IAAPA Attractions EXPO

Current Trends in Amusement Industry Biomechanics

Thursday, November 16, 2006
4:30 PM to 5:45 PM
Room # B409

IAAPA

Current Trends in Amusement Industry Biomechanics:

Introduction to Biomechanics and Rider Kinematics

Exponent

Robert S. Cargill II, Ph.D., P.E.
Irving Scher, Ph.D., P.E.
William Bussone, M.S.
Michelle F. Heller, Ph.D.

2006 IAAPA Attractions Expo Education Programs

Exponent has worked in the amusement industry in a variety of areas, including thermal engineering, civil engineering, biomechanics, and human factors. In a seminar focusing on biomechanics, we will present the relevant current research in biomechanics, as it applies to the amusement industry. Specifically, we will address new data and current research in the areas of human tolerance; ride vehicle accelerations; rider accelerations, including both linear and angular accelerations; spectral analysis; and jerk (the rate of change of acceleration). We will put these in the context of forces and accelerations seen in daily events and vigorous activities. Our primary focus is head tolerance and daily exposure, although neck and general body tolerance will also be discussed.

We will also touch on the differences between impact accelerations and inertial accelerations and their ramifications. Basic background information will be presented before progressing through the current data and each area will be discussed as it applies to the amusement industry.

This seminar is intended for an intermediate audience, one with a basic knowledge of physics, including acceleration. We will review the appropriate human anatomy as the need arises. The goal is to provide the audience with a broad overview of the biomechanical issues currently facing the amusement industry and a summary of the existing research and capabilities in this field.

The following topics will be covered:

- Human tolerance, focusing on linear and angular acceleration tolerance of the head
- Difference between ride and rider dynamics
- Spectral analysis of on-ride and daily event accelerations
- Magnitude of jerk (rate of change of acceleration) seen in daily events

Kinematic Relationships in One Dimension (1-D)

A block is accelerated to the right and moves at constant velocity. A larger, leftward acceleration reverses the direction of travel and the block moves at a larger velocity to the left. The block is then exposed to an even larger, rightward acceleration that brings it to an abrupt stop. Figure 1 shows the graphic relationships between the position (displacement), velocity (rate of change of displacement), acceleration (rate of change of velocity), and the jerk (rate of change of acceleration).

There are corresponding relations for each of the three coordinate axes as well as for rotations about each of the three axes (angle of rotation, rate of change of angle, rate of change of angular velocity, etc.).

