

Measurements of Non-Injurious Head Accelerations of a Pediatric Population

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ABSTRACT

While adult head injuries have been studied over the past six decades, few studies have investigated pediatric head injury mechanics. This paper presents non-injurious head accelerations during various activities in a pediatric population. Six males and six females aged 8-11 years old were equipped with a validated head sensor package and head kinematics were measured while performing a series of playground-type activities. Maximum resultant values across all participants and activities were 25.7 g (range 3.0 g to 25.7 g), 16.0 rad/s (range 10.4 rad/s to 16.0 rad/s), and 1705 rad/s² (range 520 rad/s² to 1705 rad/s²) for linear acceleration, angular velocity, and angular acceleration, respectively. Mean maximum resultant values across all participants and activities were 9.7 g (range 2.1 g to 9.7 g) and 734 rad/s² (range 188 rad/s² to 734 rad/s²) for linear and angular acceleration, respectively. The peak accelerations measured in this study are approximately twice that of previous everyday acceleration studies undertaken with adult subjects. The present study increases the upper limit of known non-injurious activities and closes the gap between the lower limit of injurious loading and the upper limit of non-injurious loading.

INTRODUCTION

Head injury is an important concern in the pediatric population. Traumatic brain injury is a common cause of hospitalization and death in childhood [1-3]. Ten percent of school-age children suffer a significant head injury [2]. Investigations into head injury biomechanics have been conducted and published in peer-reviewed journals, and tolerance values, tissue properties, and structural data are available for the adult head. While adult head

injuries have been studied over the past four decades, few studies have investigated pediatric head injury mechanics.

Children are not miniature adults. One difference is that the mass and body proportions of a child differ from an adult and continuously change throughout childhood [4, 5]. For example, the head mass constitutes approximately 25% of the total body mass in an infant, but only 6% in an adult. Other differences between children and adults include anatomy, tissue mechanical properties, muscle strength, coordination, and behavior [6-8].

To investigate tolerance limits for the population, it is important to understand the mechanical loads during injurious and non-injurious situations. Several studies have described the loads experienced by children in various situations such as in automotive crashes [9, 10], falls [11, 12], and shaking [13, 14]. Non-injurious head accelerations sustained by teenage and adult participants in football, soccer, boxing, and hockey have also been quantified [15-26]. However, there is a paucity of data regarding the loads generated during non-injurious situations for children below the age of 13 years.

Investigations using animals and post mortem human subjects (PMHS) have been conducted to examine pediatric injury mechanics. Infant piglets have been used to study head injury in the young child [27, 28]. Neck injuries have been examined using age-matched non-human primates, porcine, and caprine specimens [29-32]. Few studies have used PMHS to investigate pediatric injury biomechanics [8, 9, 33]. Because of the lack of data for children, injury assessment reference values (IARVs) and tolerance values for children have

been specified using adult data that has been scaled based on differences in material properties and anthropometry between adults and children [6, 7, 34, 35].

While post-mortem tissue remains difficult to acquire, and anthropomorphic test device (ATD) -based measurements are sensitive to the ATD specifics, such as biofidelity, instrumentation, and component design, *in vivo* testing of children during non-injurious everyday activities is feasible. Previous studies have investigated the head accelerations experienced by adults in daily activities [36-48]. These researchers have measured non-injurious activities using a variety of methods, including high-speed planar photography; helmet-mounted, vertex of head-mounted, or biteplate-mounted accelerometer arrays. However, non-injurious activities have not been measured in children.

The purpose of this study is to measure non-injurious head accelerations found in typical childhood activities for subjects 8 to 11 years of age. This study reports *in-vivo* head kinematics from pediatric subjects during various activities using a head sensor package.

METHODS

The study used a head sensor package that was designed and constructed with micro-electromechanical (MEMs) gyroscopic rate sensors and linear accelerometers that were mounted to an adjustable lightweight headband. The sensor group (1201F, Measurement Specialties, Aliso Viejo, California) had a range of ± 50 Gs (resolution: 0.002 g) along each axis and the gyroscopic rate sensors (3103-1200, Ingenieurbüro für Elektronikentwicklung und Spezialgerätebau, Braunschweig, Germany) were capable of measuring ± 20.94 rad/s (resolution of 0.0006 rad/s) about each axis.

