was placed over the axis of rotation.

The MOI of the backpack (I_p) is given by

$$I_p = I_{CMp} + M_p d_p^2 \tag{10}$$

where I_{CMp} is the MOI of the backpack about the axis that passes through the COM of the backpack, M_p is the mass of the backpack, and d_p is the distance the COM of the backpack is from the axis of rotation.

Substituting equations 8, 9, and 10 into 6 permits the calculation of I_{CMp} and gives the following equations for the backpack MOI about the x, y, and z axes, respectively:

$$I_{xx} = I_{CMpxx} = I_T - I_{pl} - I_{CMhxx} - M_h d_{hx}^2 - M_p d_{px}^2 \quad (11)$$

$$I_{yy} = I_{CMpyy} = I_T - I_{pl} - I_{CMhyy} - M_h d_{hy}^2 - M_p d_{py}^2 \quad (12)$$

$$I_{zz} = I_{CMpzz} = I_T - I_{pl} - I_{CMhzz} - M_h d_{hz}^2 - M_p d_{pz}^2 \quad (13)$$

To obtain the products of inertia (I_{xy}, I_{xz}, I_{yz}), a custom made aluminum cradle, similar to that used by Albery, Schultz, and Bjorn (1998), was utilized. The MOI about the noncardinal axes in the xy, xz, and yz planes ($I_{\alpha\alpha}$, $I_{\beta\beta}$, and $I_{\gamma\gamma}$, respectively) was needed for the calculations of the products of inertia. The $\alpha\alpha$, $\beta\beta$, and $\gamma\gamma$ axes were oriented 45 degrees from the chosen coordinate axes. Therefore, the cradle was designed to hold the composite at a 45-degree angle from its chosen coordinate axes, as illustrated in Figure 8. The cradle and holder were considered one fixture, and the above COM and MOI determination procedures were followed. Once $I_{\alpha\alpha}$, $I_{\beta\beta}$, and $I_{\gamma\gamma}$ were determined, the products of inertia were computed using the following equations:

$$I_{xy} = (I_{xx} + I_{yy} \tan^2\alpha - (1+ \tan^2\alpha)\, I_{\alpha\alpha}) / 2 \tan\alpha \quad (14)$$

$$I_{xz} = (I_{xx} + I_{zz} \tan^2\beta - (1+ \tan^2\beta)\, I_{\beta\beta}) / 2 \tan\beta \quad (15)$$

$$I_{yz} = (I_{yy} + I_{zz} \tan^2\gamma - (1+ \tan^2\gamma)\, I_{\gamma\gamma}) / 2 \tan\gamma \quad (16)$$

where α is the angle between the x and $\alpha\alpha$ axes, β is the angle between the x and the $\beta\beta$ axes, and γ is the angle between the y and the $\gamma\gamma$ axes (Hinrichs et al., 1982). With the composite placed in the cradle, α, β, and γ are all 45 degrees. If the chosen axes correspond to the "principal axes of inertia", the products of inertia (I_{xy}, I_{xz}, and I_{yz}) vanish, and the terms describing the MOI about the x, y, and z axes (I_{xx}, I_{yy}, and I_{zz}) are the only terms that need to be considered.

Relative to the reference axes. The MOI of the backpack in the nine load positions was also related to reference axes originating on the lower left corner of the backpack frame. Figure 1 shows the location of the reference axes origin on the frame. Since the nine COM positions were related to the corner of the holder, the distance (x, y, z component) from the corner of the holder to the reference axes origin was measured to determine the COM positions relative to the reference axes origin. Those components were subtracted from the x, y, and z components of the COM of the backpack referenced to the corner of the holder to obtain the coordinates of the COM relative to the reference axes origin on the backpack frame. The new coordinates were then used to determine the distance the backpack COM was from the reference axes origin, and the parallel-axis theorem was again utilized to determine the MOI about the x, y, and z axes:

$$I_r = I_{CMp} + M_p d^2 \quad (17)$$

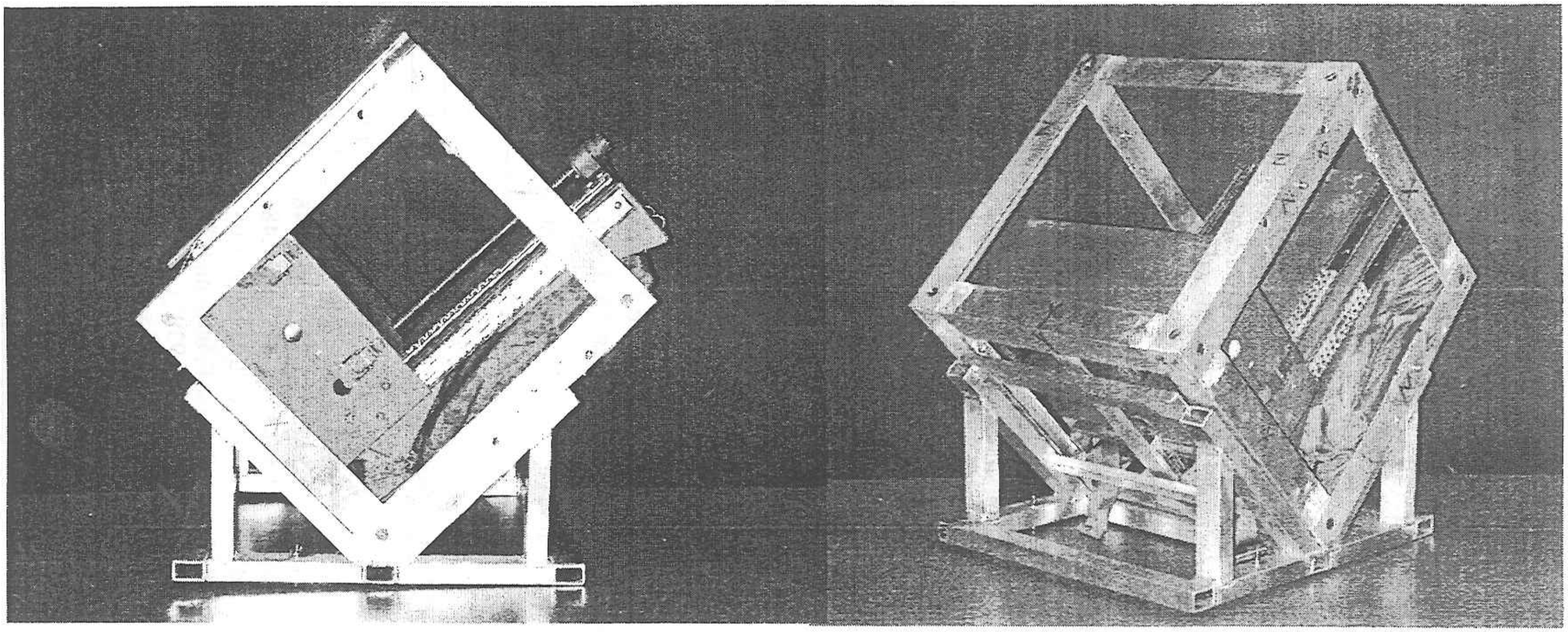

Figure 8. The custom made aluminum cradle designed to hold the composite at a 45-degree angle from its chosen coordinate axes.

where I_r is the backpack MOI relative to the reference axes origin, I_{CMp} is the backpack MOI relative to its COM, M_p is the backpack mass, and d is the distance the COM of the backpack is from the axis of rotation.

Relative to torso & backpack system COM and body & backpack system COM. Data reported by Chandler et al. (1975) were used to represent the mass properties of the human component of the system. Chandler et al. studied the cadavers of six adult male Caucasians. They made anthropometric measurements and determined the inertial properties (mass, COM, and principal MOI) of the intact body and of body segments. The cadavers were embalmed and frozen in either a standing or a sitting position. The torso and the whole-body data from the three cadavers measured in a standing position, with the arms at the sides, were used here. Chandler et al. designated these cadavers as Subjects 1, 2, and 3.

Some of the anthropometric measurements made by Chandler et al. (1975) on cadaver subjects 1, 2, and 3 are presented in Table 1, along with the means for these measurements calculated over the three subjects and the subjects' ages. Also included in Table 1 are means for comparable measurements made on 1774 U.S. Army men, who participated in the Army's most recent anthropometric survey (Gordon et al., 1989). Descriptions of the techniques used to make the anthropometric measurements on the cadavers and on the live subjects are presented in Appendix A. The data presented in Table 1 provide a basis for a general assessment of the differences between the cadaver and the male soldier measurements. However, the cadaver measurements, taken on only three subjects, are not representative of the male population. Furthermore, the relationship between data obtained from cadavers and data obtained from living subjects has not been established (Reynolds, 1978).

Table 1. *Anthropometric Measurements of Male Cadaver Subjects 1, 2, and 3 (Chandler et al., 1975) and Comparable Measurements Made on U.S. Army Men (Gordon et al., 1989)*

	Male Cadaver Subjects					U.S. Army Men[a]	
Measurement	Subj. 1	Subj. 2	Subj. 3	Mean	*SD*	Mean	*SD*
Age (years)	65	45	47	52.3	11.0	27.2	6.8
Weight (kg)	58.700	76.2	89.2	74.68	15.30	78.49	11.10
Stature (m)	1.678	1.817	1.742	1.746	0.070	1.756	0.067
Cervicale Ht. (m)	1.406	1.570	1.478	1.485	0.082	1.519	0.063
Omphalion Ht. (m)	1.015	1.103	1.039	1.052	0.045	1.059	0.051
Trochanterion Ht. (m)	0.857	0.969	0.867	0.898	0.062	0.928	0.048
Ant Sup Iliac Spine Ht. (m)	0.913	1.029	0.930	0.957	0.063	--	--
Iliac Crest Ht (m)	1.005	1.109	1.009	1.041	0.059	1.073	0.051
Chest Circum. (m)	0.940	1.014	1.055	1.003	0.058	0.991	0.069
Waist Circum. (m)	0.813	0.873	0.933	0.873	0.060	0.862	0.086
Waist Depth (m)	0.168	0.213	0.215	0.199	0.027	0.226	0.026

Note. A dash indicates that the measurement was not made.
[a]*N* = 1774

Tables 2 and 3 contain additional information from the study by Chandler et al. (1975). Table 2 is a list of the mass and the MOI values for the torso and for the whole body of Subjects 1, 2, and 3. Table 3 is a quantitative description of the location of the COM of the torso and of the whole body for these subjects. Research has shown that the COM of the whole body is approximately at the pelvis (Reynolds, 1978). The omphalion is an easily identified body surface landmark in the area of the pelvis. In Table 3, the x, y, and z coordinates of the omphalion referenced from the COM of the torso and from the COM of the whole body are presented.

Table 2. *Inertial Properties of the Torso and the Body (Mass (kg), MOI (kg·m^2); Chandler et al., 1975)*

Inertial Properties	Subj. 1	Subj. 2	Subj. 3	Mean	*SD*
Torso					
Mass	30.63	41.06	46.18	39.29	7.92
I_{xx}	1.4436	2.0449	2.3142	1.9342	0.4457
I_{yy}	0.9315	1.4320	1.8063	1.3899	0.4389
I_{zz}	0.2643	0.5008	0.6194	0.4615	0.1808
Body					
Mass	58.7	76.15	89.15	74.67	15.28
I_{xx}	9.8807	15.0886	16.9127	13.9607	3.6492
I_{yy}	8.9223	12.5580	14.1888	11.8897	2.6961
I_{zz}	1.1644	1.7424	2.2388	1.7152	0.5377

Table 3. *Omphalion Location Referenced From the Torso COM and the Body COM (m; Chandler et al., 1975)*

Axis	Subj. 1	Subj. 2	Subj. 3	Mean	*SD*
		Omphalion From Torso COM			
x	0.129	0.171	0.164	0.155	0.023
y	-0.007	-0.002	0.004	-0.002	0.006
z	0.126	0.160	0.155	0.147	0.018
		Omphalion From Body COM			
x	0.101	0.152	0.139	0.131	0.027
y	-0.017	0.006	-0.022	-0.011	0.015
z	-0.036	-0.024	-0.039	-0.033	0.008

The torso COM and the body COM were combined with the backpack COM to estimate each system COM separately. The point of contact between the reference point on the backpack frame and the torso and between the reference point on the frame and the body was defined to be at anterior superior iliac spine height, located at the posterior portion of the waist. The length of the ALICE frame is not adjustable and the frame is made in only one length. Thus, the actual location of the reference point on the frame relative to the body is likely to vary with load-carriers' body dimensions, such as waist back length. Furthermore, the length of the shoulder straps attached to the frame can be adjusted. Therefore, the relationship between the reference point on the frame and the body can change, depending upon the manner in which the load carrier adjusts the straps on a given occasion. From viewing a few soldiers wearing the backpack, we found that the reference point on the frame was in close proximity to the anterior superior iliac spine landmark. Thus, this landmark was used in the calculations presented here. Recognizing that the frame-body relationship can vary, we also carried out the calculations using a landmark slightly lower on the body, the trochanterion. Results related to that landmark are presented in Appendix B.