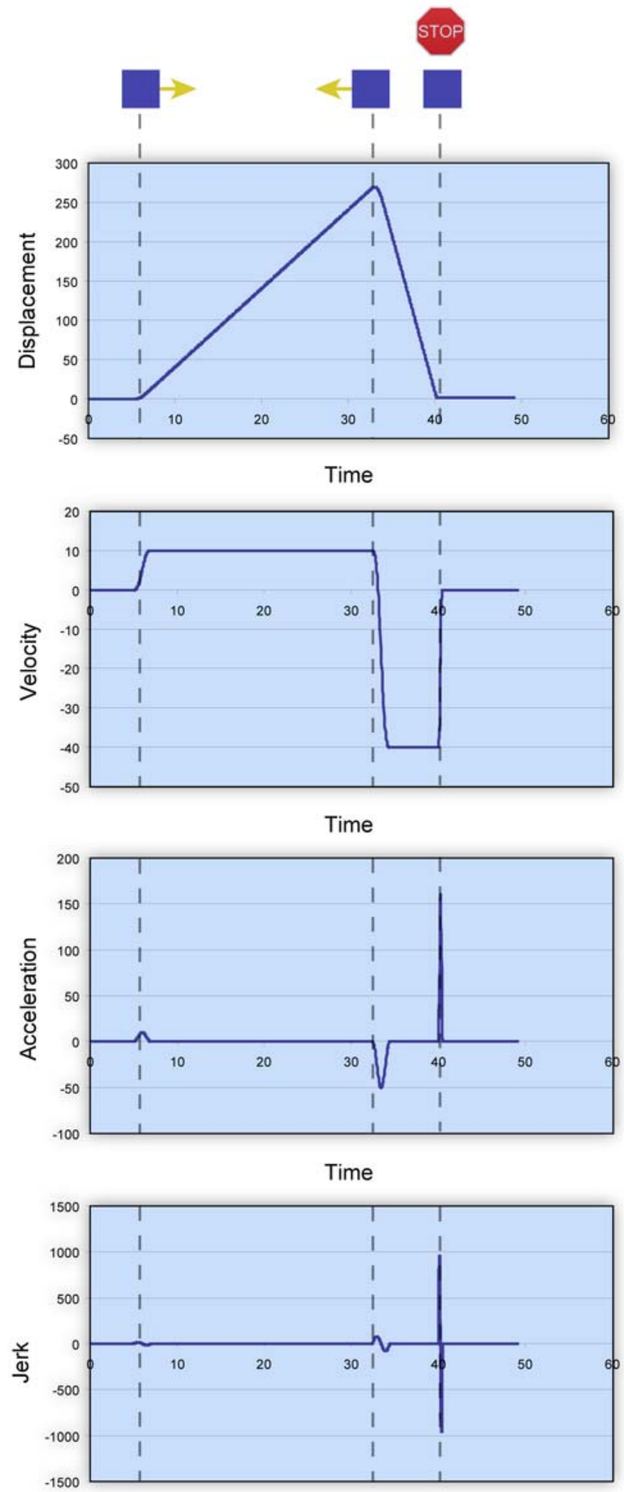

Figure 1

Vectors

A vector has magnitude and direction and can be used to describe position, velocity, acceleration, and jerk. Linear measures in three axes can be added vectorially and produce a resultant vector. Vectors that are at right angles to each other are orthogonal. For example, in two dimensions, if you move your body one foot forward and one foot to the left, you are only 1.4 feet from where you started. Non-orthogonal vectors can also be added as shown in Figure 2.