VALIDATION OF INSTRUMENTATION

Tests were conducted to validate the accuracy of the head sensor package to measure head accelerations. To this end, the head of a 50th percentile male Hybrid-III ATD (1846-D head, Denton ATD, Milan, Ohio) was instrumented with three linear accelerometers (7264-2000, Endevco, San Juan Capistrano, California) at the center of mass (COM). The ATD head was also instrumented with triaxial angular rate sensors (ARS-1500, Diversified Technical Systems, Seal Beach, California). The ATD was then fitted with the head sensor package, which was positioned such that the sensors were at the top of the head, above the COM of the ATD head (Figure 1).

A 50th percentile male Hybrid-III was used, as the child ATDs could not accommodate the sensors necessary for this study, and the 50th percentile head circumference was only 0.5 cm greater than that of the largest subject.

The ATD torso was perturbed to inertially move the head in each axis for linear and angular motion by the following mechanisms:

1. With the ATD seated in a wheeled chair, the chair was slid forward and backward
2. With the ATD seated in a wheeled chair, the chair was slid side to side
3. With the ATD seat-belted in a chair, the ATD was rocked back and forth laterally by pushing it at the shoulders
4. With the ATD seat-belted in a chair, the ATD was rocked forward and backward by pushing it at the shoulders
5. With the ATD seated on a stool, the ATD was twisted back and forth by rotating it at the shoulders
6. With the ATD seated on a stool, the stool was spun around
7. With the ATD seated on a stool, the stool was spun around more quickly
8. With the ATD seated in a wheeled chair, the chair was slid quickly backwards into a desk
9. With the ATD seated in a wheeled chair, the chair was slid quickly sideways into a desk

After the test sequence was complete, a wig was securely affixed to the ATD head using double-sided tape, the head sensor package was re-mounted, and the sequence repeated. Linear acceleration at the head COM, angular acceleration, and angular velocity calculated from the head sensor package were compared to the accelerations and velocities measured in the ATD head.

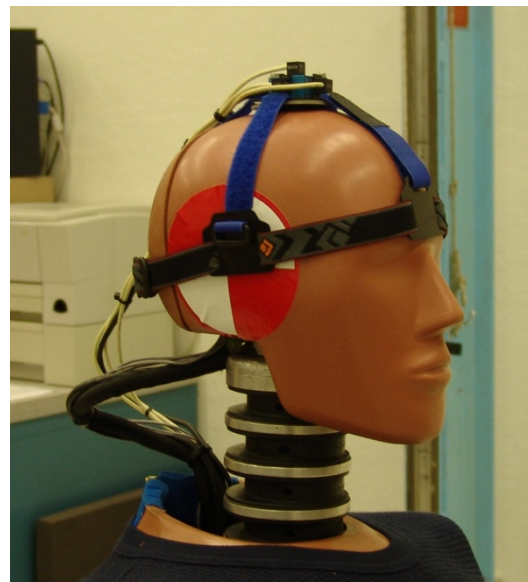


Figure 1 - Head sensor package equipped on an ATD

Additional tests were conducted after data collection to validate the accuracy of the head sensor package for the larger head accelerations demonstrated in the child data. A series of fourteen tests were conducted using a 50th percentile male Hybrid-III ATD equipped with the head sensor package and wig positioned as in the initial

validation. The first seven tests consisted of dropping the ATD onto a concrete floor from initial heights of 2, 3, 5, 8, 10, 14, and 17 inches from buttocks to floor. The second series of seven tests consisted of striking the ATD in the lower part of the face by a suspended pendulum for various distances, corresponding to head accelerations of approximately 5, 10, 15, and 20 g.

