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*INJURY BIOMECHANICS RESEARCH*
*Proceedings of the Thirty-Second International Workshop*

# Linear and Angular Accelerations of the Head During Activities of Daily Living. Part I: Instrumentation and Methodology

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*This paper has not been screened for accuracy nor refereed by any body of scientific peers and should not be referenced in the open literature.*

## ABSTRACT

*Biomechanics research and volunteer testing has quantified and described injury mechanisms and thresholds for many types of injuries throughout the human body. However, little if any mechanism or threshold quantification exists for minor injuries or injuries that can only be diagnosed based upon a patient's complaints of pain. A method commonly used to evaluate the effects of a minor automotive accident on the occupants of the vehicles involved is to compare the forces and accelerations the occupants were exposed to in the accident with the forces and accelerations experienced when performing a variety of daily living type activities, or while riding amusement park rides. There are few studies that have been conducted using human volunteers to measure their linear head accelerations during various activities of daily living. Presently, no studies have been found that measure the angular acceleration of the head during minor accidents or during activities of daily living. There are, however, studies that attempt to associate various head, neck, and brain injuries to these minor accidents with or without a head impact.*

*The present work is being conducted to quantify the linear and angular head accelerations humans experience during various activities of daily living. This work is being performed in order to, among other things, compare these accelerations to those experienced by an occupant involved in a minor vehicular accident. The work presented here briefly details the design of a head mounted accelerometer array fixture, derivation of the system of equations for this array, and quasi-planar validation of the fixture and calculation methodology. Planar validation testing indicates that up to an event duration of 0.200 seconds the angular acceleration and linear acceleration at the center of gravity can be determined by measuring the triaxial acceleration at three different locations on the head and then applying the relative velocity and relative acceleration equations. Events with durations longer than 0.200 seconds require the direct measurement of angular velocity on each coordinate axis in order to determine the head angular accelerations and the head center of gravity linear accelerations.*

## INTRODUCTION

In order to accurately compare the acceleration of the human head during daily activities to those in a low speed accident, both linear and angular accelerations of the head are required. This paper presents the instrumentation and a methodology to compute these accelerations. In the methods presented here the linear accelerations are documented through the use of linear accelerometers. The angular accelerations are calculated from the linear acceleration data through the use of relative acceleration equations. Once the angular acceleration is known, the linear acceleration of the center of gravity of the head can be calculated based upon an estimation of the center of gravity.

The solution of the relative acceleration equation with the use of linear accelerometer data is not trivial: many difficulties arise in the solution process. Published literature presents a few accelerometer schemes that require precise placement of the accelerometers and manipulation of the relative acceleration equation to form a set of three equations to solve for angular velocity or angular acceleration directly from linear acceleration data. Most notably of these are the six, as shown by Shuler in 1967, and nine-accelerometer schemes. The nine-accelerometer setup was established by Padgaonkar in 1975 and is commonly referred to as the 3-2-2-2 method. Common to both of these arrangements is the placement of accelerometers on each local coordinate axes and an assumption that gravitational effects can be ignored. This allows there to be a common origin collinear with each of the accelerometers. While in most cases this origin is selected as the center of gravity, any arbitrary point may be selected for the origin as long as the accelerometers are placed on the orthogonal axis to this origin. This then reduces the radius vector to one term so when the cross product is carried out in the angular acceleration equation some of the angular acceleration and angular velocity terms cancel out. These cancellations result in a system of equations that can be manipulated to form a set of three equations that are functions of only measured linear acceleration and angular acceleration. In theory, this set of equations can be solved directly for the angular acceleration without the use of numeric techniques or further measurements.

In practice, the six-accelerometer method has proven difficult. The Jacobian determinant of the six-accelerometer system of equations is zero; therefore the set is unstable. The nine-accelerometer scheme has been shown to have its own difficulties, but has been used successfully to determine angular velocities and accelerations. Mital and King in 1979 discussed one such problem occurs when the Euler angles go through 90 degrees. In 2001, Baselli et al. presented a paper using a four triaxial accelerometer setup positioned orthogonally on human heads to estimate the acceleration of the origin from the average of two of the accelerometer sets. The equations Basselli derived are similar to those of the 3-2-2-2 method, but also provide a correction algorithm for misalignment errors based upon using the component of gravity to determine the angle of tilt. In 2003, Takhounts et al. further examined the 3-2-2-2 method and found that because the set of equations are overdetermined, a set of constraint equations can be developed and used to identify if one of the accelerometers is not operating correctly.

The solutions of the above methods rely upon the precise and controlled placement of accelerometers to allow cancellations in the relative acceleration equation. In the current study, because of the geometry of the human head and the desire to create a head gear adjustable for numerous subjects, it is very difficult to arrange the accelerometers to allow for the above cancellations. Therefore, a method is presented here to solve for a more general or random arrangement of accelerometers.

## METHODS

Thorough examination of published literature has shown that the use of linear accelerometers and the relative acceleration equation is sufficient to calculate angular acceleration, velocity, and position. A general form of the relative acceleration equation relating the accelerations of two points on a rigid body can be defined as:

$$a_i := a_j + \alpha \times r_{ij} + \omega \times (\omega \times r_{ij})$$

Where:
$a_i$ is the linear acceleration of point i on the rigid body;
$a_j$ is the linear acceleration of point j on the rigid body;
$\alpha$ is the angular acceleration of the rigid body;
$\omega$ is the angular velocity of the rigid body;
$r_{ij}$ is the radius vector between points i and j.

Expanding this equation to its vector form, a set of three non-linear second order differential equations can be formed which theoretically are sufficient to solve for the angular accelerations and velocities:

$$\begin{aligned}
a_{ix} - a_{ix} + \alpha_y \cdot r_{ijz} - \alpha_z \cdot r_{ijy} + \omega_y \cdot (\omega_x \cdot r_{ijy} - \omega_y \cdot r_{ijx}) - \omega_z \cdot (\omega_z \cdot r_{ijx} - \omega_x \cdot r_{ijz}) &= 0 \\
a_{jy} - a_{iy} + \alpha_z \cdot r_{ijx} - \alpha_x \cdot r_{ijz} + \omega_z \cdot (\omega_y \cdot r_{ijz} - \omega_z \cdot r_{ijy}) - \omega_x \cdot (\omega_x \cdot r_{ijy} - \omega_y \cdot r_{ijx}) &= 0 \\
a_{jz} - a_{iz} + \alpha_x \cdot r_{ijy} - \alpha_y \cdot r_{ijx} + \omega_x \cdot (\omega_z \cdot r_{ijx} - \omega_x \cdot r_{ijz}) - \omega_y \cdot (\omega_y \cdot r_{ijz} - \omega_z \cdot r_{ijy}) &= 0
\end{aligned}$$

Where:
$a_{ix}$, $a_{iy}$, $a_{iz}$ are the linear accelerations of point i in the X, Y, and Z directions, respectively;
$a_{jx}$, $a_{jy}$, $a_{jz}$ are the linear accelerations of point j in the X, Y, and Z directions, respectively;
$\alpha_x$, $\alpha_y$, $\alpha_z$ are the angular accelerations in the X, Y, and Z directions, respectively;
$\omega_x$, $\omega_y$, $\omega_z$ are the angular velocities in the X, Y, and Z directions, respectively;
$r_{ijx}$, $r_{ijy}$, $r_{ijz}$ are the radius vectors between points i and j in the X, Y, and Z directions, respectively.