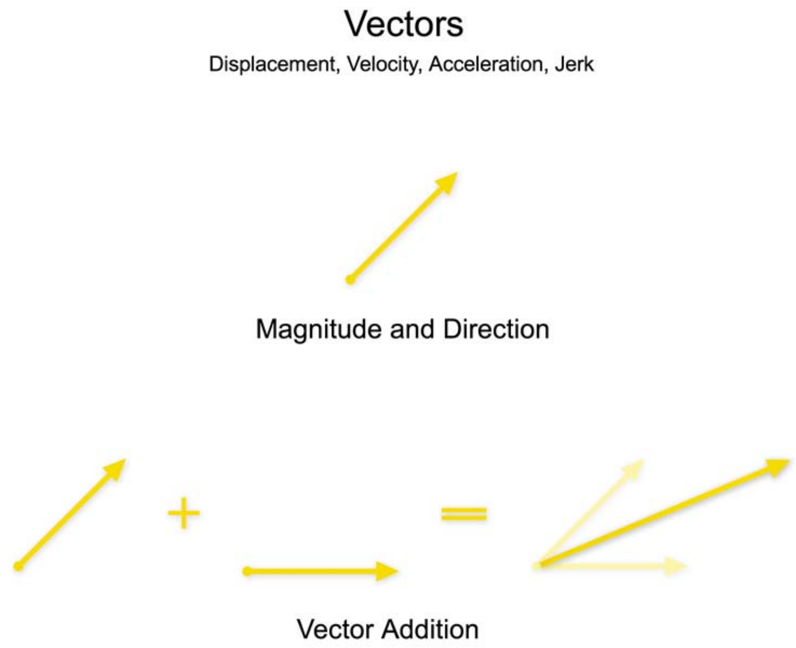

Figure 2

Angular motion can be characterized by pseudovectors. Angular velocity, acceleration, and jerk have both magnitude and direction. The effect of these angular motions on linear motions is often broken down into its tangential and normal (directed towards the center of rotation) components. The example in Figure 3 illustrates a vinyl record rotating at a constant rate. In this instance, the angular position is constantly changing, the angular velocity is a constant, and the angular acceleration and jerk are zero. It is interesting to note that even as the whole object rotates at a constant angular velocity, at any given location on the record, the magnitude of the linear velocity is constant, but the direction is constantly changing due to the rotation. The constantly changing direction causes each point to experience a linear acceleration directed towards the center of the rotation of the record. The magnitude of this normal acceleration vector becomes larger as the distance from the center becomes greater.

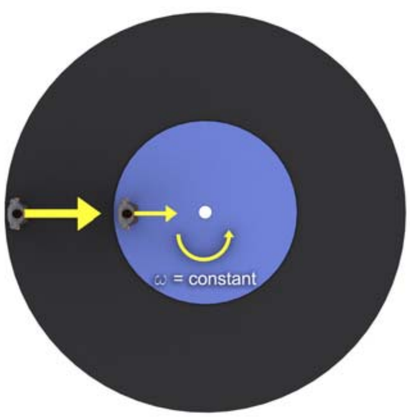

Figure 3

Axes

A body can move and be moved in three orthogonal linear directions, which are commonly referred to as x, y, and z. The definition of the axes can vary, but generally one axis is fore-aft, one is up-down, and one is left-right, relative to the body. The name of each axis can be arbitrarily assigned, but needs to be well defined and remain consistent throughout an analysis. The axis names are also dependent on context and the body configuration (i.e. sitting or standing). For instance, the “up” direction for the leg of a sitting rider is different than the “up” direction of the leg of a standing rider. The standard coordinate system for amusement rides is depicted in Figure 4, as defined by ASTM F 2137.

The body’s tolerance to acceleration is not the same for all axes, referred to as axis sensitivity. For example, the body’s tolerance to accelerations across the body (forward or rearward) is higher than its tolerance to accelerations in the axial direction (upward or downward). Additionally, the body also has different tolerances depending on the direction of the force along the same axis, known as sign sensitivity. For example, humans can tolerate larger forward accelerations of the body than rearward accelerations. As a result of this knowledge, astronauts are positioned during takeoff so that the largest acceleration components act in the direction to which they have the highest tolerance.

The body is also sensitive to rotation and the rotational axes. Based on the coordinate system shown in Figure 4, rotations about the x-axis at the hips are called roll, rotations about the y-axis are called pitch, and rotations about the z-axis are called yaw. The body responds differently to each of these rotations and is sensitive to the sign of pitch. As for linear axes, rotational axes are arbitrary and context-sensitive. Before any analysis, the rotational axes need to be properly defined.

The vehicle has its own coordinate system that is independent of the rider’s coordinate system (Figure 5). These two coordinate systems may be coincident, but usually have a relative motion between them in most real-world applications. Depending on how the rider moves, the rider’s z-axis could be pointed in the vehicle’s x-direction, or vice-versa. Also, yaw for the ride, for example, may not indicate a yaw for the rider, depending on how the rider is positioned on the ride. It is for these reasons that it is imperative to properly define all coordinate systems and be consistent throughout an analysis.

Additionally, due to the compliance of the human body, parts of the body can translate (move linearly) and rotate relative to other parts. As such, it may be desirable under certain circumstances to designate separate coordinate systems for each body segment.