The equations that follow were used to derive an estimate of the torso & backpack system COM (x_{ts}, z_{ts}) and the MOI of the torso & backpack system (I_{tsxx}, I_{tsyy}, I_{tszz}) relative to the COM of the system. For the following calculations, symmetry about the sagittal plane was assumed.

$$x_{ts} = (M_t x_t + M_p x_p)/(M_t + M_p) \quad (18)$$

$$z_{ts} = (M_t z_t + M_p z_p)/(M_t + M_p) \quad (19)$$

$$I_{tsxx} = I_{txx} + M_t d_t^2 + I_{xx} + M_p d_p^2 \quad (20)$$

$$I_{tsyy} = I_{tyy} + M_t d_t^2 + I_{yy} + M_p d_p^2 \quad (21)$$

$$I_{tszz} = I_{tzz} + M_t d_t^2 + I_{zz} + M_p d_p^2 \quad (22)$$

where x_{ts} and z_{ts} are the x and z coordinates of the torso & backpack system, M_t and M_p are the mass of the torso and backpack, x_t and z_t are the x and z coordinates of the torso COM, x_p and z_p are the x and z coordinates of the backpack COM relative to the axes passing through the torso COM, I_{tsxx}, I_{tsyy}, and I_{tszz} are the torso & backpack system MOI values about the x, y, and z axis, respectively, I_{txx}, I_{tyy}, and I_{tzz} are the torso MOI values about the x, y, and z axis, respectively, I_{xx}, I_{yy}, and I_{zz} are the backpack MOI values about the x, y, and z axis passing through the backpack's COM, and d_t and d_p are the distances from the torso COM and backpack COM to the axis of rotation, respectively. The same set of equations, with the torso components replaced by the body components, was then used to derive an estimate of the body & backpack system COM (x_{bs}, z_{bs}) and the MOI of the body & backpack system (I_{bsxx}, I_{bsyy}, I_{bszz}) relative to the COM of the system.

Results

Center of Mass

Table 4 reports the COM results for the nine load positions of the backpack relative to: the reference axes origin located in the lower left corner of the backpack frame; the torso COM; and the body COM. All x-axis values are negative, indicating the convention used here of assigning a negative value to locations along that axis posterior to the reference location (i.e., away from the frame and the load-carrier's back and toward the pack). The values associated with the y axis are positive because the convention adopted was to assign positive values to all locations to the right of the reference point on the pack frame. The convention used for the z axis was to assign a positive value to all locations above the reference location and a negative value to all locations below that point.

Backpack COM relative to the reference axes. Since the movable lead weight was symmetrically placed about the midline of the pack, the variation in the y component of the backpack COM relative to the reference point on the frame is minimal (Table 4). Furthermore, it can be seen in Table 4 that, relative to the reference axes originating on the lower portion of the pack frame, positions 1, 2, and 3 yielded highly similar COM values along the z axis, as did positions 4, 5, and 6 and positions 7, 8, and 9. These results reflect the fact that the positions comprising each of these three sets were in approximately the same location relative to the z axis. The distance along the z axis between the three high and the three intermediate COM positions is approximately 0.14 m. Likewise, the distance along this axis between the intermediate and the low positions is approximately 0.14 m. Overall, the nine COM locations along the z axis, relative to the pack frame reference point, have a maximum value of 0.364 m and a minimum value of 0.094 m, a range of 0.270 m (Table 4).

With regard to the x component of the backpack COM relative to the reference point on the frame, positions 1, 4, and 7 yielded highly similar values, as did positions 2, 5, and 7 and positions 3, 6, and 9 (Table 4). These results reflect the fact that the positions comprising each of these three sets were in approximately the same location relative to the x axis, with positions 1, 4, and 7 being furthest away from the backpack frame and positions 3, 6, and 9 being closest. The distance along the x axis between the COM positions furthest from the frame and the central positions is approximately 0.05 m; the distance between the central positions and those closest to the frame approximates 0.06 m (Table 4).

Backpack COM relative to torso COM and to body COM. The values for backpack COM relative to torso COM and to whole body COM are also presented in Table 4 for each of the nine load positions (y-axis symmetry assumed). The backpack COM values along the x axis, expressed relative to torso COM, are greater, by 0.04 m, than the values along the x axis relative to the reference point on the lower portion of the pack frame. On the other hand, the values along the z axis are decreased by 0.24 m when

Table 4. *Backpack COM Relative to Reference Point on Backpack Frame (m) and to Torso COM (m), Torso & Backpack System COM Relative to Torso COM (m), Backpack COM Relative to Body COM (m), and Body & Backpack System COM Relative to Body COM (m)*

Load Position	Backpack COM Relative to Reference Point on Backpack Frame			Backpack COM Relative to Torso COM		Torso & Backpack COM Relative to Torso COM		Backpack COM Relative to Body COM		Body & Backpack COM Relative to Body COM	
	x	y	z	x	z	x	z	x	z	x	z
1	-0.232	0.162	0.364	-0.276	0.122	-0.130	0.058	-0.300	0.302	-0.096	0.096
2	-0.182	0.162	0.363	-0.226	0.121	-0.106	0.057	-0.249	0.301	-0.080	0.096
3	-0.125	0.162	0.359	-0.169	0.117	-0.080	0.055	-0.193	0.297	-0.061	0.095
4	-0.234	0.164	0.228	-0.278	-0.014	-0.131	-0.007	-0.301	0.166	-0.096	0.053
5	-0.185	0.165	0.227	-0.229	-0.015	-0.108	-0.007	-0.252	0.165	-0.080	0.053
6	-0.128	0.165	0.226	-0.172	-0.016	-0.081	-0.007	-0.195	0.164	-0.062	0.052
7	-0.231	0.167	0.095	-0.275	-0.147	-0.130	-0.069	-0.299	0.033	-0.095	0.010
8	-0.182	0.167	0.094	-0.226	-0.148	-0.106	-0.070	-0.249	0.032	-0.080	0.010
9	-0.127	0.167	0.094	-0.171	-0.148	-0.080	-0.070	-0.194	0.032	-0.062	0.010

backpack COM is expressed relative to torso COM, as opposed to relative to the reference point on the frame (Table 4). The values along the z axis are negative for positions 4 through 9, indicating that, in this axis, COM of the backpack was below the torso COM. The backpack COM values for the nine load positions relative to the torso COM are presented graphically in Figure 9.

Along the x axis, backpack COM values relative to whole body COM are increased by 0.07 m, compared with the values relative to the reference point on the pack frame. The COM values along the z axis are decreased by 0.06 m. The values along the z axis are all positive, indicating that the backpack COM in the z axis was above the whole body COM (Table 4). In Figure 10, the backpack COM values for the load positions relative to the whole body COM are presented.

Torso & backpack system COM relative to torso COM. The torso & backpack system COM values for the nine load positions are listed relative to the torso COM in Table 4 (y-axis symmetry assumed). As is the case for the backpack COM values relative to the pack frame reference point and relative to the torso COM, the values along the z axis for the torso & backpack system COM relative to the torso COM are highly similar for positions 1, 2, and 3. Positions 4, 5, and 6 also yielded highly similar z-axis values, as did positions 7, 8, and 9. Again, these results reflect the fact that the positions comprising each of these three sets were in approximately the same location relative to the z axis. The distance along the z axis between the three high and the three intermediate COM positions is about 0.06 m, as is the distance between the intermediate and the low positions. The highest COM value along the z axis is 0.058 m and the lowest is -0.070 m, for a range of 0.128 m (Table 4). Thus, the backpack and torso, considered together as a system, resulted in a reduction of the range of load position values along the z axis compared with the ranges for the backpack COM values relative to the pack frame reference point and relative to the torso COM.

For the torso & backpack system values along the x axis, relative to the torso COM, positions 1, 4, and 7 again yielded highly similar values, as did positions 2, 5, and 8 and positions 3, 6, and 9 (Table 4). As is the case with the backpack COM relative to the frame reference point and relative to the torso, the similar values for these three sets of data reflect the similar locations along the x axis of the positions comprising each set. The distance along the x axis between the COM positions furthest from the torso and the central positions is approximately 0.02 m, and the distance between the central positions and those closest to the torso is approximately 0.03 m (Table 4). Therefore, along the x axis, as well as along the z axis, combining the torso and the backpack as a single system resulted in a reduction in the range of COM values for the load positions compared with the ranges for the backpack COM values relative to the pack frame reference point and relative to the torso COM. The COM values for the torso & backpack system in the nine load positions relative to the torso COM are presented graphically in Figure 9, along with those of the backpack COM relative to the torso COM. The figure shows that the COMs for the nine load positions are condensed when the torso and backpack are considered as a system, as opposed to the backpack alone being considered.

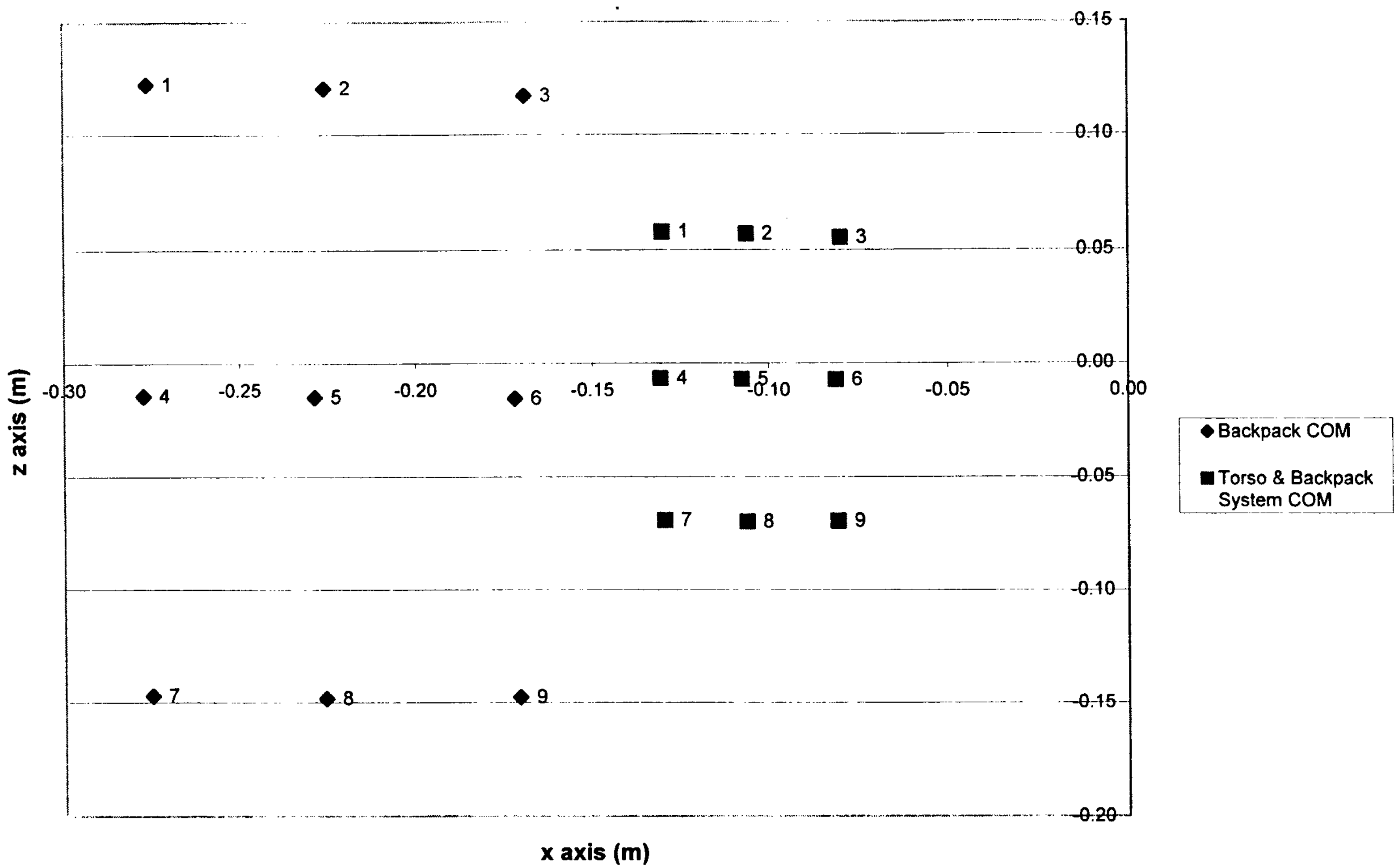

Figure 9. Backpack COM and torso & backpack system COM for the nine load positions relative to the torso COM (0,0).