In practice, it has been determined that because of small errors in linear acceleration measurements that compound through integration, numerical techniques (such as Runge-Kutta) are insufficient for solving this set of equations (Padgaonnkar et al., 1975). Past research has been meticulous in choosing the number and position of accelerometers as well as the manipulation of the relative acceleration equations in order to be successful in finding the angular components. This previous research involves having accelerometers on precisely aligned orthogonal axes, a condition difficult to achieve on living subjects. The 3-2-2-2 method is very good for use on ATD's because one tri-axial accelerometer can be placed at the center of gravity of the ATD's head. This method, however, is difficult to adapt to human testing. Therefore, the present study utilizes a set of nine linear accelerometers secured to a relatively rigid headgear apparatus that can be adjusted to fit snugly on most adult heads. The nine linear accelerometers are grouped to create three tri-axial accelerometers. A redundant scheme of accelerometers was chosen with the intent that calculations could be checked and verified to acquire more accurate results. The choice of the positions of the three sets of accelerometers was based upon the expectation that having one set of accelerometers out of plane with the others may yield better results. When used on a volunteer, the locations of each accelerometer and appropriate anatomical landmarks are precisely identified using a three-dimensional coordinate measuring apparatus. The positional data is utilized, along with published anthropometrical data (Zatsiorsky and Seluyanov, 1983; Pavol et al., 2002), to estimate the location of the volunteer's head center of gravity and the relative position of each accelerometer. The positions and numbering system of the accelerometers can be seen in Figure 1 below.

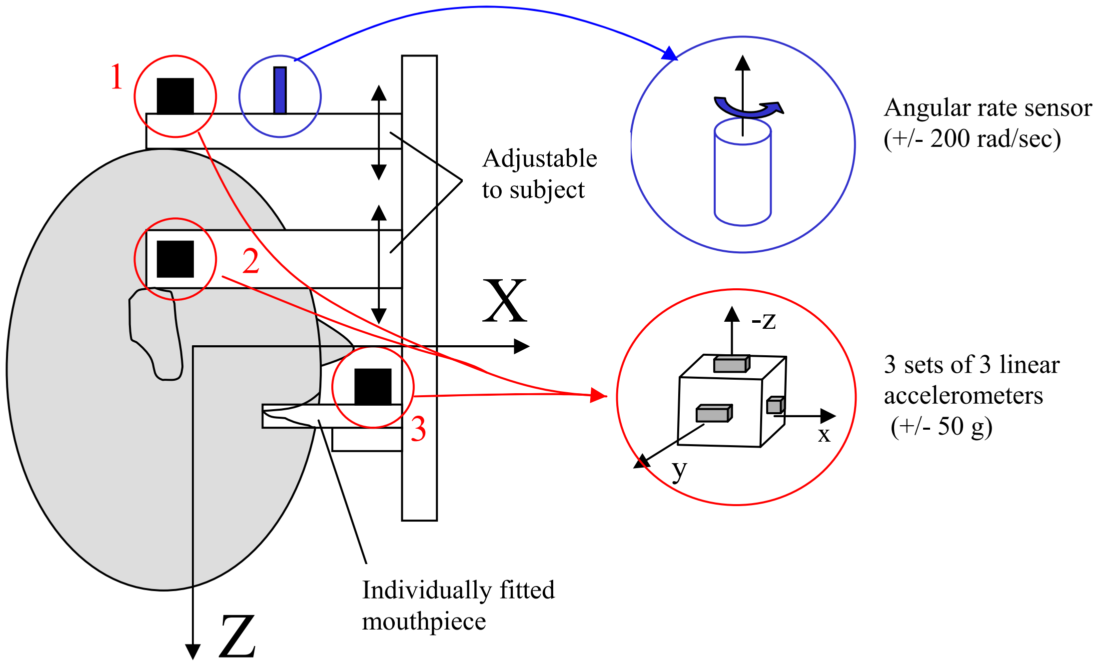


Figure 1: Measurement instrument positions and nomenclature on headgear.

Using the above accelerometer scheme, a set of nine over-determined nonlinear differential equations are formed. Set one relates accelerometers located at point 1 to those at 2, set two relates point 1 to point 3 and set three relates point 2 to point 3, as represented in Figure 1:

Set one:

$$a_{2x} - a_{1x} + \alpha_y \cdot r_{12z} - \alpha_z \cdot r_{12y} + \omega_y \cdot \left(\omega_x \cdot r_{12y} - \omega_y \cdot r_{12x}\right) - \omega_z \cdot \left(\omega_z \cdot r_{12x} - \omega_x \cdot r_{12z}\right) = 0$$

$$a_{2y} - a_{1y} + \alpha_z \cdot r_{12x} - \alpha_x \cdot r_{12z} + \omega_z \cdot \left(\omega_y \cdot r_{12z} - \omega_z \cdot r_{12y}\right) - \omega_x \cdot \left(\omega_x \cdot r_{12y} - \omega_y \cdot r_{12x}\right) = 0$$

$$a_{2z} - a_{1z} + \alpha_x \cdot r_{12y} - \alpha_y \cdot r_{12x} + \omega_x \cdot \left(\omega_z \cdot r_{12x} - \omega_x \cdot r_{12z}\right) - \omega_y \cdot \left(\omega_y \cdot r_{12z} - \omega_z \cdot r_{12y}\right) = 0$$

Set two:

$$a_{3x} - a_{1x} + \alpha_y \cdot r_{13z} - \alpha_z \cdot r_{13y} + \omega_y \cdot \left(\omega_x \cdot r_{13y} - \omega_y \cdot r_{13x}\right) - \omega_z \cdot \left(\omega_z \cdot r_{13x} - \omega_x \cdot r_{13z}\right) = 0$$

$$a_{3y} - a_{1y} + \alpha_z \cdot r_{13x} - \alpha_x \cdot r_{13z} + \omega_z \cdot \left(\omega_y \cdot r_{13z} - \omega_z \cdot r_{13y}\right) - \omega_x \cdot \left(\omega_x \cdot r_{13y} - \omega_y \cdot r_{13x}\right) = 0$$

$$a_{3z} - a_{1z} + \alpha_x \cdot r_{13y} - \alpha_y \cdot r_{13x} + \omega_x \cdot \left(\omega_z \cdot r_{13x} - \omega_x \cdot r_{13z}\right) - \omega_y \cdot \left(\omega_y \cdot r_{13z} - \omega_z \cdot r_{13y}\right) = 0$$