HEAD ACCELERATIONS OF CHILDREN

Six male and six female pediatric (ages 8 to 11 years old) participants performed the activities chosen for this study; none of the subjects knew any of the experimenters or had any interest in the outcome of our work. Upon arrival, each participant and their guardian listened to a standardized description of the activities and goal of the study, and provided their consent to participate and be videotaped. The participants were allowed to withdraw from the tests at any time and for any reason. An Institutional Review Board at Exponent approved the test procedures. The experimenters measured the participants' height, weight, head circumference, neck circumference, vertex to occiput height, and the height of the vertex to the T1 spinous process and fitted the participant with the head sensor package.

Channel orientations were in accordance with the SAE J211 standardized dummy head coordinate system: x-axis positive forward, y-axis positive right, z-axis positive down (SAE, 1995). For testing, the headband was positioned such that the sensors were at the top of the head and its axes were coincident with the mid-sagittal plane and the coronal plane through both external auditory meati. The sensor array weighed 49 g (1.7 oz). The complete apparatus, including head sensor, cabling, and waist-mounted data recorder, weighed approximately 800 g (28 oz).

To record the data, the sensors were connected to a small, lightweight (less than 450 g), 16-bit data acquisition system located in a waist pack worn by the test subject (PicoDAS, EME Corporation, Arnold, Maryland). The data acquisition system was capable of sampling at frequencies up to 100 kHz. A flexible cable ran from the sensor package to the data logger along the subject's back. Each participant verified that the placement and attachment of the cable did not impede normal head motion relative to the torso.

Each participant voluntarily performed eight activities:

1. jumping as high as possible
2. running and jumping
3. skipping rope
4. swinging on a swing
5. spinning on a tire swing
6. riding a zip line
7. sliding down a slide
8. climbing on monkey bars or rings

Jumping as high as possible involved three attempts, however the subjects chose, to jump vertically as high as they were able. Running and jumping involved three attempts, however the subjects chose, to jump as far as possible after a running start. Skipping rope involved the subjects attempting to jump for approximately 25 successful jumps, with as many consecutive successful jumps as possible. These jumping activities (vertical jump, run and jump, and skipping rope) were conducted with the subject on an asphalt sidewalk. Swinging on a swing involved the subjects receiving a push from a parent or guardian, and swinging at whatever height they were comfortable for a period of approximately one minute. Spinning on a tire swing involved the subjects receiving a twisting start from a parent or guardian, and spinning at their own discretion for approximately one minute, or until they wished to stop. Riding a zip line involved running and jumping onto a free-hanging handle, and riding a trolley device. The zip line was ridden down the length of the line, and then back. The subjects rode down an undulating slide for the slide task. Climbing on monkey bars or rings involved the subjects jumping or being lifted onto the first bar or rings, and attempting to traverse a gap as far as they were able, and then dropping down to the ground. Photographs and measurements of the equipment are provided in the Appendix as Figure A1.

The subjects were asked to perform the tasks as they would normally, and each task was recorded using a real-time digital video camera recording at 29.97 frames per second. Subjects were cautioned not to jump from the swings during their dismount to prevent snagging of the cables or waist pack. The subjects' parents or guardians were asked to give the subjects an initial push on the swings and an initial spin on the tire swing, because most participants could not touch their feet to the ground while seated on the swings. Before each activity, the subjects were asked to perform a set of head motions (rotating the head in the sagittal, axial, and coronal planes) that was used to synchronize the data with the video. These motions were also used to verify the relative alignment of the sensors. Data were collected for 60 seconds for each activity. When jumping rope and during the two swinging activities, the participants were prompted to stop before the data collection ended. All other activities were completed by all the subjects in less than 60 seconds.

The subjects were contacted three weeks after testing. Responding subjects were asked whether they had soreness or pain in their head, neck, or body immediately after, within one day, and within three weeks after the tests.

Data Processing

During testing, each channel was low-pass filtered using a 400 Hz low-pass anti-aliasing filter, then digitally sampled at 1000 Hz. All data processing was completed using Matlab (The MathWorks, Natick, Massachusetts).