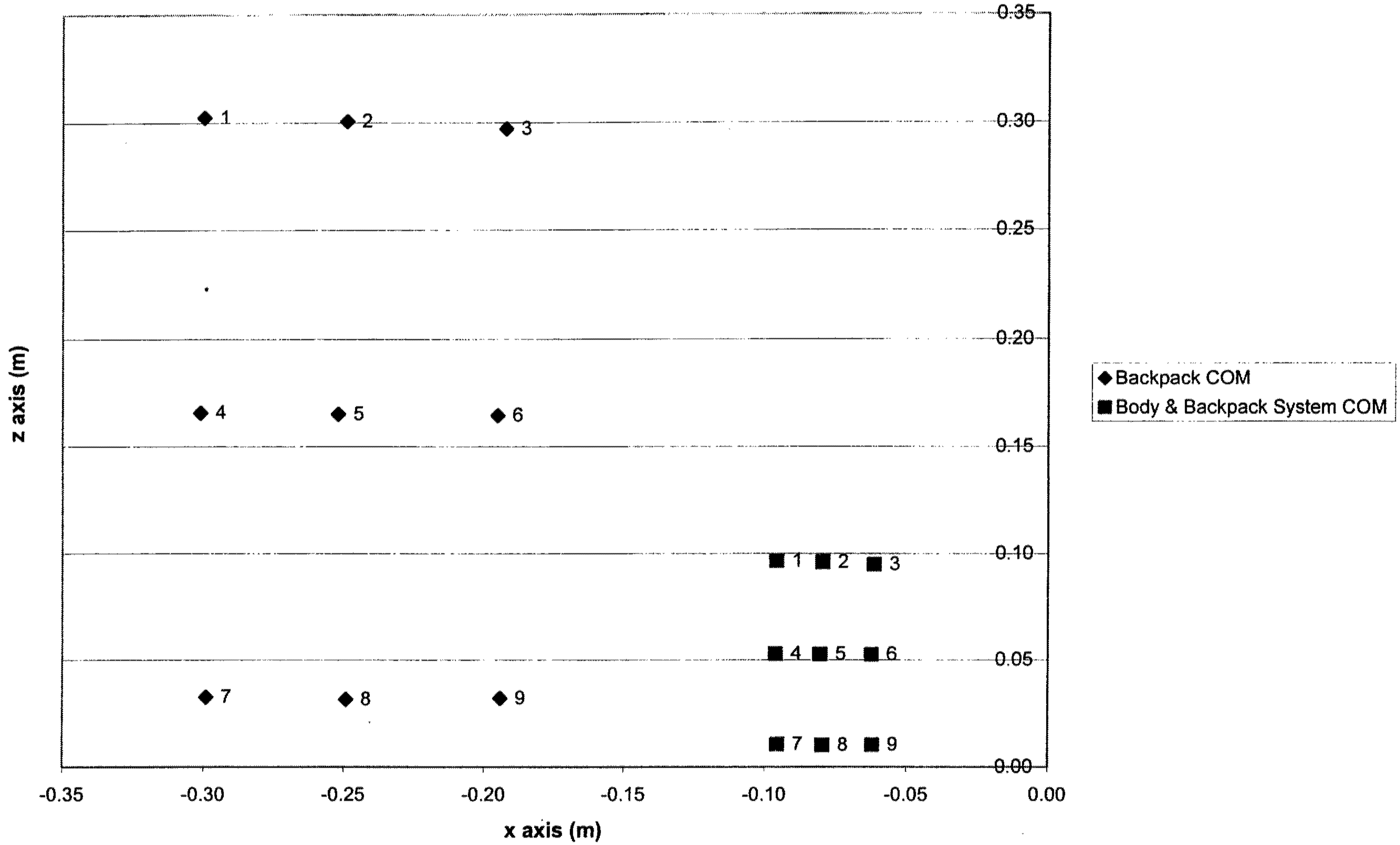

Figure 10. Backpack COM and body & backpack system COM for the nine load positions relative to the body COM (0,0).

Body & backpack system COM relative to body COM. The body & backpack system COM values for the nine load positions relative to the body COM are also presented in Table 4. Again, the values along the z axis for positions 1, 2, and 3 are similar, as are the values for positions 4, 5, and 6 and for positions 7, 8, and 9. The distance along the z axis between the three high and the three intermediate load positions and between the intermediate and the low positions is about 0.04 m. The maximum COM value along the z axis is 0.096 m and the minimum is 0.010 m, a range of 0.086 m (Table 4). Thus, the body and backpack system yielded a range of COM values along the z axis that is less than the range for the torso & backpack system.

The COM values along the x axis for the body & backpack system, relative to the body COM, are again similar for positions 1, 4, and 7, as are those for positions 2, 5, and 8 and for positions 3, 6, and 9 (Table 4). The distance along the x axis between the positions furthest from the torso and the central positions is approximately 0.02 m and the distance between the central positions and those closest to the torso is also about 0.02 m. Thus, the body & backpack system is associated with ranges of COM values along both the x and the z axes that are less than the ranges along these two axes that were obtained for the torso & backpack system. Figure 10 is a graphic presentation of the COM values for the body & backpack system in the nine load positions relative to the body COM. Also presented in the figure are the values for the backpack COM in the nine load positions relative to the body COM. As is illustrated in Figure 9 for the torso & backpack system, Figure 10 illustrates the extent to which the COMs for the load positions are condensed when the whole body and backpack are considered as a system, rather than the backpack alone being considered.

Moment of Inertia

Backpack MOI relative to backpack COM. Figure 11 displays the backpack MOI about the backpack COM for the nine load positions, and Table 5 lists the MOI values. Positions 1 and 7, which are, respectively, the highest and the lowest load positions along the z axis and those furthest away from the load-carrier's back along the x axis, have the highest MOI values overall. Load positions 5 and 6, which are in an intermediate location along the z axis, exhibit the lowest overall MOI values (Table 5). However, positions 5 and 6 also have well-defined intermediate I_{zz} values (Figure 11).

The products of inertia for the backpack in the nine load configurations are listed in Table 5. The presence of product terms for load positions 1, 2, 3, 7, 8, and 9 indicates that the principal axes were rotated relative to the chosen coordinate axes of the backpack. The product terms for load positions 4, 5, and 6 were relatively small indicating that the chosen coordinate axes approximated the principal axes for these load positions.

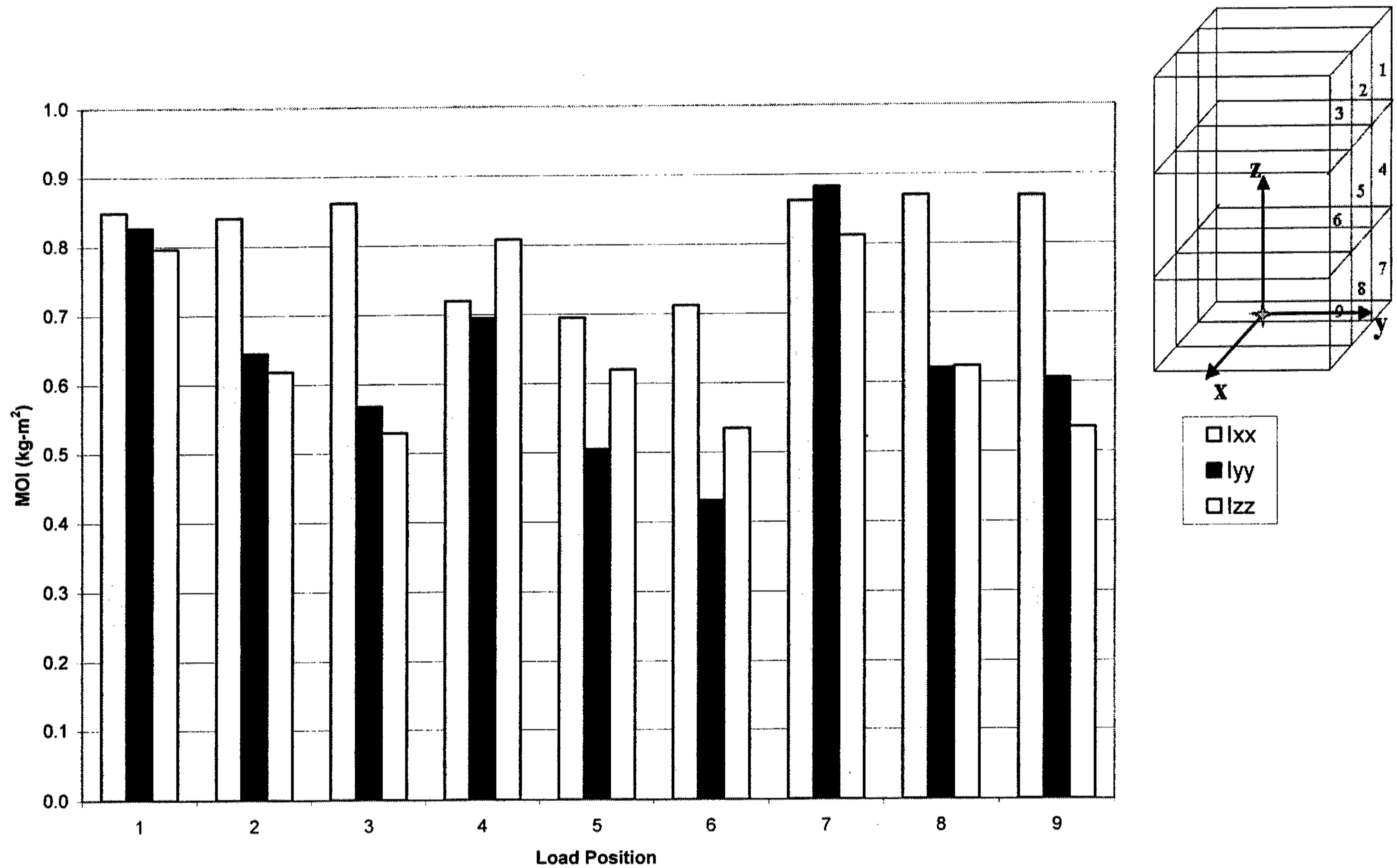

Figure 11. Backpack MOI about the backpack COM for the nine different load positions.

Table 5. *Backpack MOI (kg·m²) and Backpack Products of Inertia (kg·m²) Relative to Backpack COM*

Load Position	Backpack MOI Relative to Backpack COM			Backpack Products of Inertia Relative to Backpack COM		
	I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{xz}	I_{yz}
1	0.849	0.827	0.796	0.023	0.248	-0.061
2	0.841	0.645	0.618	0.036	0.199	-0.052
3	0.862	0.568	0.529	0.071	0.164	-0.034
4	0.720	0.695	0.808	0.011	-0.006	-0.020
5	0.695	0.504	0.620	0.009	-0.003	-0.008
6	0.712	0.431	0.535	0.031	0.034	-0.014
7	0.862	0.882	0.812	0.018	-0.291	0.029
8	0.870	0.620	0.623	-0.016	-0.212	-0.011
9	0.869	0.606	0.535	0.055	-0.126	0.022

Backpack MOI relative to the reference axes. Figure 12 displays the MOI values of the backpack relative to the reference axes originating on the lower left corner of the backpack frame, and Table 6 lists the MOI values. The values for all load positions relative to the reference axes on the frame are higher than the values expressed relative to the backpack COM (Table 5). This is attributable to the fact that the distance from each load position to the reference point on the frame was greater than the distance from the load positions to the backpack COM.