Set three:

$$a_{3x} - a_{2x} + \alpha_y \cdot r_{23z} - \alpha_z \cdot r_{23y} + \omega_y \cdot \left(\omega_x \cdot r_{23y} - \omega_y \cdot r_{23x}\right) - \omega_z \cdot \left(\omega_z \cdot r_{23x} - \omega_x \cdot r_{23z}\right) = 0$$

$$a_{3y} - a_{2y} + \alpha_z \cdot r_{23x} - \alpha_x \cdot r_{23z} + \omega_z \cdot \left(\omega_y \cdot r_{23z} - \omega_z \cdot r_{23y}\right) - \omega_x \cdot \left(\omega_x \cdot r_{23y} - \omega_y \cdot r_{23x}\right) = 0$$

$$a_{3z} - a_{2z} + \alpha_x \cdot r_{23y} - \alpha_y \cdot r_{23x} + \omega_x \cdot \left(\omega_z \cdot r_{23x} - \omega_x \cdot r_{23z}\right) - \omega_y \cdot \left(\omega_y \cdot r_{23z} - \omega_z \cdot r_{23y}\right) = 0$$

In theory, if the proper initial conditions are well defined, only one set of these differential equations is required to solve for angular velocity and acceleration in the X, Y, and Z directions. However, it has been determined that using six accelerometers from two tri-axial locations results in a set of three equations whose determinant is zero, and thus singular. Therefore, the equations must be rearranged by choosing one equation from each set to form three new sets of equations whose determinants are not zero. The solution of any one of these three new sets of differential equations is theoretically feasible for determining the angular components. However, because of the errors accumulated in numerical differential equation techniques, another method of solution is required. Since the above accelerometer scheme is not constructed for the position of the accelerometers to allow for cancellation of radius vector terms, the aforementioned solution methods used by Shuler and Padgaonkar are not used.

The methods presented in this paper are based upon the fact that if the angular velocity terms are known, the above equations can be solved directly for the angular accelerations. Two methods are presented for determining the angular velocities: 1) direct measurement and 2) computation.

The first method requires that, in addition to the linear accelerometers, angular rate sensors be positioned on the head gear to measure the angular velocity about each of the three coordinate axes. Since the linear accelerations and angular velocities are measured, the angular acceleration equations can be solved directly for the angular acceleration terms. This yields a reliable method where neither numeric integration nor manipulation is required to solve for the angular accelerations.

The second method requires only the use of linear accelerometers to solve for all of the unknowns. The linear acceleration data is integrated to find linear velocity, and then used in the relative velocity equation to find angular velocity. The linear accelerometer data and the computed angular velocities can then be used in the relative acceleration equations to solve directly for the angular accelerations. The computed results from this method can then be checked against the measured results obtained from the first method.

Since the relative velocity equation is a function of the known radius vectors and linear velocities it can be solved directly for angular velocity. The general form of the relative velocity equation between two points on a rigid body is given as:

$$v_i = v_j + \omega x r_{ij}$$

Where:
$v_i$, $v_j$ are the linear velocities of points i and j, respectively.

In vector form this becomes:

$$\begin{aligned} v_{jz} - v_{iz} + \omega_x \cdot r_{ijy} - \omega_y \cdot r_{ijx} &= 0 \\ v_{jx} - v_{ix} + \omega_y \cdot r_{ijz} - \omega_z \cdot r_{ijy} &= 0 \\ v_{jy} - v_{iy} + \omega_z \cdot r_{ijx} - \omega_x \cdot r_{ijz} &= 0 \end{aligned}$$

Where:
$v_{ix}$, $v_{iy}$, $v_{iz}$ are the linear velocities of point i in the X, Y, and Z directions, respectively;
$v_{jx}$, $v_{jy}$, $v_{jz}$ are the linear velocities of point j in the X, Y, and Z directions, respectively.

Since the linear velocity is obtained through numeric integration of the linear accelerometer data, it must be noted that the linear accelerometer data does contain a component of gravity. This data, when integrated, may contribute to the linear velocity measurements diverging over time. However, using the assumption that the accelerometers in each orthogonal direction are positioned to measure accelerations directly parallel to one another, the accelerometers measuring acceleration in the same axis direction should experience the same gravitational force. When the velocities are subtracted in the relative velocity equation, this identical component of gravity will ideally cancel out.

## RESULTS

The method of determining both linear and angular acceleration using the aforementioned head gear, was evaluated utilizing a set of quasi-planar bench validation tests. These tests involved rotational movement in one plane about a fixed rotational axis with measurements taken from nine accelerometers and one angular rate sensor.

In each test the headgear was rigidly mounted onto a test platform. This test platform was constructed to only allow rotation about one axis: the Z-axis. This axis was setup perpendicular to the floor, aligned with gravity. The location of each accelerometer with respect to the rotational axis was precisely measured. All tests then, ideally involved rotation only about the Z-axis and linear translations only in the X-Y plane.

The accelerometers consisted of six Sensotec piezoresistive accelerometers with +/- 50 g full scale range, two Sensotec piezoresistive accelerometers with +/- 100 g full scale range, one Endevco 7264B accelerometer with +/- 1000 g full scale range, and one ATA ARS-06s angular rate sensor with +/- 200 radians/sec full scale range. Each set of three accelerometers was calibrated in-situ as a tri-axial accelerometer block, and the output was calibrated to +/- 15 to +/- 100 g. Data was collected at a rate of 2000 Hz for up to 10 seconds using an IOTECH Daqbook 2001 with DBK 43A and DBK 13. Tests were performed varying the rate, the magnitude, and the type of event including both impact and non-impact (i.e. inertial) events.

The computational method of determining angular velocity involves integration of the measured linear acceleration data to determine the linear velocities, which are then used in the relative velocity equations to determine the angular velocities. Due to the nature of the system, this results in three different solution sets for the angular velocity vector. Each of these angular velocities are then utilized along with the measured linear acceleration in the relative acceleration equation to determine the angular acceleration. Again, due to the use of three triaxial accelerometers, there are three solution sets for the angular acceleration as well. Ideally all these results would be equal. However, due to the inherent difficulties in precise accelerometer placement, this is not always the case. Currently, all these results are compared to the result found through direct measurement of the angular velocity and the one that best matches is utilized. In future studies it is anticipated that an optimization technique, or similar, will be developed for determining which angular acceleration is correct.