Unlike impact testing, there is no standard method by which to filter linear acceleration and angular rate data for non-impact kinematics. Data were filtered using the residual analysis method from Winter [49] because it provides an analytical method of selecting appropriate cutoff frequencies. Winter's residual analysis is based upon calculating the difference (residual) between a filtered and unfiltered signal over a wide range of cutoff frequencies. Theoretically a signal containing solely random noise would have a residual plot with a straight line decreasing from an intercept at 0 Hz to an intercept on the abscissa at the Nyquist frequency (half the sample rate). This line represents the noise residual, with the intercept at 0 Hz representing the rms value of the noise. When data consist of true signal plus noise, the residual will rise above the straight line as the cutoff frequency is reduced. By setting the amount of distortion and the amount of passed noise equal, then a cutoff can be selected by projecting a line horizontally from the noise residual 0 Hz intercept to intersect the residual line. The frequency at the intersection is the appropriate cutoff frequency.

Appropriate frequency cutoffs for each channel of data were analyzed on a per task and per subject level by an automated routine in accordance with Winter's residual analysis method [49]. To determine the noise residual, a linear regression was calculated backwards from the Nyquist abscissa at 500 Hz until a linear fit of at least $r^2 = 0.9$ could no longer be attained. An example of the output is shown in Figure A2 in the Appendix. Data were filtered digitally using low-pass, four-pole, zero phase shift Butterworth filters.

To calculate angular accelerations, angular velocities for all three axes were filtered to the minimum cutoff found amongst the three axes on a per-task and a per-subject basis, prior to 2-point numeric differentiation. The calculated angular accelerations were subsequently filtered in accordance with the Winter analysis described previously.

At rest, all linear accelerometers measured zero output except the z-axis linear accelerometer, which measured +1 g. The linear acceleration and angular velocity and acceleration data were used to determine the linear accelerations at the approximate center-of-mass (COM) of the head using the three-axis vector equation (1).

$$a_{COM} = a_{Sensor} + \alpha \times r_{COM-Sensor} + \omega \times (\omega \times r_{COM-Sensor}) \quad (1)$$

The distance from the sensor to the COM of the head was estimated using the anthropometric measurements and regression formulae given in Zatsiorski and Selujanov [50], where COM is the head COM, a_{COM} is the linear acceleration at the COM, a_{Sensor} is the linear acceleration measured by the sensor, α is the angular acceleration calculated from the sensor, $r_{COM-Sensor}$ is the vector from the COM to the sensor center, and ω is the angular velocity of the head measured by the sensor. Each variable indicates a three-axis vector quantity.

Resultant linear and angular acceleration and angular velocity vectors were determined. For each participant in each activity, the maximum linear acceleration at the head COM, angular velocity, and angular acceleration were determined. The maxima were determined for each axis and for the resultant vectors. The activity maxima was determined across all phases of the activity including mounting and dismounting the playground equipment as well as the synchronization phases. These values were averaged across participants for each activity and reported as the mean maximum linear and angular accelerations for that activity.

RESULTS

VALIDATION OF INSTRUMENTATION

The kinematics data from the head sensor package were compared with the corresponding data measured by the ATD head (Figures 2-3). For linear acceleration, the head sensor package slightly underestimated peak accelerations. Sensor values were typically within 2 g of the ATD center of mass array values. For angular velocity and angular acceleration, sensor package x- and z-axis values closely matched the ATD sensor values with an average difference of approximately 1 rad/s and 10 rad/s² respectively. For y-axes values for angular velocity and angular acceleration, ATD values were approximately 75% of the values as measured by the head sensor package. These data are depicted in figures A3-A5 in the appendix. Regression equations comparing the measured acceleration from the head sensor package and measured from the ATD headform for y-axis angular acceleration data show a high correlation ($R^2=0.98$, figure A6 in the appendix). Measured y-axis angular velocity and angular acceleration values in the child data were multiplied by the slope of the linear regression (0.75) to correct for the difference indicated by validation testing. Angular resultants were calculated using the adjusted y-axis values. Examples of validation traces for linear and angular acceleration are depicted in figures A7-A10.