Comparisons among the values of I_{rxx} for the nine load positions reveal an obvious trend in the data: The I_{rxx} values for the three high positions are approximately equal, as are the values for the three intermediate and for the three low positions (Table 6). That is, positions 1, 2, and 3 yielded highly similar MOIs about the x axis, as did positions 4, 5, and 6 and positions 7, 8, and 9. The I_{rxx} of the three high positions has a mean of 6.359 kg·m². The values for the three intermediate positions are smaller, with a mean of 3.460 kg·m². At 2.153 kg·m², the three low positions have the smallest mean value.

For the MOI about the y-axis (I_{ryy}), there is an increase in I_{ryy} as load position along the z axis changed from low to high, as well as an increase as load position on the x axis changed from close to further away from the reference point on the frame (Figure 12). Thus, the highest I_{ryy} value, 7.364 kg·m², is associated with position 1 and the lowest, 1.477 kg·m², with position 9. With regard to the MOI about the z-axis (I_{rzz}), the values for positions 1, 4, and 7 are approximately equal, as are the values for positions 2, 5, and 8 and positions 3, 6, and 9 (Table 6). Therefore, the away positions at the low,

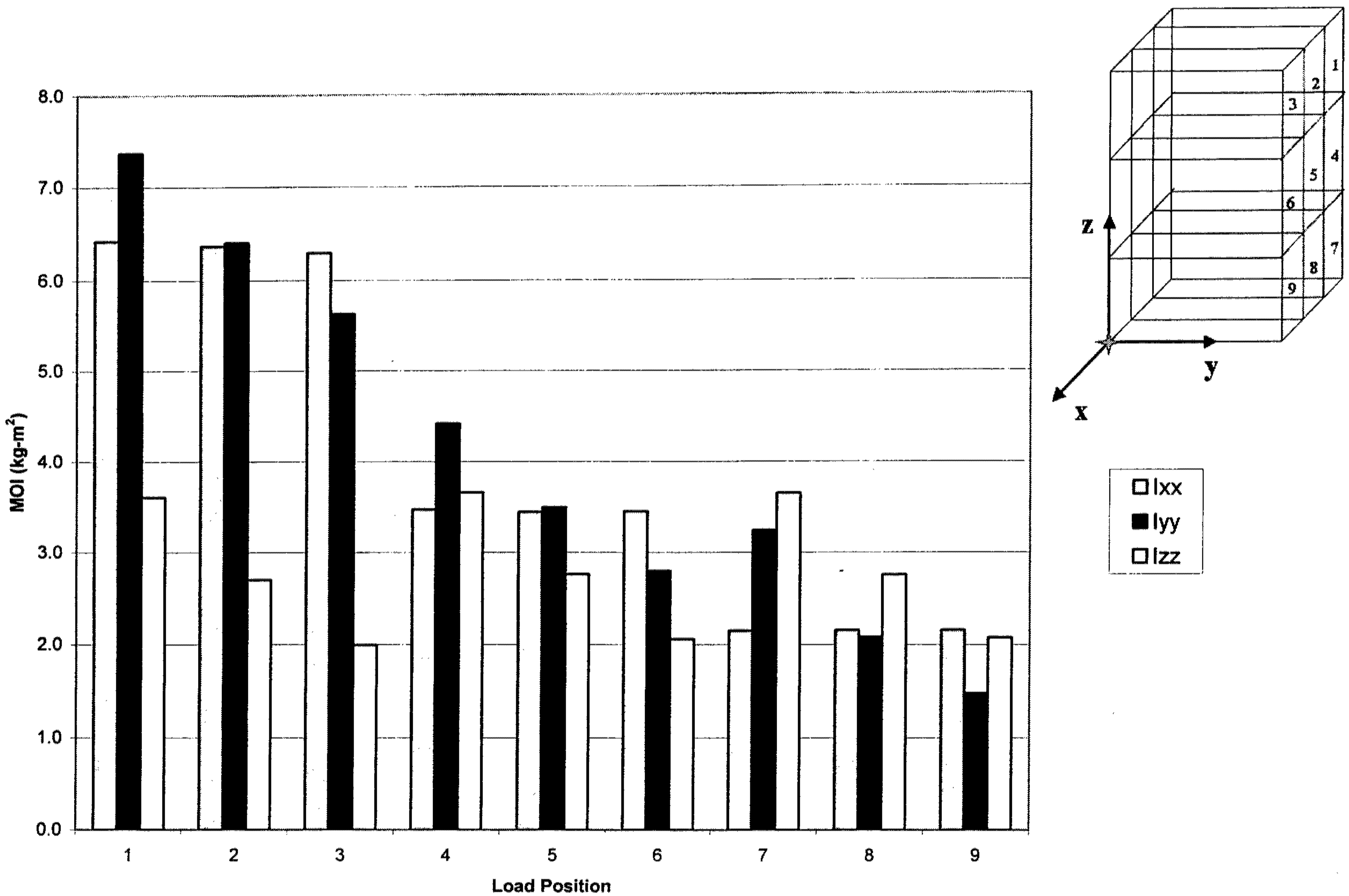

Figure 12. Backpack MOI relative to the reference axes originating on backpack frame for the nine different load positions.

Table 6. *Backpack MOI ($kg \cdot m^2$) Relative to Reference Point on Backpack Frame, Torso & Backpack System MOI ($kg \cdot m^2$) Relative to Torso & Backpack System COM, and Body & Backpack System MOI ($kg \cdot m^2$) Relative to Body & Backpack System COM*

Load Position	Backpack MOI Relative to Reference Point on Backpack Frame			Torso & Backpack MOI Relative to Torso & Backpack COM			Body & Backpack MOI Relative to Body & Backpack COM		
	I_{rxx}	I_{ryy}	I_{rzz}	I_{tsxx}	I_{tsyy}	I_{tszz}	I_{bsxx}	I_{bsyy}	I_{bszz}
1	6.419	7.364	3.611	3.060	3.908	2.672	16.988	17.041	4.658
2	6.365	6.400	2.696	3.044	3.246	2.022	16.954	16.168	3.814
3	6.292	5.627	1.992	3.050	2.740	1.519	16.926	15.444	3.128
4	3.476	4.418	3.663	2.658	3.516	2.697	15.334	15.401	4.687
5	3.448	3.499	2.763	2.634	2.865	2.048	15.304	14.558	3.851
6	3.456	2.797	2.057	2.651	2.372	1.543	15.317	13.875	3.161
7	2.147	3.244	3.657	3.198	4.078	2.678	14.848	14.929	4.659
8	2.154	2.081	2.755	3.212	3.360	2.027	14.854	14.015	3.819
9	2.157	1.477	2.074	3.207	2.939	1.535	14.854	13.420	3.149

intermediate, and high levels have similar MOIs about the z axis, as do the central positions at the low, intermediate, and high levels, and the close positions at the low, intermediate, and high levels. The I_{rzz} values for the away positions have a mean of 3.644 kg·m^2; the mean value of the central positions is 2.738 kg·m^2. The smallest mean, 2.041 kg·m^2, is associated with the close positions. In the case of all three axes, the closer the load position was to the axis of rotation, the lower the MOI about that axis.

Positions 1, 3, 6, and 7 have well-defined intermediate MOIs, as shown in Figure 12. In position 3, 6, and 7, the intermediate MOI is the I_{ryy}, and, in position 1, the intermediate MOI is the I_{rxx}.

Torso & backpack system MOI relative to torso & backpack system COM. The MOI values for the torso & backpack system are presented graphically in Figure 13, and Table 6 lists the MOI values. For the MOI about the z axis, the torso & backpack system values relative to the torso and backpack system COM (I_{tszz}) are lower for each load position than the respective value for each position when calculated for the backpack relative to the reference axes (Table 6). With regard to the x axis, the I_{tsxx} values for positions 1 through 6 are also lower than the I_{rxx} values for these positions. On the other hand, the I_{tsxx} values for positions 7 through 9 are higher than the I_{rxx} values for these positions. The greatest differences between the MOIs about the x axis calculated for the torso & backpack system relative to the torso and backpack COM and for the backpack relative to the reference axes are for positions 1, 2, and 3, those at the highest level along the z axis. The larger values for these positions are associated with the MOIs for the backpack relative to the reference axes (Table 6). Comparisons of the I_{tsyy} and the I_{ryy} reveal relationships similar to those obtained for the MOI about the x axis. That is, the I_{tsyy} values for positions 1 through 6 are lower than the I_{ryy} values for these positions and, for positions 7 through 9, the I_{tsyy} values exceed the I_{ryy} values. Furthermore, the greatest differences between the I_{tsyy} and the I_{ryy} values are again for positions 1, 2, and 3, with the higher values for these positions associated with the MOIs for the backpack relative to the reference axes (Table 6).

Considering the MOI relationships among load positions for the torso & backpack system relative to the torso and backpack system COM, the I_{tsxx} values for positions 1, 2, and 3 are approximately the same, as are those for positions 4, 5, and 6, and positions 7, 8, and 9 (Table 6). Load positions 7, 8, and 9 have the highest I_{tsxx} values and 4, 5, and 6 have the lowest. Positions 1, 4, and 7, the positions farthest from the load-carrier's back along the x axis, resulted in the highest I_{tsyy} values. For each vertical level of the backpack, high, intermediate, and low, I_{tsyy} decreased as the load moved from away (positions 1, 4, and 7) to central (positions 2, 5, and 8) to close (positions 3, 6, and 9) (Table 6). For the MOI about the z axis (I_{tszz}), positions 1, 4, and 7 have approximately the same value, as do the central positions, positions 2, 5, and 8, and the positions closest to the back, positions 3, 6, and 9 (Table 6).

With regard to overall MOI values for the load positions, positions 3 and 6 have the lowest values, followed by positions 5 and 9. Positions 1 and 7 have the highest values over all axes. An intermediate MOI is apparent in all load positions for the torso &

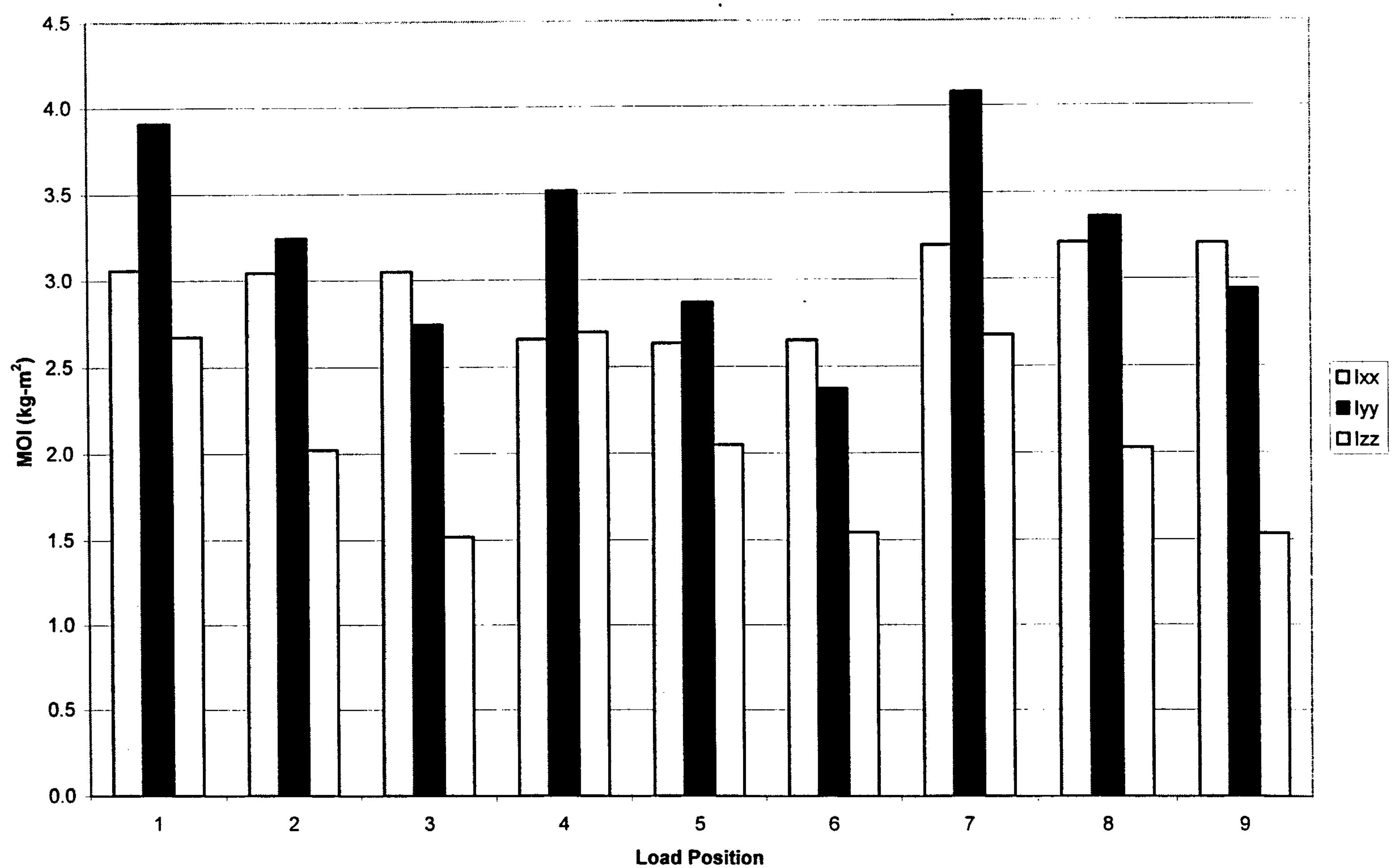

Figure 13. Torso & backpack system MOI about the torso & backpack system COM for the nine different load positions.

backpack system, with the exception of position 4 (Figure 13). Positions 1, 2, 5, 7, and 8 have intermediate MOIs about the x axis. The intermediate MOIs for positions 3, 6, and 9 are about the y axis.