Conversely, when measuring the angular velocity directly, the angular acceleration can be determined directly via the relative acceleration equation. Since the testing involves rotation about only one axis, angular velocity is only measured about this axis. It is assumed that the rotational velocities about the other two orthogonal axes are zero. In these tests, all motion is in the X-Y plane, and therefore all rotation is about the Z-axis. The angular acceleration about the Z-axis found using the measured angular velocity about the Z-axis and assuming no rotational components about the X- or Y-axes is referred to here as the "ideal". This ideal angular acceleration is compared to the angular acceleration determined through use of the computational method presented.

The computational method and its comparison to the direct measurement method are depicted, using one test, in the following series of plots. In Figure 2 the X-axis linear acceleration measured during a test is shown, while the measured linear accelerations on the Y- and Z-axes are shown in Figures 3 and 4, respectively.

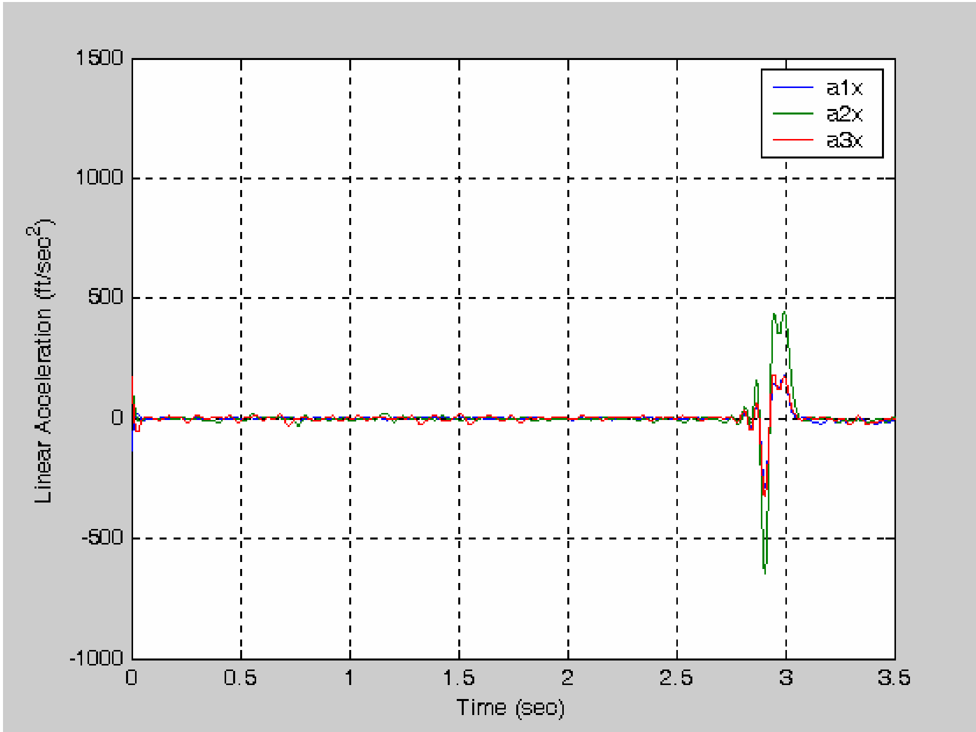


Figure 2: Measured X-axis linear acceleration.

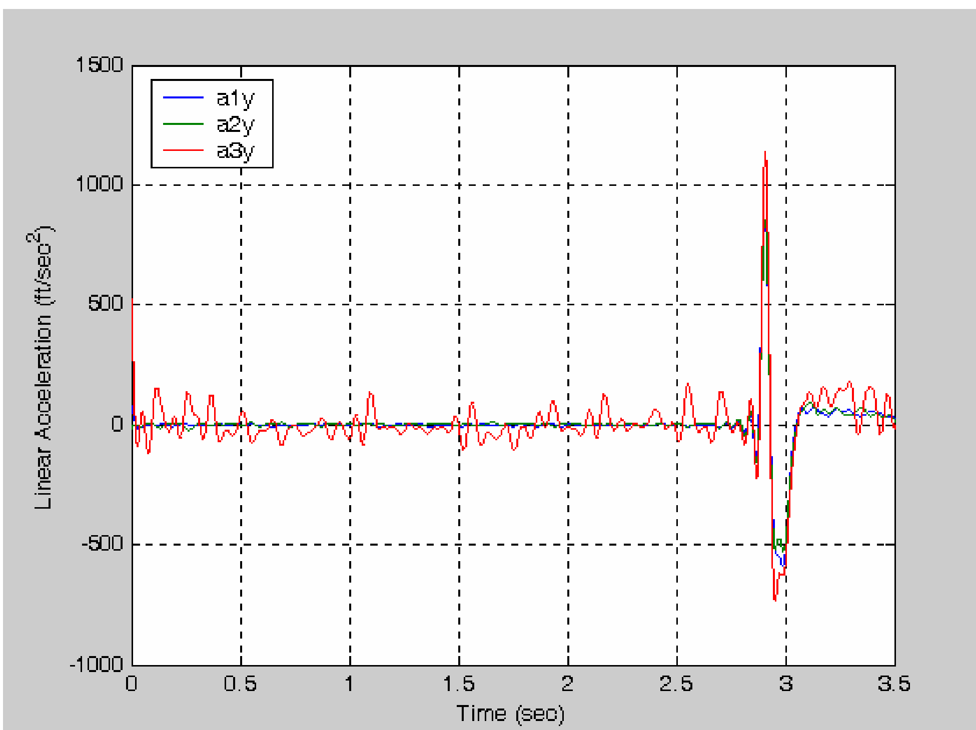


Figure 3: Measured Y-axis linear acceleration.