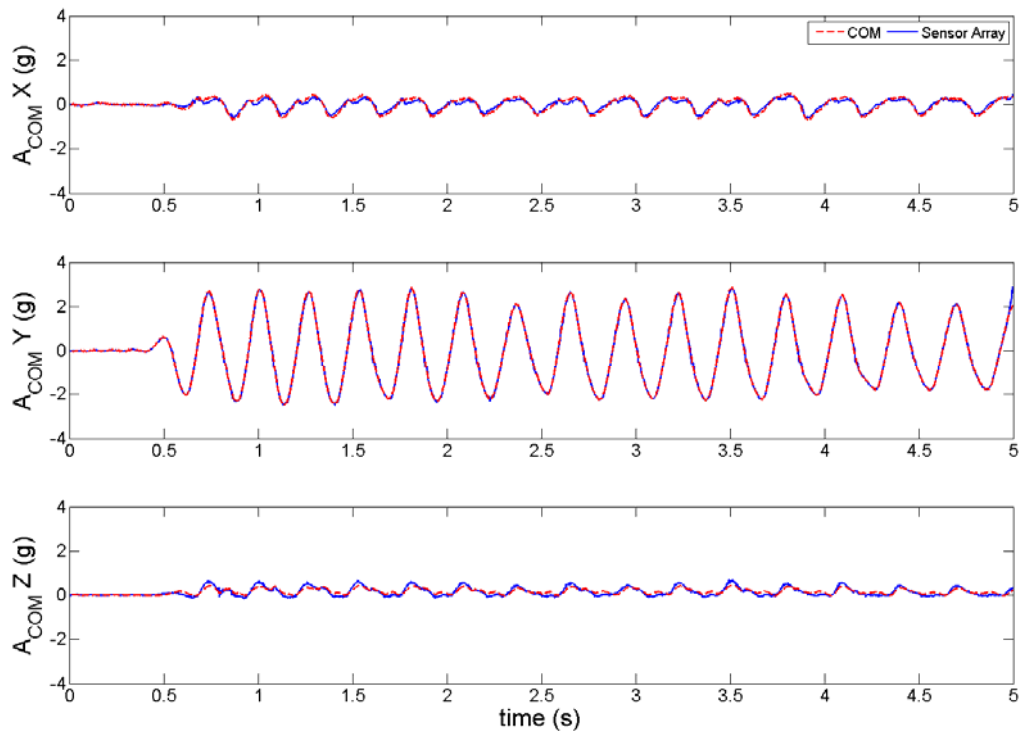


Figure 2 – Example linear acceleration comparison between ATD head COM (dashed red) and vertex head sensor package accelerations transformed to the COM (solid blue), for side-to-side rocking of the ATD.