Body & backpack system MOI relative to body & backpack system COM. Figure 14 displays the MOI values for the body & backpack system, and Table 6 lists the MOI values. The body & backpack system MOI relative to the body & backpack system COM is greater along each axis for each load position than the values are for the respective positions in the other three series of MOIs presented here (Tables 5 and 6). With regard to the x and y axes, the load position MOI values calculated for the body & backpack system relative to the body and backpack system COM are 366% to 581% larger than the values for the same positions calculated for the torso & backpack system MOI relative to torso and backpack system COM. For the z axis, the differences between the MOI values for the body & backpack system and the torso & backpack system are not as great as they are for the x and the y axes; at a given load position, the values for the body & backpack system are approximately 2 times those for the torso & backpack system (Table 6).

With regard to the relationships among the MOIs about the x, y, and z axes for the body & backpack system, the values are much greater in all load positions about the x and y axes than about the z axis (Figure 14). The additional mass of the body compared to the torso is located farther along the x and y axes of rotation than along the z axis of rotation. Therefore, the greater MOI values observed for the body & backpack system about the x and y axes than about the z axis are expected. In terms of relationships among MOIs for the nine load positions, load position 1 has the highest overall MOI and position 9 has the lowest. Six positions, positions 2, 3, 5, 6, 8, and 9, have well-defined intermediate MOIs about the y axis, I_{bsyy}.

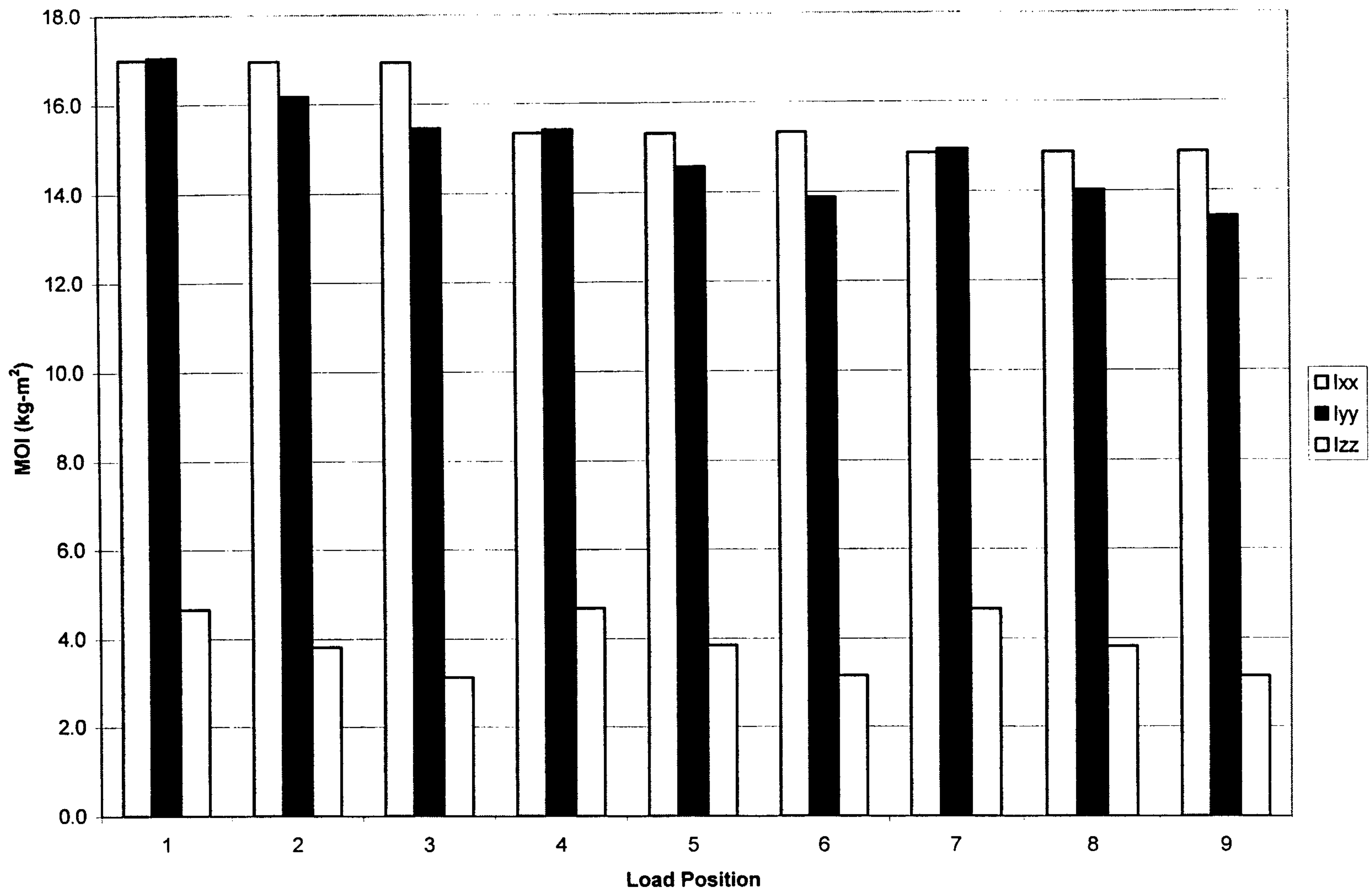

Figure 14. Body & backpack system MOI about body & backpack system COM for the nine different load positions.

Discussion

The backpack device that was the focus of this work was designed to enable the location of a weight to be varied along the x and the z axes in a controlled manner for the purpose of studying soldiers' physiological responses to changes in pack COM (Obusek et al., 1997). To measure the inertial properties of the device, we set the mass of the backpack at 35 kg. A lead brick, which could be placed in any one of nine specific locations in the pack, comprised 24.9 kg of the total mass. The mass of the brick and the total mass of the backpack were the same as those used by Obusek et al. in their study of the effects of load position on soldiers' energy cost while walking with the pack. Among the measurements we made were COM of the backpack with the brick in each of the nine locations. These measurements established the extent of the variations in backpack COM that it is possible to achieve with the masses used. Expressing backpack COM relative to reference axes originating on the backpack frame, we found that the x and the z components of the COM had a range of 0.109 m and 0.270 m, respectively.

The measurements we presented here for the COMs of the backpack device relative to the reference point on the frame were consistent with the respective locations of the nine load positions. Those positions that yielded highly similar or identical values for the x component of the COM were situated in the same location relative to the x axis. This was also the case for the values of the z component. Furthermore, there was little variation across load positions in the values for the y component of the COM, reflecting the fact that the location of the lead brick was fixed relative to the y axis. In this axis, the weight was symmetrically placed about the midline of the pack.

The measurements of backpack MOI relative to the backpack COM revealed that positions 1 and 7, which were, respectively, the highest and the lowest load positions along the z axis and those furthest away from the load-carrier's back along the x axis, had the highest MOI values overall. Load positions 5 and 6, which were in an intermediate location along the z axis, exhibited the lowest overall MOI values. However, positions 5 and 6 also had well-defined intermediate MOIs about the z axis, I_{zz}. Thus, although positions 5 and 6 had the lowest overall MOIs, in these positions, rotation of the backpack device about the z axis is likely to be unstable. Therefore, the motion of the pack will tend to rotate off the z axis and spin about the x and y axes as well, which may make it difficult to control (Greenwood, 1965).

Classification of positions 5 and 6 as having a well-defined intermediate axis when backpack MOI was measured relative to backpack COM was based upon the relatively large differences in the data for the three axes between the highest and the middle MOI values and the middle and the lowest MOI values. This approach for identifying intermediate axes is arbitrary. Although accuracy of the MOI device itself appears to be quite high, data were not acquired in the present study for quantifying the human error that may be introduced during execution of the MOI measurement procedures used here. Thus, the errors associated with the MOI values are not known. Furthermore, the differences among the axes in MOI values that are of practical importance insofar as they result in unstable rotation of the backpack about a given intermediate axis are unknown. Therefore, throughout the report, identification of load positions as having an intermediate axes was based upon differences in MOI values that were large relative to those for other load positions.

The measurements of backpack MOIs relative to the reference axes originating on the pack frame revealed relationships among the nine load positions that were consistent with their respective locations. Positions 1, 2, and 3, which were located in the high position along the z axis, had very similar MOI values about the x axis. The intermediate positions along the z axis, positions 4, 5, and 6, also had similar MOIs about the x axis, as did the low positions, positions 7, 8, and 9. Likewise, positions 1, 4, and 7, the positions farthest away from the load-carrier's back along the x axis, had similar MOIs about the z axis. The three positions in a central location relative to the x axis, positions 2, 5, and 8, also had similar MOIs about the z axis, as did the positions closest to the back, positions 3, 6, and 9.

The consistency in the MOI values for the three load positions at each level along the x and the z axes was expected because the d^2 terms in the parallel-axis theorem were equal at each level. However, obtaining the expected findings lends support to the validity of the methodology we used to take the MOI measurements.

Comparison of the values of the MOI about the x axis, expressed relative to the reference point on the frame, indicated that the largest MOIs were associated with the high positions along the longitudinal axis of the frame and the smallest MOIs with the low positions. About the z axis, the largest MOI values were obtained for the positions farthest from the load-carrier's back along the anterior-posterior axis and the smallest for the positions closest to the back. For the MOIs about the y axis, the largest MOI values at the high, the intermediate, and the low load position levels were found for the positions farthest from the back and the smallest values were for the positions closest to the back. Furthermore, the high load positions had larger values than the intermediate or the low positions, with the low load positions having the smallest values. Therefore, considering the MOIs about all three axes, the lower the load position and the closer to the back, the smaller the MOI. Overall, position 9 had the smallest MOIs, followed by positions 8 and 6. The largest MOIs overall were associated with position 1, which was located high along the z axis and away from the back along the x axis.

Position 1 was one of four positions found to have a well-defined intermediate MOI when backpack MOIs were expressed relative to the reference point on the backpack frame. The intermediate MOI for position 1 was about the x axis. The other positions with intermediate MOIs were positions 3, 6, and 7, where the intermediate MOI was about the y axis. Thus, although position 6 had relatively small MOIs overall, in this position, rotation of the backpack device about the y axis is likely to be unstable Therefore, the motion of the pack may rotate off the y axis and spin about the x and z axes as well, which may make it difficult to control (Greenwood, 1965).

Martin et al. (1982) reported on the inertial properties of a carrier-backpack system, representing the human body by a mathematical model that was developed by Hanavan (1964). The Hanavan model assumes a rigid, homogeneous body with the shape approximated by symmetrical, geometric shapes. Martin et al. investigated several load weights and backpack systems, one of which was the ALICE. They placed 9.07 kg of military clothing and equipment in the ALICE pack and then added point loads of 13.6 kg in various locations within the pack for a total mass, including the pack and frame, of 26.11 kg.