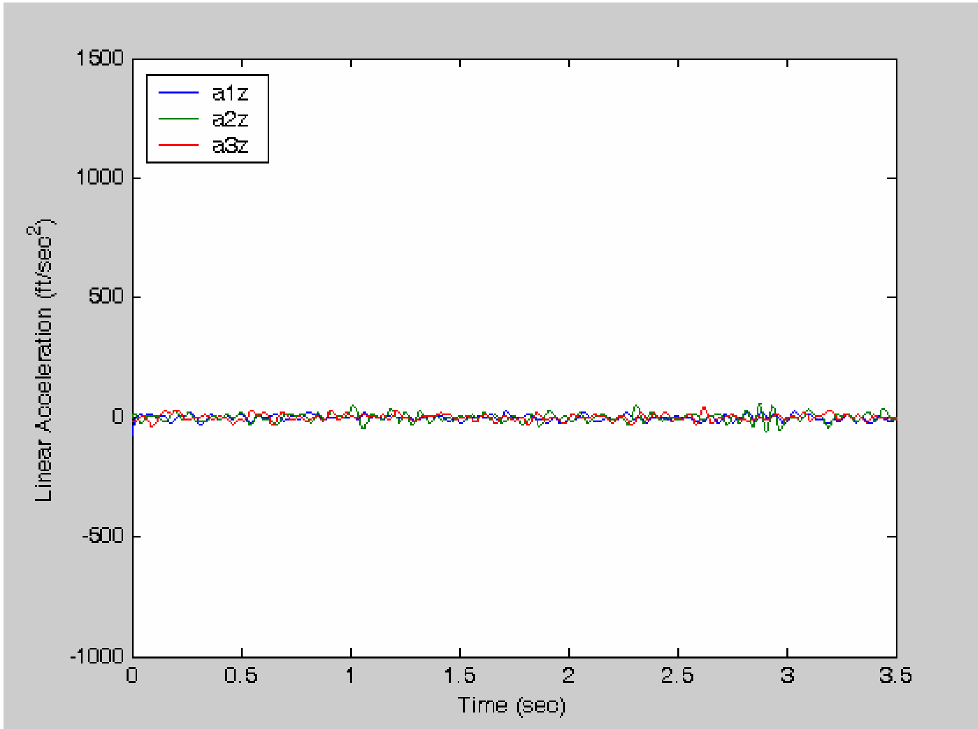


Figure 4: Measured Z-axis linear acceleration.

It can be seen from Figures 2 through 4 that this test is an example of a relatively hard impact with components of the impact force represented in each of the three axes. Motion in each of these tests was limited primarily to the X-Y plane. Therefore, the X- or Y- direction linear accelerations can be used for the determination of the impact response characteristics, including the pulse duration, as shown in Figure 5. For the current validation, a consistent method of determining the pulse duration was utilized. The first major peak magnitude in the linear X-acceleration data was identified. The last zero crossover point prior to the signal continuously increasing or decreasing towards its peak value is considered the pulse start. The first zero cross-over point after the peak signal value is considered the pulse end. A method for choosing and characterizing the even pulse during an unconstrained random three-dimensional event is being developed for use during three-dimensional validation.

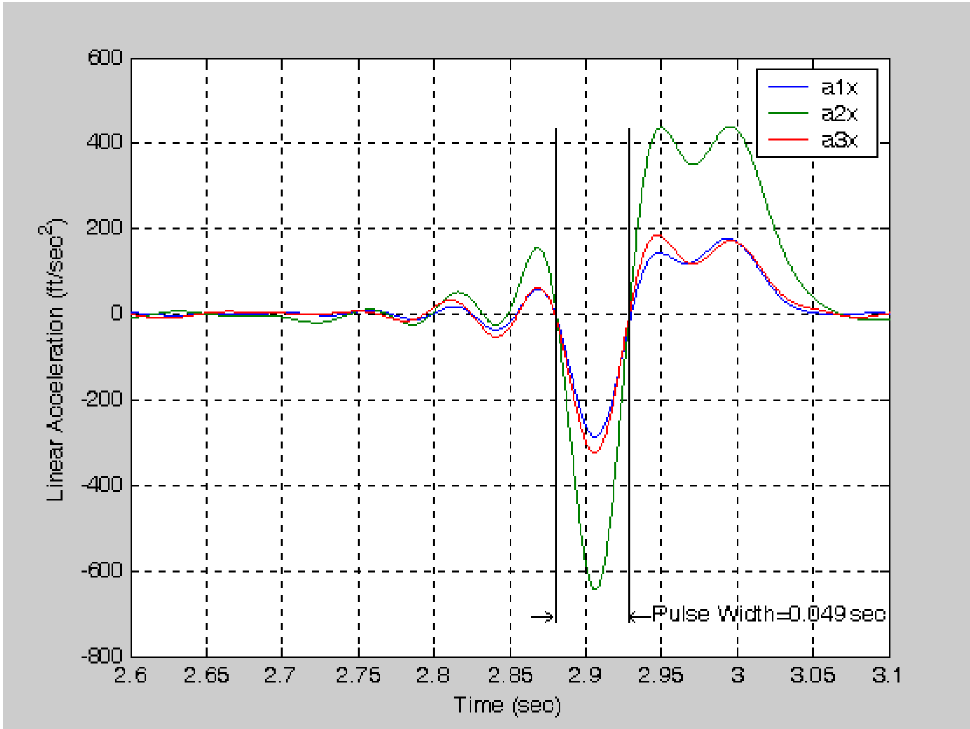


Figure 5: Portion of measured X-axis linear acceleration data used for analysis.

The computed linear velocities and angular velocities are not being presented, since their use is fully demonstrated in the angular acceleration. The computed angular accelerations about the X- and Y-axes are shown below in Figures 6 and 7, respectively.

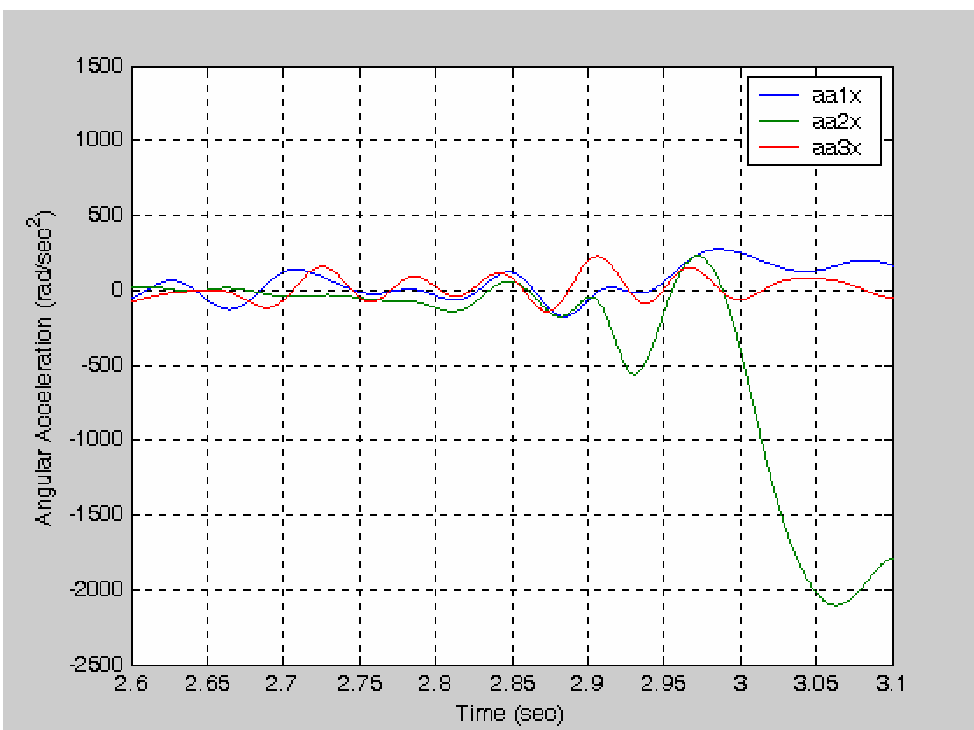


Figure 6: Computed X-axis angular accelerations.