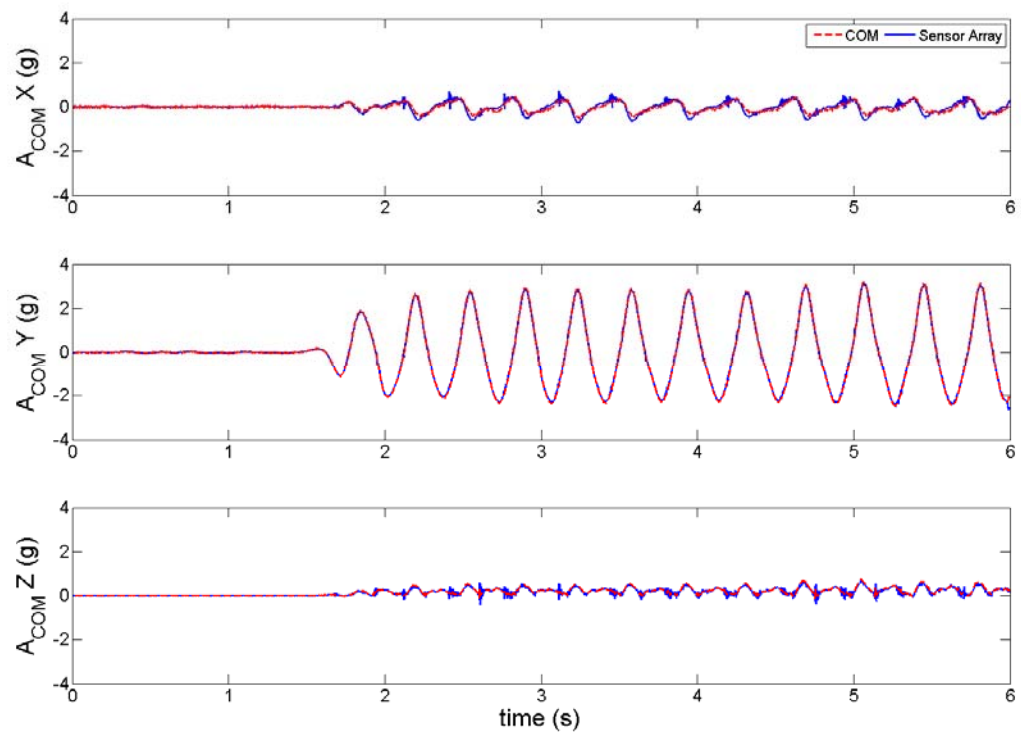


Figure 3 – Example linear acceleration comparison between wig-equipped ATD head COM (dashed red) and vertex head sensor package accelerations transformed to the COM (solid blue), for side-to-side rocking of the ATD.

HEAD ACCELERATIONS OF CHILDREN

The participants exhibited a range of ages (from 8 to 11 years old, mean 10 years old), heights (1.27 to 1.52 m, mean 1.41 m), and masses (25 to 43 kg, mean 32 kg). Subject anthropometry is reported in the appendix–(Table A1).

Across all subjects and all activities, a maximum resultant linear acceleration of 25.7 g, maximum resultant angular velocity of 16.0 rad/s, and maximum resultant angular acceleration of 1626 rad/s² were observed (Figures 4-6). The largest linear and angular accelerations occurred during jumping activities, such as running and jumping and jumping rope. The largest angular velocities were generated in the jump rope and tire swing activities. Large angular velocities were also generated during the synchronization head movements (Figure 7). Frequently, the largest angular velocities during a task were generated during the head motions used to synchronize the data to the video. Cutoff frequencies for each channel ranged from 7 Hz to 189 Hz. Means and maxima across all activities are shown in Figures 8-9. Per activity maxima are shown in Tables A2-A4.

The largest mean maximum resultant linear and angular accelerations (9.7 g and 734 rad/s², respectively) were observed in the jump rope activity. The largest linear and angular accelerations occurred during jumping activities, such as running and jumping and jumping rope (Figures 8-9). Per activity data are shown in Tables A5-A6.

Certain data records were influenced by brief contacts between the head sensor array and objects in the test environment, such as the jump rope or the chains of the tire swing. These records were detected by iteratively identifying outliers in the data (two standard deviations from mean), and reviewing the data and video recordings for the causes, such as head contacts. Data associated with head contacts were not considered in this analysis. If the effect on the data from a removal of a portion of the signal generated new outliers, those new outliers were also reviewed.

Linear acceleration (g)

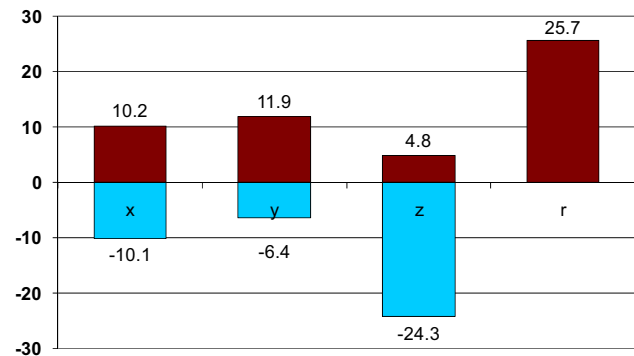


Figure 4 – Maximum linear accelerations (g) at the head COM across all activities. From left to right: x-axis, y-axis, z-axis, and the resultant acceleration. Negative values indicate maxima in the negative direction.