Martin et al. (1982) made one set of measurements with the added load of 13.6 kg placed near the top of the pack and centered about the x and the y axes; measurements were also carried out with the 13.6-kg load placed near the bottom of the pack, and again centered about the x and the y axes. The x and the y components of the COM were the same for these two load locations, but the z component of the COM was increased by 0.056 m when the added load was moved from the bottom to the top of the pack. The MOI about the z axis for the carrier-backpack system relative to the system COM did not change when the added load was moved from the low to the high position. However, the MOI values about the x and the y axes increased. Thus, in their modeling of the carrier-backpack system, Martin et al. found that smaller MOIs were associated with lower placement of the load in the pack.

Like Martin et al. (1982), we acquired data to describe the inertial properties of a carrier-backpack system. However, we did not use a rigid-body, human model, as Martin et al. had done. The one we used was based upon empirical data gathered by Chandler et al. (1975), who measured the mass distribution properties of six male cadavers, three in a sitting and three in a standing position. We used the data obtained on the male cadavers measured in a standing position.

In measuring the COMs of the body and backpack system relative to the body COM with the 24.9-kg lead brick in each of the nine load positions within the backpack device, we found that the x and the z components had a range of 0.035 m and 0.086 m, respectively. Thus, the ranges of COM values associated with the body and backpack system relative to the body COM were reduced by about 70% compared with the COM values associated with the backpack COM relative to the reference axes originating on the backpack frame. However, the measurements for the COMs of the body and backpack system relative to the body COM were again consistent with the locations of the nine load positions. The positions that yielded highly similar or equal values for the x component of the COM were in the same location relative to the x axis of the system. The findings for the z component of the COM were also consistent with load position location.

The body and backpack MOIs relative to the body and backpack COM indicated relationships among the nine load positions that were in consonance with their respective locations as well. Positions 1, 2, and 3, located in the high position along the z axis, had similar MOI values about the x axis. The intermediate positions, positions 4, 5, and 6, had similar values, as did the low positions, positions 7, 8, and 9. Positions 1, 4, and 7, the positions farthest from the load-carrier's back along the x axis, had similar MOI values about the z axis, as did the central positions, positions 2, 5, and 8, and the positions closest to the back, positions 3, 6, and 9. The consistency of the MOI values for the three load positions at each level along the x and the z axes was again expected because the d^2 terms in the parallel-axis theorem were equal at each level. However, obtaining the expected relationships again lends support to the methodology employed here for measuring the inertial properties and for incorporating a model of the carrier-backpack system.

Comparing the MOI values about the x axis for the body and backpack system, expressed relative to the body and backpack COM, yielded relationships similar to those obtained when comparing the MOI values for the backpack relative to the reference axes originating on the backpack frame. That is, the largest MOIs about the x axis were associated with the high positions along the z axis and the smallest with the low positions. The relationships of the MOI values about the z axis were also similar, with the largest MOIs being obtained for the positions farthest from the load-carrier's back and the smallest for the positions closest to the back. In addition, the relationships among MOI values about the y axis for the body and backpack system were similar to those obtained for the backpack relative to the reference axes. For the y axis, the largest MOIs at the high, intermediate, and low load position levels were found for the positions farthest from the back and the smallest MOIs were for the positions closest to the back. The high load positions also tended to have larger values than the intermediate or the low positions, and the low positions tended to have the smallest values. Considering the MOIs for the body and backpack system about the three chosen coordinate axes, the lower the load position and the closer to the back, the smaller the MOI. As was the case for the MOIs of the backpack relative to the reference point on the frame, the body and backpack system data revealed that the smallest MOIs overall were associated with position 9; the largest MOIs were again found for position 1.

The comparisons among MOIs for the body and backpack system yielded findings compatible with those obtained for the carrier-backpack system devised by Martin et al. (1982). Martin et al. also reported that smaller MOIs were associated with lower placements of the load in the pack. They proposed that the placement of loads low in a pack is the optimal loading configuration because this placement results in a low z component of the COM and low MOIs about the x and the y axes. However, we found low load positions, specifically positions 8 and 9, were among those positions reflecting a well-defined intermediate MOI. In the case of the body and backpack system, these two positions, along with positions 2, 3, 5, and 6 had intermediate MOIs about the y axis, indicating that rotation about that axis is likely to be unstable and may result in rotation about the x and z axes as well.

The geometric model of the human used by Martin et al. (1982) to investigate the mass distribution properties of the carrier-backpack system and the human model based on cadaver data that we used treat the body as a rigid object (Chandler et al., 1975; Hanavan, 1964). These might not be the best models to apply in estimating MOIs for application to soldiers, who must often perform rapid maneuvers, where limbs are moving and accelerating. Therefore, we additionally examined the inertial properties of the torso and backpack system. The backpack attached to the torso might better approximate a rigid body when the human body is in motion. For the torso model, we again used data acquired by Chandler et al., who had measured the mass distribution properties of body segments, as well as of intact cadavers.

The MOI results for the torso and backpack system indicated that load positions 3 and 6 had the smallest overall MOI values about the x, y, and z axes, followed by positions 5 and 9. Position 3 was at the high level of the backpack device; positions 5 and 6 were at the intermediate level; and position 9 was at the low level. Thus, these findings, with the exception of position 9, are similar to the reports of Hinrichs et al. (1982), who found smaller MOIs relative to the COM of the ALICE backpack when lead weights of 9.12 kg were placed on the top of the pack than when they were placed on the bottom. Although load positions 3 and 6 had relatively small overall MOIs, there was also a well-defined intermediate MOI about the y axis associated with these two positions. Thus, a greater external force, such as muscular force exerted by the soldier, may be needed to keep the rotation about this axis controlled. However, the extent of the instability due to the rotation about the intermediate axis that may occur as soldiers perform physical activities while carrying backpack loads is not known.

Although position 3 for the torso and backpack system had one of the smallest overall MOI values about the x, y, and z axes, placing the COM high in the pack raises the system COM along the z axis, which decreases the stability of the soldier-backpack system (Hinrichs et al., 1982). However, placing the load high, as opposed to low, results in less forward lean needed to support the load and place the COM over the base of support (Harman et al., 1999; Martin & Nelson, 1982). Therefore, depending upon the mission, the soldier may require stability at the expense of a greater forward lean, which may increase the activity of the stabilizing muscles of the trunk.

The data we presented here using two approaches to a load carrier-backpack model, as well as the similar work reported by Hinrichs et al. (1982) and Martin et al. (1982), indicate the sensitivity of the estimated inertial properties to the particular human model underlying the data. Furthermore, the data that are available for modeling the mass distribution properties of the human body are limited and the empirical models are based upon small sample sizes (Reynolds, 1978). In spite of the limitations, modeling of the mass properties of the carrier-backpack system, as opposed to considering only the local MOIs of the backpack relative to its COM or some arbitrarily established reference point, seems preferable. As Hinrichs et al. (1982) pointed out, consideration of the load carrier and the backpack as a system may shed light on interactions between elements that are important considerations in loading backpacks and designing such equipment for optimal human performance.

In the next phase of this research, the data on the mass distribution properties of the backpack device as a function of load position that we presented here will be applied in analyses of the data obtained by Obusek et al. (1997) on the energy costs associated with carrying the device while walking. The MOI values, along with the metabolic cost results for the nine load positions, may provide insight as to how soldiers should manipulate their backpack loads to achieve a COM position that exhibits both a low MOI and a low metabolic cost of carrying the backpack.

Conclusions

In conclusion, the inertial properties of a custom external-frame backpack were determined. Two approaches to a load carrier-backpack model were examined, the torso and backpack system and the body and backpack system. The comparisons among MOIs for the body and backpack system yielded findings compatible with those obtained for the carrier-backpack system devised by Martin et al. (1982). However, for application to the soldier, who must often perform rapid maneuvers, where limbs are moving and accelerating, the whole body models might not be the best models to apply in estimating MOIs. Therefore, we additionally examined the inertial properties of the torso and backpack system. The findings demonstrated that keeping the load high and close and intermediate and close to the torso resulted in the smallest overall MOI values about the x, y, and z axes for the system. The load position that resulted in the highest overall MOI values for the system was low and away from the torso.

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References

Albery, C.B., Schulz, R.B., & Bjorn, V.S. (1998). Measurement of whole-body human centers of gravity and moments of inertia. *SAFE, 28* (2), 78-88.

AMTI (1991). *Instruction manual Model OR6-5 Biomechanics Platform* (Brochure). Watertown, MA: Author.

Chandler, R.F., Clauser, C.E., McConville, J.T., Reynolds, H.M., & Young, J.W. (1975). *Investigation of inertial properties of the human body* (Tech. Rep. AMRL-TR-74-137). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory.

Department of the Army. (1990). *Foot marches* (Field Manual 21-18). Washington, DC: Author.

Gordon, C.C., Bradtmiller, B., Churchill, T., Clauser, C.E., McConville, J.T., Tebbetts, I., & Walker, R.A. (1989). *1988 anthropometric survey of U.S. Army personnel: methods and summary statistics* (Tech. Rep. NATICK/TR-89/044). Natick, MA: U.S. Army Natick Research and Development Center.

Greenwood, D.T. (1965). *Principles of dynamics*. Englewood Cliffs, NJ: Prentice Hall.

Hanavan, E.P. (1964). *A mathematical model of the human body* (Tech. Rep. AMRL-TR-64-102). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratories.

Harman, E., Frykman, P., Pandorf, C., Tharion, W., Mello, R., Obusek, J., & Kirk, J. (1999, February). *Physiological, biomechanical, and maximal performance comparisons of female soldiers carrying loads using prototype U.S. Marine Corps Modular Lightweight Load-Carrying Equipment (MOLLE) with Interceptor body armor and U.S. Army All-Purpose Lightweight Individual Carrying Equipment (ALICE) with PASGT body armor* (Tech. Rep. T99-9). Natick, MA: U.S. Army Research Institute of Environmental Medicine.

Hinrichs, R.N., Lallemant, S.R., & Nelson, R.C. (1982). *An investigation of the inertial properties of backpacks loaded in various configurations* (Tech. Rep. NATICK/TR-82/023). Natick, MA: U.S. Army Natick Research and Development Laboratories.

LaFiandra, M., Holt, K.G., Wagenaar, R.C., & Obusek, J.P. (2002a). *The effect of backpack moment of inertia on transverse plane kinetics and kinematics and oxygen consumption during walking* (Tech. Rep. T03-2). Natick, MA: U.S. Army Research Institute of Environmental Medicine.

LaFiandra, M., Holt, K.G., Wagenaar, R.C., & Obusek, J.P. (2002b). Transverse plane kinetics during treadmill walking with and without a load. *Clinical Biomechanics, 17* (2), 116-122.

Martin, P.E., Hinrichs, R.N., Shin, I., & Nelson, R.C. (1982). *Volume IV. A mathematical model of the inertial properties of a carrier-backpack system* (Tech. Rep. NATICK/TR-82/022). Natick, MA: US Army Natick Research and Development Laboratories.

Martin, P. E., & Nelson, R. C. (1982, April). *Volume III. Effects of gender, load, and backpack on the temporal and kinematic characteristics of walking gait* (Tech. Rep. NATICK/TR-82/021). Natick, MA: U.S. Army Natick Research and Development Laboratories.

Obusek, J.P., Harman, E.A., Frykman, P.N., Palmer, C.J., & Bills, R.K. (1997). The relationship of backpack center of mass location to the metabolic cost of load carriage. *Medicine and Science in Sports and Exercise, 29* (5), S205.

Reynolds, H.M. (1978). The inertial properties of the body and its segments. In Staff of Anthropology Research Project (Eds.), *Anthropometric source book, Volume I: anthropometry for designers* (NASA Reference Publication 1024) (pp. IV-1-IV-76). Yellow Springs, OH: Anthropology Research Project.

Serway, R.A. (1990). *Physics for scientists and engineers*. Philadelphia, PA: Saunders College Publishing

Space Electronics, Inc. (n.d.). *Model XR250 operation manual* (Brochure). Berlin, CT: Author.

Synge, J.L., & Griffith, B.A. (1942). *Principles of mechanics*. New York, NY: McGraw-Hill.