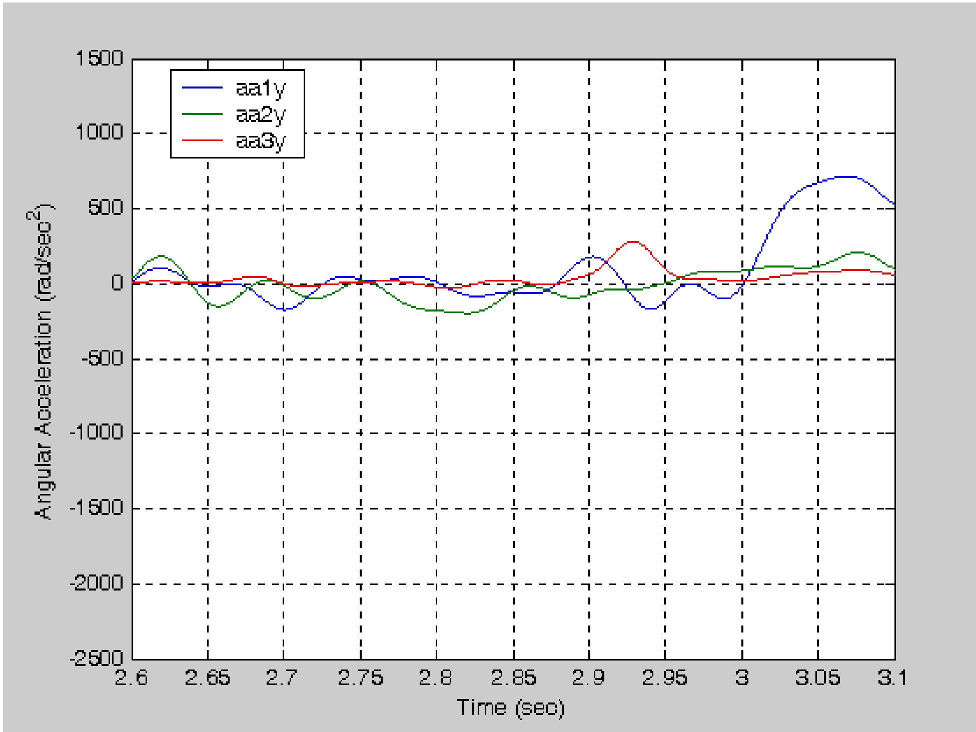


Figure 7: Computed Y-axis angular accelerations.

In Figures 6 and 7, it is observed that the angular accelerations about the X- and Y-axes, determined using the angular velocities obtained from the relative velocity equations, vary about zero for the first 100 to 150 milliseconds, and then averages start to diverge away from zero as errors accumulate due to increasing analysis time. Since this was a planar test with rotation only about the Z-axis, the X- and Y-axis angular accelerations would ideally be zero. The Z-axis angular acceleration using the computational method is shown in Figure 8. This result is then compared to the ideal angular acceleration found using the direct measurement method, assuming X- and Y- axis rotational components are zero, is shown below in Figure 8.

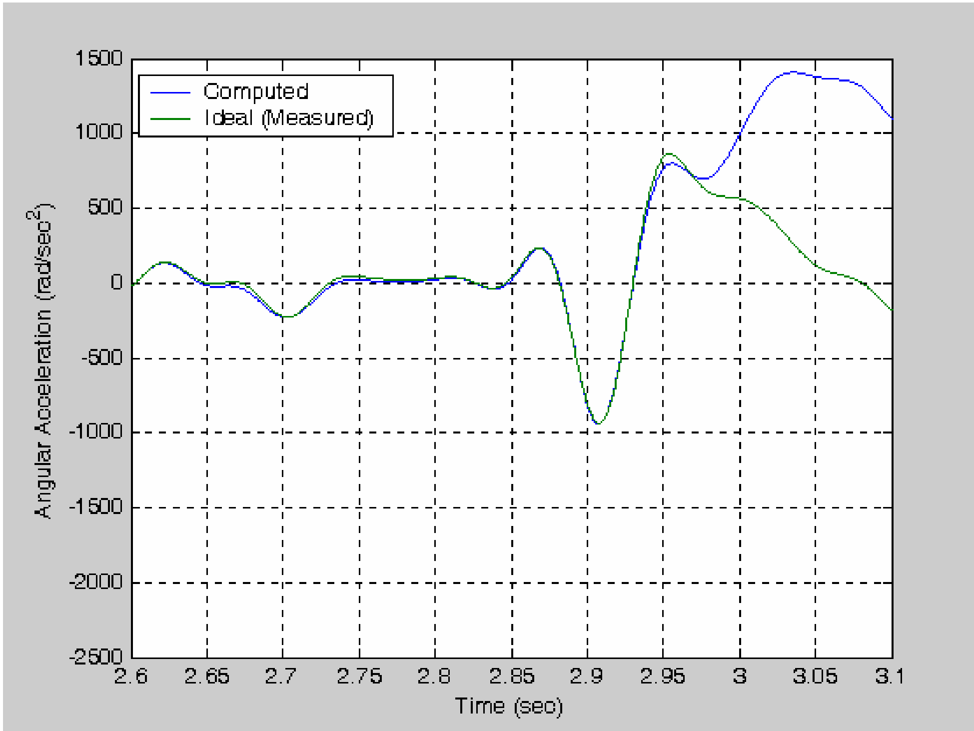


Figure 8: Computed Z-axis angular acceleration compared to the ideal angular acceleration.

Figure 8 demonstrates the utility of the computational method presented in this work to determine the angular acceleration using only linear acceleration measurements. For this test, the impact pulse duration was about 50 milliseconds. The angular acceleration from the computational method is able to track the angular acceleration from the direct measurement method well for the entire impact response. There is a 0.30 percent error in the magnitude at the peak response magnitude, and only a 1.0 percent time lag at the end of the response when the magnitude again reaches zero. In fact, the error is only about 6.0 percent in magnitude at the next response peak. However, as seen in Figure 8, the error continuously increases as the analysis time increases.