Angular velocity (rad/s)

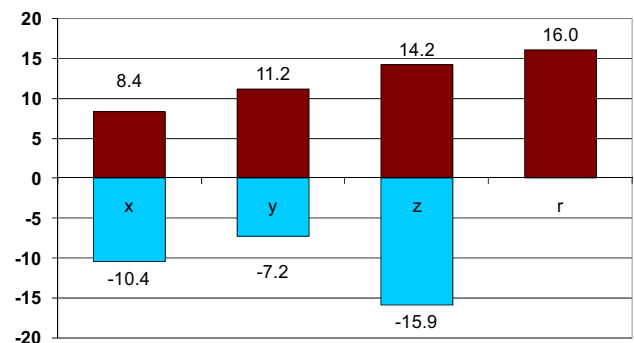


Figure 5 – Per-axis maximum angular velocities (rad/s) across all activities. From left to right: x-axis, y-axis, z-axis, and the resultant acceleration. Negative values indicate maxima in the negative direction.

Angular acceleration (rad/s²)

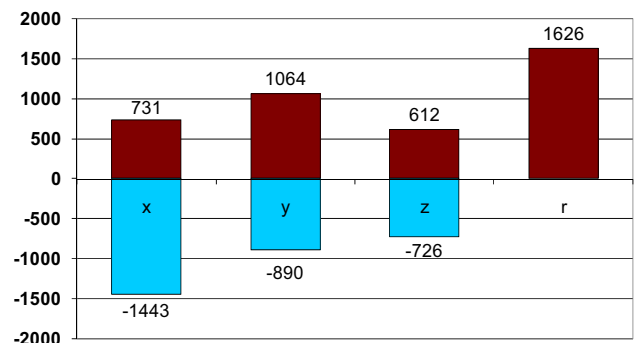


Figure 6 – Per-axis maximum angular accelerations (rad/s²) across all activities. From left to right: x-axis, y-axis, z-axis, and the resultant acceleration. Negative values indicate maxima in the negative direction.

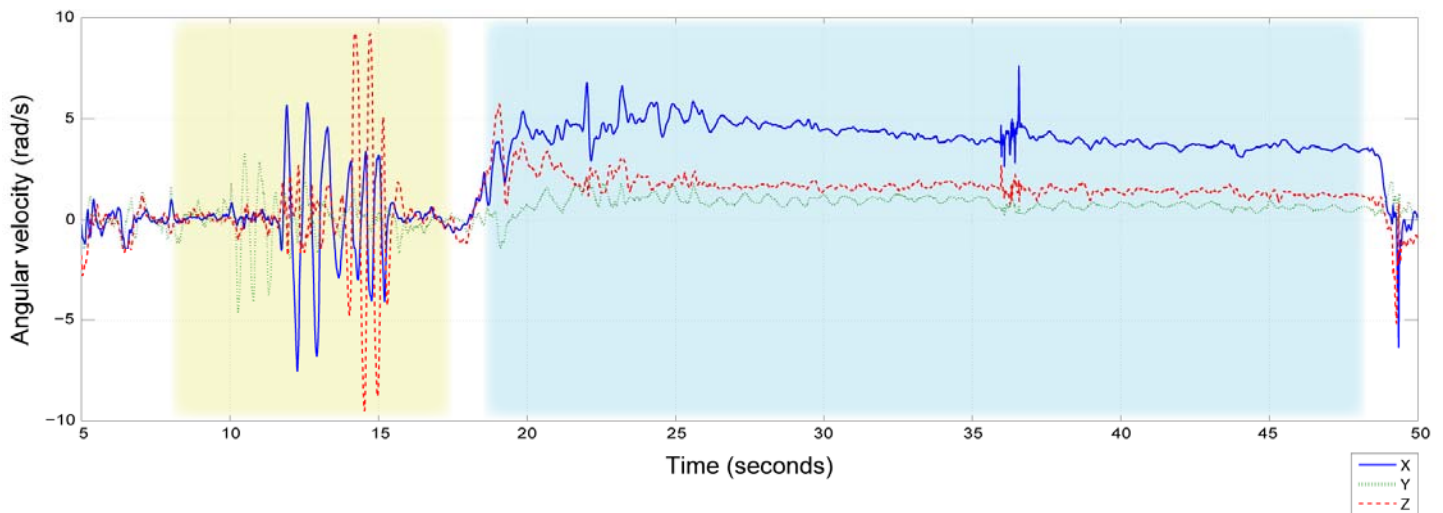


Figure 7 – Angular velocities for subject 12 during the tire swing activity. The angular velocities during the synchronization head motions (tan-shaded, from 10-16 s) are larger than those measured during the activity (light blue, from 18-48 s). X-axis data is in blue, y-axis in green, and z-axis in red.