Wardle, D.A. (2001). Unstable rotation of rigid bodies in empty space. *The Physics Teacher, 39,* 334-335.

White, A.A, & Panjabi, M.M. (1978). *Clinical biomechanics of the spine.* Philadelphia, PA: J.B. Lippincott Company.

Appendix A

Description of Anthropometric Measurements

Appendix A

Description of Anthropometric Measurements

Anthropometric measurements taken by Chandler et al. (1975) and Gordon et al. (1989) are described below. Chandler et al. (1975) and Gordon et al. (1989) use the same landmarks for each of the measurements with the exception of chest circumference. Chandler et al. took this measurement at the level of the nipples; Gordon et al. took the measurement at the fullest part of the chest. The major differences between the procedures used by Chandler et al. and Gordon et al. were that Candler et al. measured the body in the supine position, and height dimensions were taken from headboard to the landmark then subtracted from stature. In comparison, Gordon et al. measured subjects who were standing erect, and the measurements were taken from the standing surface to the landmark. In addition, Chandler et al. derived cervicale height by taking the difference between top of head to thelion and the horizontal distance between thelion and cervicale, whereas Gordon et al. measured from the standing surface directly to the cervicale landmark itself.

Chandler et al. (1975)

In order to obtain the anthropometric measurements of the three cadavers, the body was placed in a supine position, the head in the Frankfort plane (relative) and firmly in contact with a headboard, the legs extended, the torso and head aligned, and the arms extended naturally at the sides with the palms facing medially. All dimensions measured from the headboard were reported as subtractions from stature.

Anterior-superior iliac spine height. With an anthropometer, measure the horizontal distance from the headboard to the anterior iliospinale landmark, the inferior point of the anterior superior iliac spine.

Cervicale height. The horizontal distance between the headboard and cervicale measured with an anthropometer. This dimension was computed from the difference between top of head to thelion and the horizontal distance between thelion and cervicale. The thelion was defined as the center of the nipple and the cervicale as the superior palpable point of the spine of the seventh cervical vertebra.

Chest circumference. With a tape measure passing over the nipples and perpendicular to the long axis of the trunk, the circumference of the chest was measured.

Iliac crest height. With an anthropometer, measure the horizontal distance from the headboard to the iliac crest in the mid-axillary line.

Omphalion height. The horizontal distance between the headboard and omphalion measured with an anthropometer.

Stature. A derived dimension calculated by taking the average of right and left ball of foot to vertex lengths. The vertex was defined has the highest point on the top of the head.

Trochanterion height. The horizontal distance from the headboard to the trochanterion landmark, the superior point of the greater trochanter of the femur, measured with an anthropometer.

Waist circumference. With a tape measure passing over the omphalion and perpendicular to the long axis of the trunk, the circumference of the waist was measured.

Waist depth. The vertical distance between the measuring table and the anterior surface of the body at the level of the omphalion measured with an anthropometer.

Weight. Body weighed with scales read to the nearest gram.

Gordon et al. (1989)

In order to obtain the following anthropometric measurements, which were made on 1774 U.S. Army men, the subjects stood erect with their head in the Frankfort plane, their heels together distributing body weight evenly on both feet, and their shoulders and upper extremities relaxed. The measurement was taken at the maximum point of quiet respiration.

Cervicale height. The vertical distance between a standing surface and the cervicale landmark, the superior palpable point of the spine of the seventh cervical vertebra, measured with an anthropometer.

Chest circumference. The maximum horizontal circumference of the chest at the fullest part of the breast measured with a tape measure.

Iliocristale height. The vertical distance between a standing surface and the iliocristale landmark on the top of the right side of the pelvis is measured with an anthropometer.

Omphalion height. The vertical distance between a standing surface and the center of the omphalion measured with an anthropometer.

Stature. The vertical distance from a standing surface to the top of the head measured with an anthropometer.

Trochanterion height. The vertical distance between a standing surface and the trochanterion landmark on the upper side of the thigh measured with an anthropometer.

Waist circumference. The horizontal circumference of the waist at the level of the center of the omphalion measured with a tape measure.

Waist depth. The horizontal distance between the front and back of the waist at the level of the center of the omphalion measured with a beam caliper.

Weight. The subject stands on the platform of a scale and the weight of the subject was taken to the nearest tenth of a kilogram.

Appendix B

Results for Trochanterion as Contact Point on Body

Appendix B

Results for Trochanterion as Contact Point on Body

For the data presented here, we defined the point of contact between the reference point on the backpack frame and the torso and between the reference point on the frame and the body as trochanterion height, the superior point of the greater trochanter of the femur, directly below the posterior portion of the waist. This appendix contains the resulting backpack and system COM relative to the torso and body COM, with the greater trochanter height as the point of contact. For the data presented in the body of this report, anterior superior iliac spine height was taken as the point of contact. Comparing Table B-1 with Table 4 and Figures B-1 and B-2 with Figures 9 and 10, respectively, it can be seen that the COM positions of the backpack relative to the torso COM and body COM for the nine load positions are decreased along the z axis when greater trochanter height is used by a distance that is equal to the distance between the height of the anterior superior iliac spine and the greater trochanter, 0.06 m. Changing the height of the contact point did not affect the COM positions related to the x axis, therefore the COM positions for the backpack relative to the torso COM and body COM along the x axis are the same for both points of contact. Figure B-3 and B-4 contain the resulting torso and backpack system MOI and the body and backpack system MOI when the greater trochanter height is the point of contact. Comparing Figures B-3 and B-4 with Figures 13 and 14, respectively, reveal that the pattern of MOIs for the nine load positions have not changed, however the magnitudes have.

Table B-1. *Backpack COM Relative to Reference Point on Backpack Frame (m) and to Torso COM (m), Torso & Backpack System COM Relative to Torso COM (m), Backpack COM Relative to Body COM (m), and Body & Backpack System COM Relative to Body COM(m) (Greater Trochanter as Contact Point)*

Load Position	Backpack COM Relative to Reference Point on Backpack Frame			Backpack COM Relative to Torso COM		Torso & Backpack COM Relative to Torso COM		Backpack COM Relative to Body COM		Body & Backpack COM Relative to Body COM	
	x	y	z	x	z	x	z	x	z	x	z
1	-0.232	0.162	0.364	-0.276	0.063	-0.130	0.030	-0.300	0.243	-0.096	0.077
2	-0.182	0.162	0.363	-0.226	0.061	-0.106	0.029	-0.249	0.241	-0.080	0.077
3	-0.125	0.162	0.359	-0.169	0.057	-0.080	0.027	-0.193	0.237	-0.061	0.076
4	-0.234	0.164	0.228	-0.278	-0.074	-0.131	-0.035	-0.301	0.106	-0.096	0.034
5	-0.185	0.165	0.227	-0.229	-0.075	-0.108	-0.035	-0.252	0.105	-0.080	0.034
6	-0.128	0.165	0.226	-0.172	-0.075	-0.081	-0.035	-0.195	0.105	-0.062	0.033
7	-0.231	0.167	0.095	-0.275	-0.207	-0.130	-0.098	-0.299	-0.027	-0.095	-0.009
8	-0.182	0.167	0.094	-0.226	-0.208	-0.106	-0.098	-0.249	-0.028	-0.080	-0.009
9	-0.127	0.167	0.094	-0.171	-0.207	-0.080	-0.098	-0.194	-0.027	-0.062	-0.009

Table B-2. *Backpack MOI ($kg \cdot m^2$) Relative to Reference Point on Backpack Frame, Torso & Backpack System MOI ($kg \cdot m^2$) Relative to Torso & Backpack System COM, and Body & Backpack System MOI ($kg \cdot m^2$) Relative to Body & Backpack System COM (Greater Trochanter as Contact Point)*

Load Position	Backpack MOI Relative to Reference Point on Backpack Frame			Torso & Backpack MOI Relative to Torso & Backpack COM			Body & Backpack MOI Relative to Body & Backpack COM		
	I_{rxx}	I_{ryy}	I_{rzz}	I_{tsxx}	I_{tsyy}	I_{tszz}	I_{bsxx}	I_{bsyy}	I_{bszz}
1	6.419	7.364	3.611	2.856	3.704	2.672	16.213	16.266	4.658
2	6.365	6.400	2.696	2.844	3.045	2.022	16.184	15.398	3.814
3	6.292	5.627	1.992	2.857	2.547	1.519	16.166	14.684	3.128
4	3.476	4.418	3.663	2.756	3.614	2.697	14.948	15.015	4.687
5	3.448	3.499	2.763	2.733	2.965	2.048	14.920	14.174	3.851
6	3.456	2.797	2.057	2.751	2.472	1.543	14.934	13.493	3.161
7	2.147	3.244	3.657	3.589	4.469	2.678	14.840	14.921	4.659
8	2.154	2.081	2.755	3.605	3.754	2.027	14.849	14.010	3.819
9	2.157	1.477	2.074	3.600	3.331	1.535	14.847	13.413	3.149

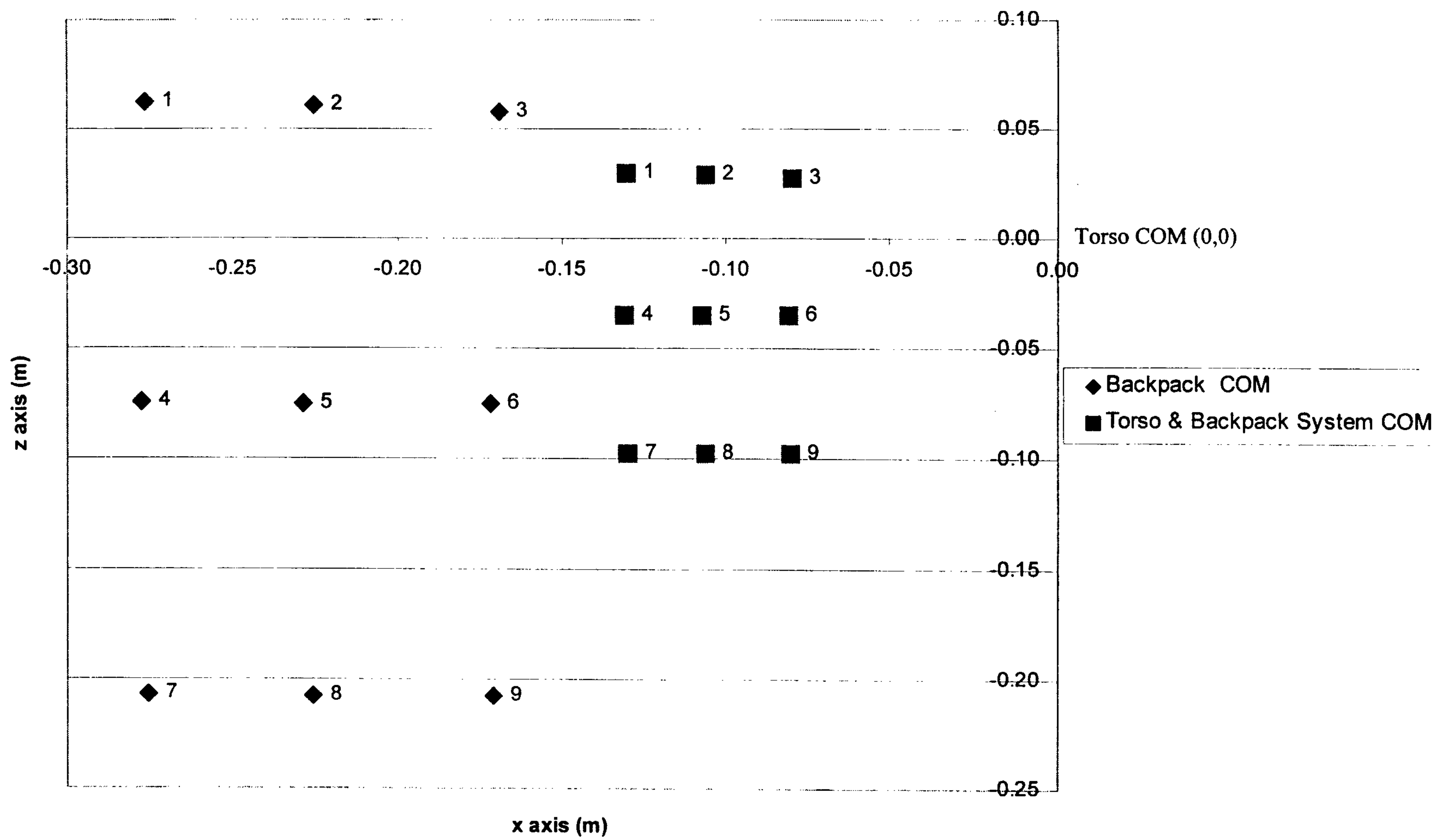

Figure B-1. Backpack COM and torso & backpack system COM for the nine load positions relative to the torso COM (0,0) (greater trochanter as contact point).