In Figure 9 below, the Z-axis angular acceleration found using the computational method is again compared with the ideal found using the direct measurement method for an event having an impact pulse of about 210 milliseconds. Tests involving impact and non-impact pulses between 50 and 200 milliseconds were also performed, but are not presented here for simplicity and brevity. Analysis of these tests shows the same trend of increasing error with analysis time.

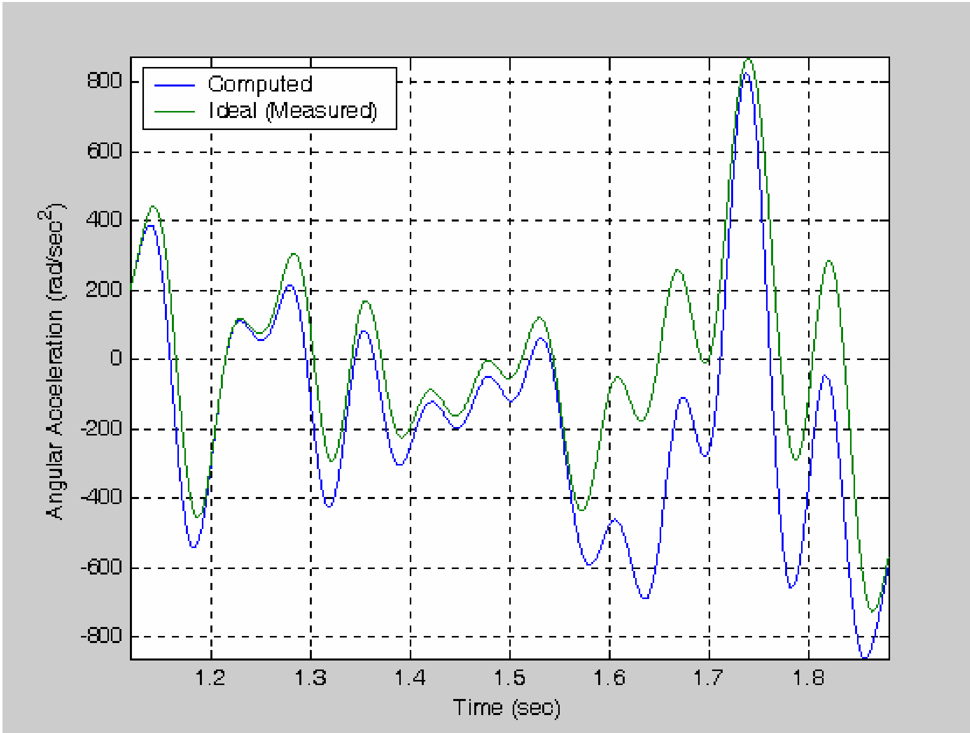


Figure 9: Computed Z-axis angular acceleration compared to the ideal angular acceleration with an initial acceleration pulse of 0.212 seconds.

In this test, with an impact pulse duration of 210 milliseconds, the error in magnitude at peak response reaches about 4.7 percent, while the error in time lag at the end of the initial response curve is about 4.6 percent. This test involved a much more complicated response pulse, but the result using the computational method is observed to track the response in both magnitude and time quite well even after over .70 seconds of analysis time. Again the error is observed to increase as the analysis time increases.

These planar tests indicate that the computational method works well in determining the angular accelerations when the event involves a pulse duration less than 200 milliseconds. Compared to the ideal result using the measured angular velocity, the computational method has a full scale error of 5.0 percent or less in the determination of the magnitude of the peak angular acceleration and has about 5.0 percent time lag error at the end of the initial response for pulse durations up to about 0.200 seconds. The error in peak angular acceleration increases as the pulse duration increases due to the accumulation of errors resulting from numerical integration as the analysis time increases. Further tests were performed involving impact and non-impact events up to pulse durations of over 0.5 seconds. At a pulse duration in the range of 300 to 350 milliseconds the error in peak angular acceleration magnitude determined using the computational method reaches 60 to 80 percent compared to that determined using the measured angular velocities. The following plot, Figure 10, depicts a non-impact event with an initial pulse greater than 210 milliseconds.

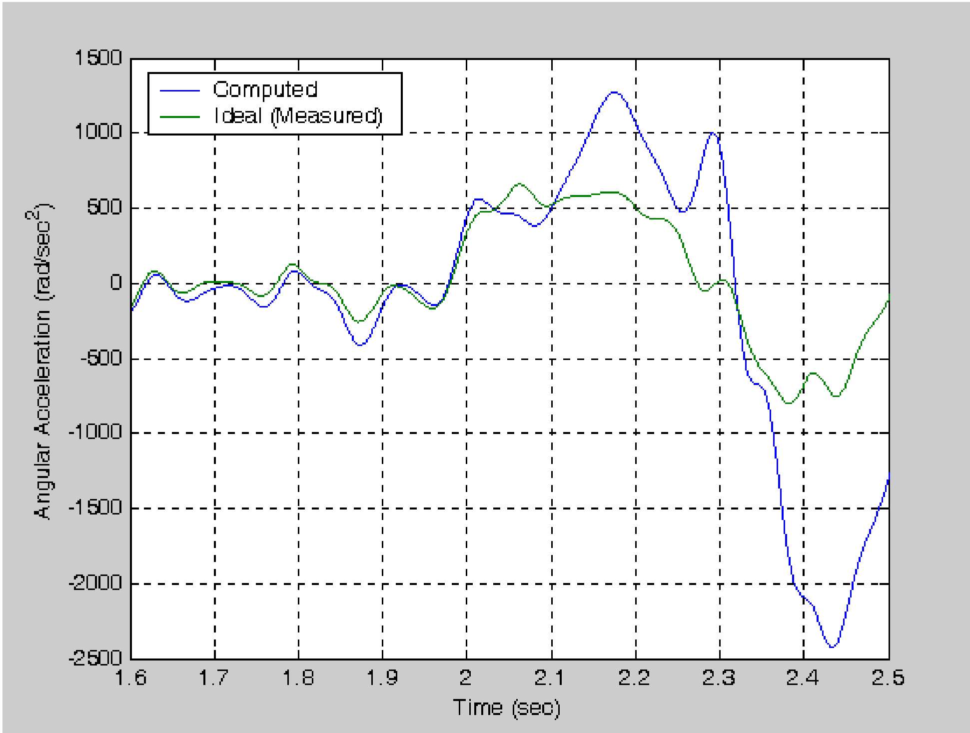


Figure 10: Computed Z-axis angular acceleration compared to the ideal angular acceleration with an initial acceleration pulse of 0.350 seconds.