Data were compared by gender using Student's T-tests, with the threshold for significance set at $p=0.05$. Positive and negative maxima were not significantly different between male and female subjects.

Two female subjects climbed on monkey bars as opposed to climbing rings. The climbing apparatus was changed starting with subject 3 when it was found that under direct sunlight, the bars became too hot to hold. The results from the climbing rings and the monkey bars were significantly different for the positive x-axis and resultant angular acceleration results, which were larger on the monkey bars than the climbing ring levels ($p=0.05$). The results from monkey bars and climbing rings were combined and reported under the climbing ring activity. The maximum head accelerations during the climbing rings and zip line activities often occurred during the dismount phase. The maximum head accelerations during the swing activity most often occurred at the peak amplitude of the swing cycle. However, one subject ignored the experimenters' instructions and jumped from the swings. That subject generated the largest resultant linear and angular accelerations for the swing activity (5.9 g , 590 rad/s^2), which coincided with the landing from the jump.

One subject reported transient dizziness immediately after the tire swing activity, which resolved prior to performing the next task. None of the subjects reported any head or neck pain during the testing. Of the nine subjects who could be contacted three weeks after the testing, none reported any head or neck pain within that three week time period.

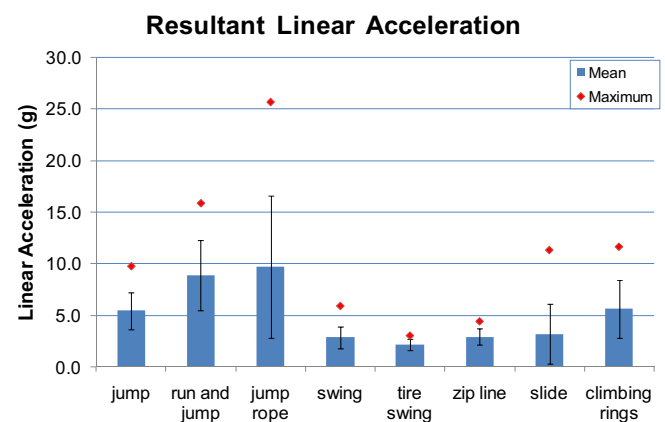


Figure 8– Mean maximum resultant linear accelerations at the head COM. Results shown are mean $\pm$ standard deviation. Maxima are shown as red diamonds.

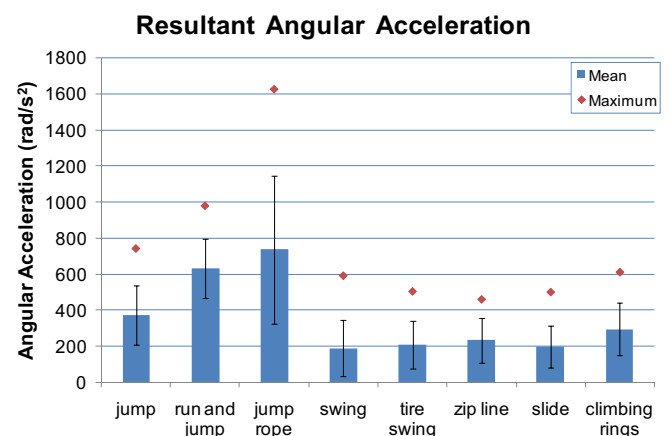


Figure 9 – Mean maximum resultant angular accelerations. Results shown are mean $\pm$ standard deviation. Maxima are shown as red diamonds.