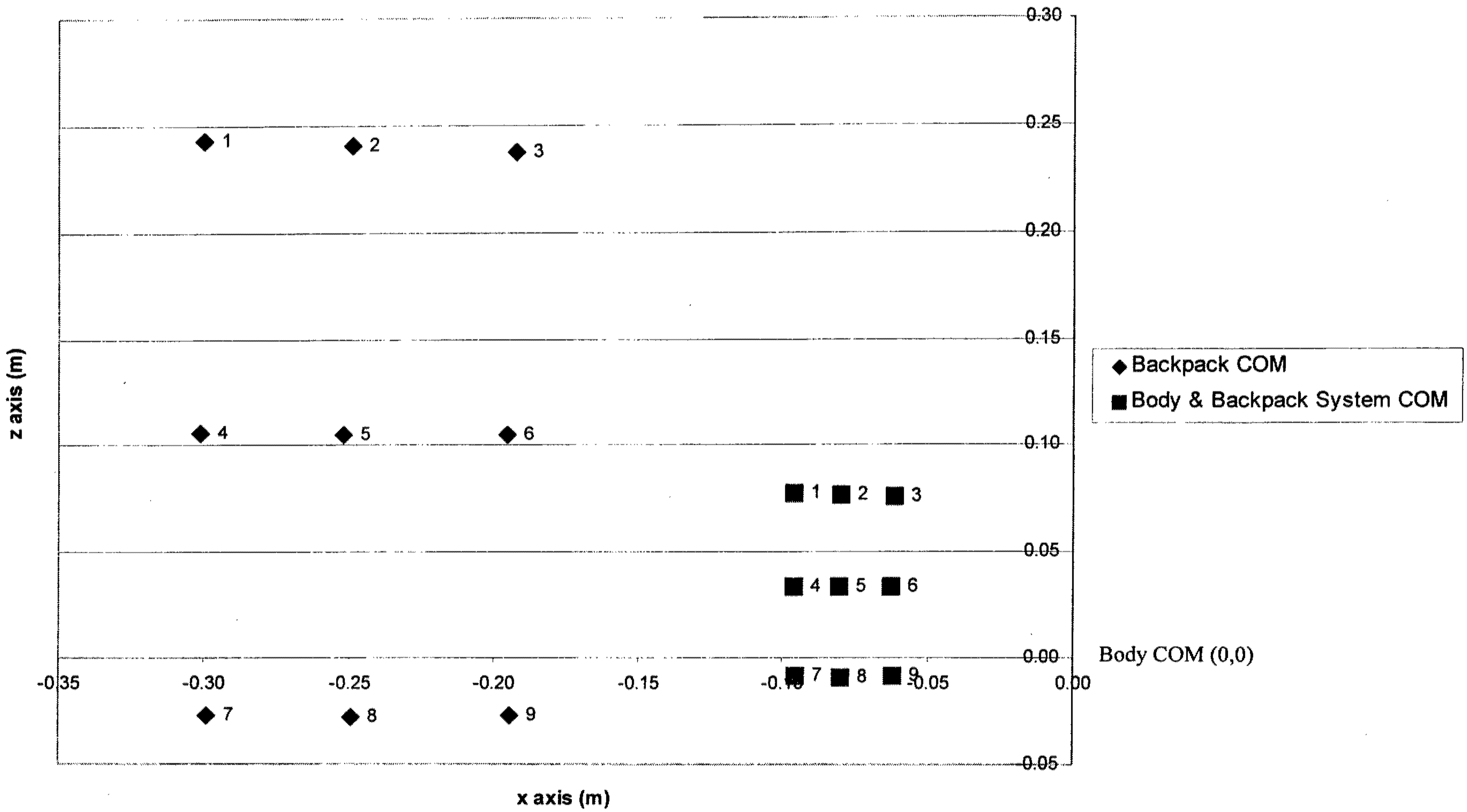

Figure B-2. Backpack COM and body & backpack system COM for the nine load positions relative to the body COM (0,0) (greater trochanter as contact point).

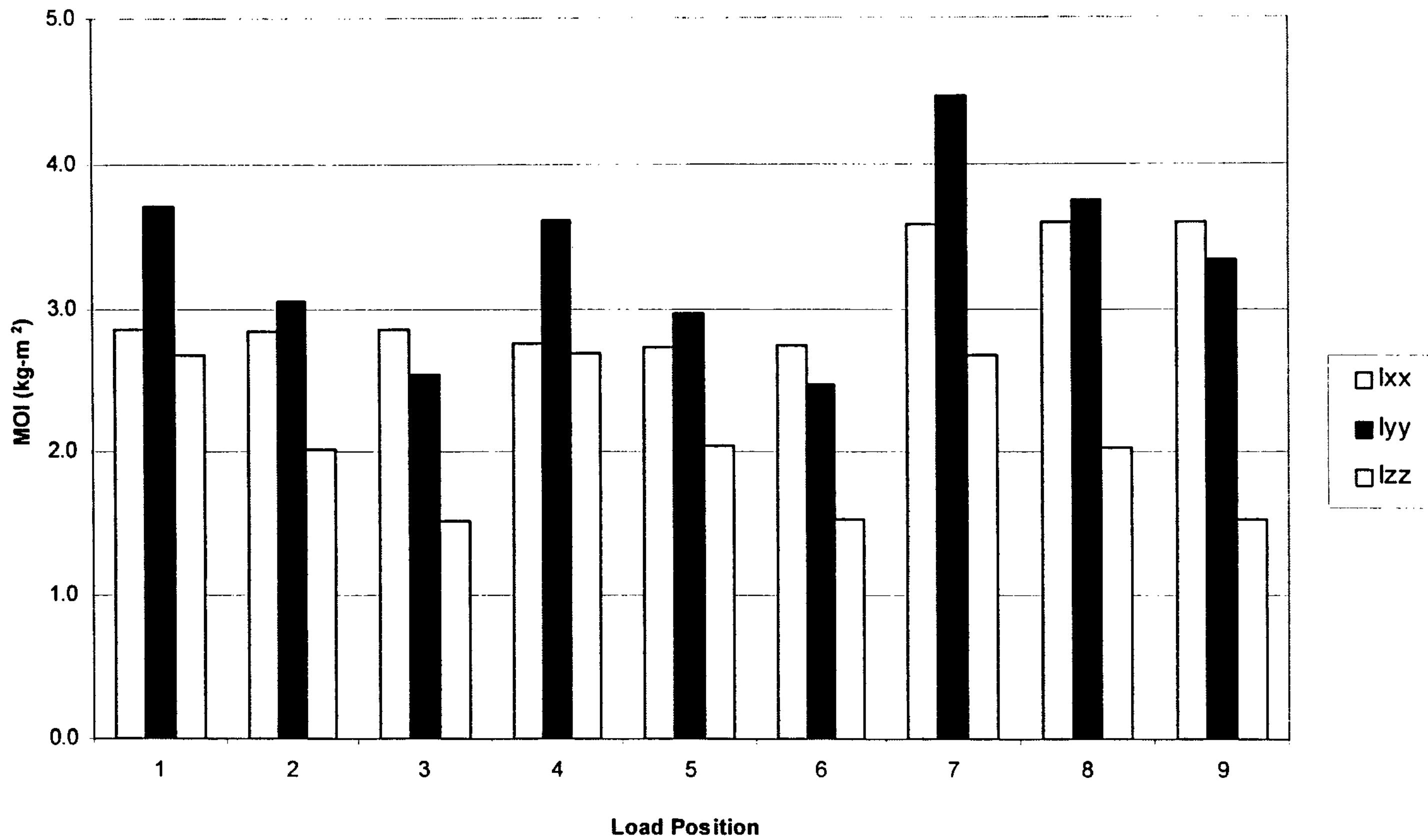

Figure B-3. Torso & backpack system MOI about the torso & backpack system COM for the nine different load positions (greater trochanter as contact point).

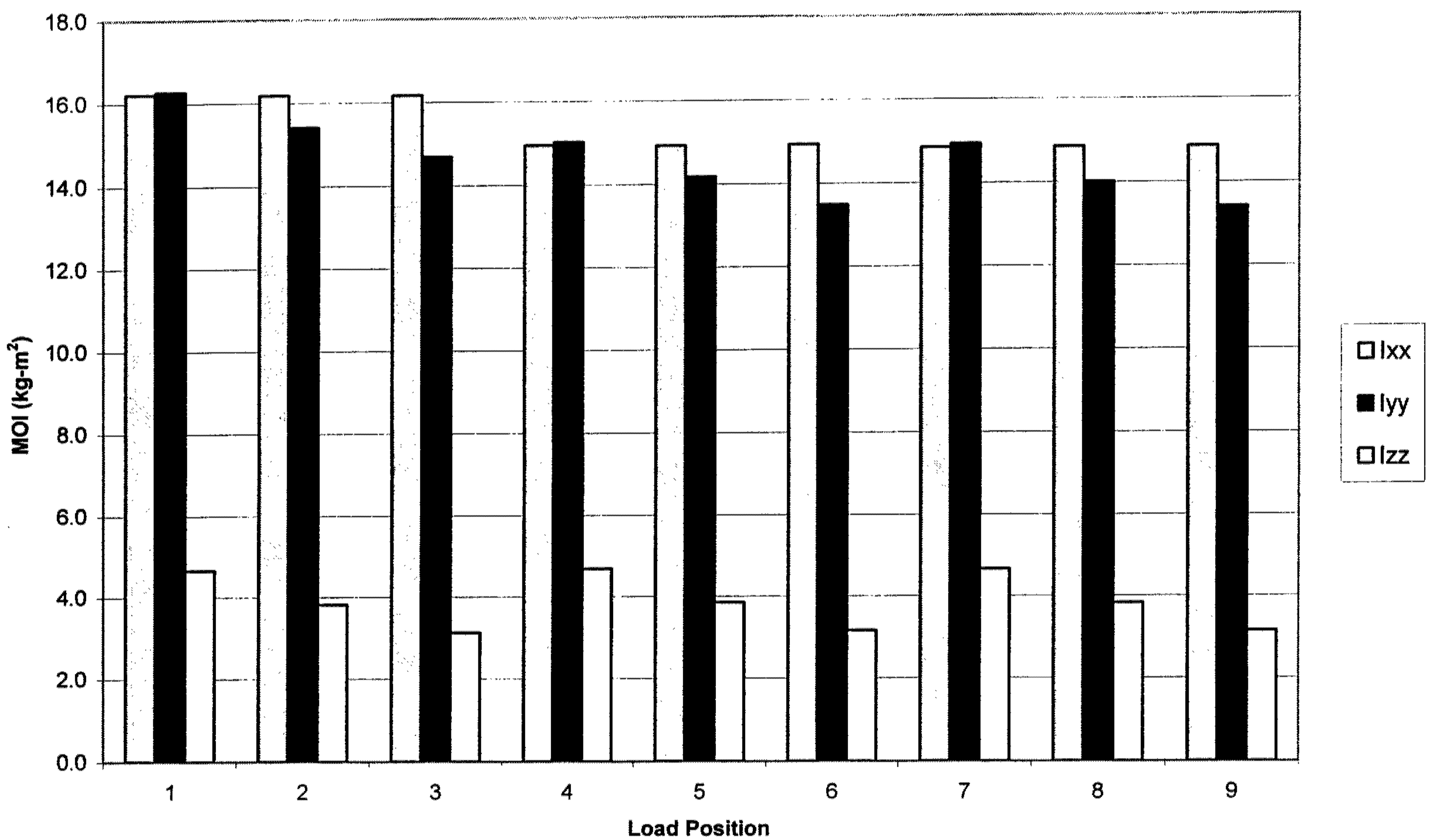

Figure B-4. Body & backpack system MOI about body & backpack system COM for the nine different load positions (greater trochanter as contact point).