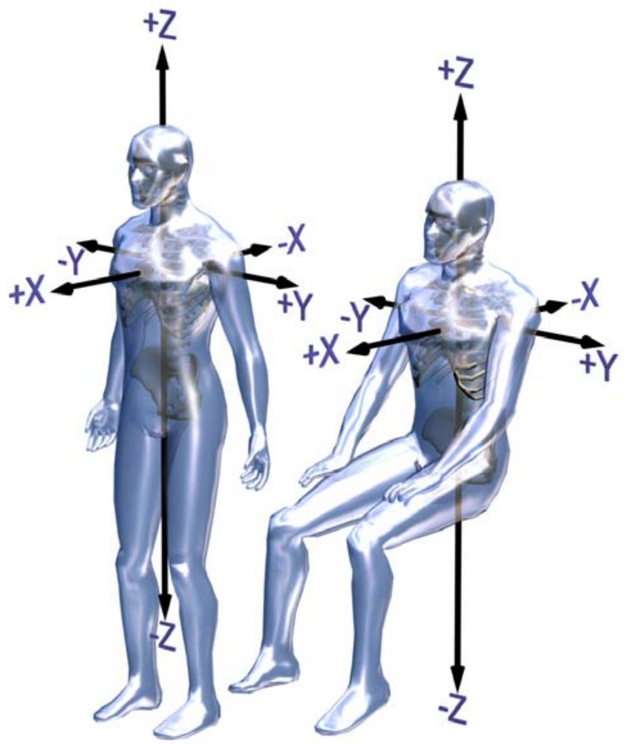

Figure 4

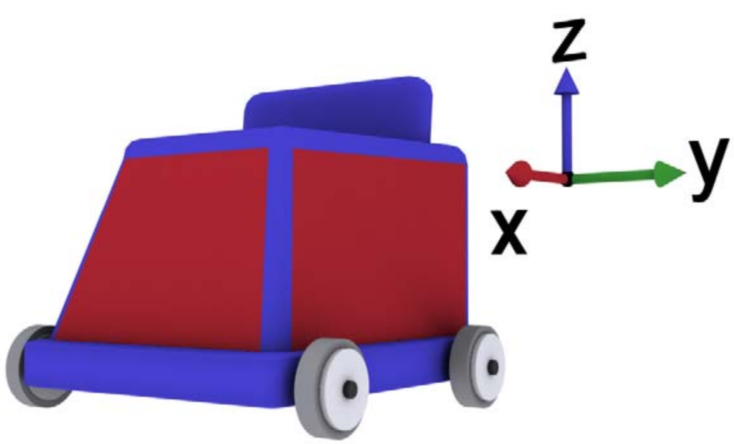

Figure 5

Rider Response

For some amusement park rides, the ride vehicle is moving and rotating in three dimensions. As described in the previous section on vectors, the recorded accelerations of the vehicle vary depending on where they are measured. In general, it is not possible to rigidly attach a rider to a ride vehicle. As a result, the rider typically has some motion within the confines of the restraints. Movement of the rider relative to the vehicle results in rider accelerations that can vary from the ride vehicle accelerations.

A rider can also experience a variety of frequency components simultaneously during an amusement park ride. A simple example of this would be a child's roller coaster with a sinusoidal track that has a "bumpy wheel" (Figure 6). As shown, the track of the ride exposes the rider to a low frequency, high amplitude motion and the "bumpy wheel" exposes the rider to a higher frequency, low amplitude motion. As a result, the rider is exposed to both of these effects simultaneously during the ride. The right column of this figure illustrates this effect using a frequency component plot. Any signal can be analyzed to determine its frequency content using the Fourier Transform. More complex rides have the potential for exposing the rider to different frequency combinations throughout the ride.