## CONCLUSIONS

In order to compare the forces exerted on the human head during daily activities to those experienced in a minor accident, both linear and angular accelerations are required. Past research has shown that the linear accelerations can be obtained from linear accelerometer data, and angular acceleration can be found with some manipulation of the relative acceleration equation. This past research, however, presents methods that are difficult to apply to human testing. For this reason, this paper discusses two methods of determining the angular acceleration of a human subjects head using the relative acceleration equation: 1) direct measurement of angular velocity using angular rate sensors, and 2) computation of angular velocity applying the relative velocity equation. Both methods involve determining the angular velocities before application of the relative acceleration equation. This bypasses erroneous attempts to solve the relative acceleration equation in differential form and eliminates the need for difficult accelerometer placements.

Planar bench testing has shown that integration of the linear acceleration data results in an accumulation of error that does not become significant until the event of interest becomes longer than about 200 milliseconds. This includes impact and non-impact events. Minor vehicular impacts have been shown to have initial impact durations usually less than 250 milliseconds but more than 50 milliseconds, and the activities of daily living that are of interest in comparing to minor impacts would have similar durations. Therefore, it is assumed that either direct measurement or calculation of angular velocity would be sufficient when measuring a majority of the activities of daily living and when used during many of the minor vehicular impacts with initial head acceleration durations up to 200 milliseconds. In events with durations longer than this, only the direct measurement of angular velocity method can be employed. Finally, it should be noted that this current effort utilized two-dimensional testing. When three dimensions are considered the effects of gravity may still have to be accounted for using some form of continuous correction.

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## DISCUSSION

PAPER: **Linear and Angular Accelerations of the Head During Activities of Daily Living. Part I: Instrumentation and Methodology**

PRESENTER: ***D. Morr, SEA, Limited***

**Q**UESTION: *Erik Takhounts, NHTSA*
I'll try to be nice. It seems to me that your system was in a bit of trouble here because—I'm nice.

**A**NSWER: That's alright.

**Q:** Because what you are doing: You are testing an in-plane. You have an in-plane test. And if you cannot match an in-plane test, you can do anything when you have an out-of-plane motion because small deviations in the out-of-plane and accelerometers: they multiply very quickly. So you are not going to be even close, even in 10 milliseconds interval, with acceleration. So if your accelerations don't match that well, your displacements, angular displacements will be way off. Your heads will show that they rotate like $360^{o}$, at best. So you got to go back and look at the methods that have developed based not on the closed form solutions as you are showing now, but the methods that have been presented before that are based on optimizations that find probably best solution on each time step. The second—I don't know--

**A:** Could I comment on that? I'll comment on that.

**Q:** Oh yeah. Go and comment on that.

**A:** We have looked at the 6 and 9 accelerometer array systems that people have used and are being used, and obviously we can't put something at center. So that's one thing I did talk about and that's not really what you're talking about. Optimization is one of the techniques that we're talking about using. However, we don't need to use it for at least a portion of what we're talking about if we measure the angular velocity.

**Q:** Is that what I asked? What I said was--

**A:** You didn't ask. You actually made a statement, so I'm just making a statement again, too that's on point to what you talked about. So, do you have a question now?

**Q:** Yeah. Okay. How accurate is your system compared to the actual motion that happened that it's supposed to measure?

**A:** That's something we have to validate. That's why—So we have to do 2D and 3D validation to figure that out.

**Q:** I thought you just showed that it's very inaccurate.

**A:** Very inaccurate?

**Q:** Yeah.

**A:** If you use only the computation, if all you do is measure linear acceleration, that's it and then integrate up to two times, yes. Inaccurate. Now if you add in the measurement of angular velocity, now you're accurate and that's what I was showing.

**Q:** You measure angular velocity with what?

**A:** With an angle rate sensor mounted to the apparatus.

**Q:** If you measure angular velocity, why do you need linear accelerations already?

**A:** Because we're trying to solve for angular acceleration and linear CG acceleration.

**Q:** Oh, you plug the angular velocity data into your linear acceleration array to get angular acceleration?

**A:** Into the relative acceleration equations.

**Q:** And if you just differentiate the angular velocity, you don't get the same angular acceleration?

**A:** If you just differentiate the angular velocity?

**Q:** Yeah.

**A:** Well, of course, you're going to have the differentiation errors now, too.

**Q:** Okay. Thank you.

**Q**UESTION: *Guy Nusholtz, DaimlerChrysler*
What's ringing?

**A:** What's ringing on the traces that you see? Where you see the high frequency? Actually, that is the low pass, low pass filter at 100 hertz. And looking at the power spectral densities, we have—We have—Excuse me?

**Q:** The filter's ringing?

**A:** I don't know what's ringing as far as where the ringing is coming from, where you see the randomness of the data.

**Q:** I recognize that you've got a filter on there.

**A:** There is a filter.

**Q:** But what is?

**A:** But we did do a power spectral density plot and we did look at that, too. And by and large, most of the magnitude in the frequency domain is less than 10 hertz. There's a small portion at 60 hertz, which is not uncommon to see; but of course, we're now low pass loading at 100 hertz and we don't see anything past there. So yeah, the traces—We're not taking an average. This isn't averaged data that you're looking at either.

**Q:** I understand. But if it's real, it shows, you know, someone's [shaking head noise].

**A:** Okay. Wait a minute. You're talking about the test itself.

**Q:** Yeah.

**A:** Okay. The test itself is actually a plane on a rotating axis, basically like a door shutting and closing, and the apparatus is mounted to the door.

**Q:** So the door's ringing?

**A:** No, the apparatus itself has a bar on it that would normally be around somebody's head. We did not fill that space with some inertial mass. So, there is a bar there that can ring.

**Q:** Okay.

**A:** So the ring you're talking about could very systematic to that particular test.

**Q:** Okay. Thank you.

**Q**UESTION: *Jeff Crandall, University of Virginia Center for Applied Biomechanics*
Maybe I can ask a quick question. What is the means of measurement for the angular rate sensor? What type of instrument is that?

**A:** It's a magnito—MHD: magnito hydrodynamic.

**Q:** So just in terms of over long periods of time, that doesn't do so well at low frequencies. So you might want to check because—

**A:** Sure. It has a DC problem over long periods of time.

**Q:** So there's some compensation techniques. I don't know if you used those or not.

**A:** We haven't had to use them yet. Obviously our duration of our actual pulse itself is small. But, did you also notice that the angle rate sensor itself did go back to 0 and did not have a DC shift over a 10-second time frame of our testing? So we didn't—We're not planning on doing anything longer than 10 seconds. Right now, we haven't seen any problems yet. We are aware of that, though. Thanks.

**Q:** Okay. Good. Thank you.