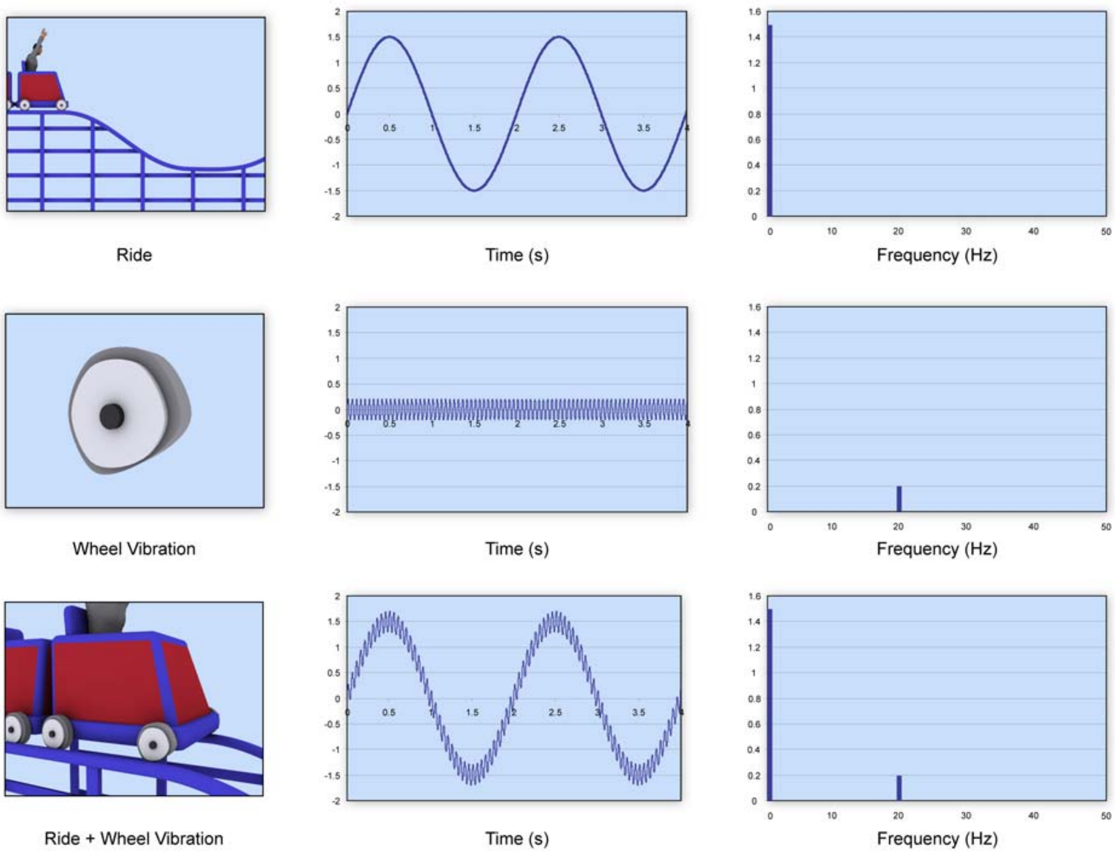

Figure 6

Frequency components can produce both mechanical and biological responses within the human rider. An occupant's body can dissipate mechanical energy by virtue of the viscoelastic nature of soft tissues: The body itself acts as a low pass filter for higher frequency signals such as vehicle vibration. As a result, a rider's head is likely to experience less amplitude of vibration than would be measured within the ride vehicle or at the rider's pelvis. Figure 7 illustrates this concept in a simplified mechanical model of this effect.

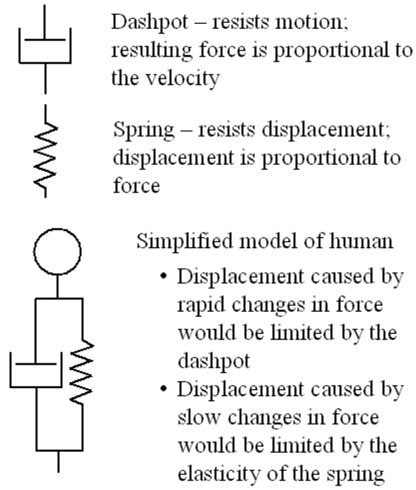

Figure 7

Each location in the human body is mechanically sensitive to frequencies within a defined range unique to that location. Figure 8 presents a simplified mechanical model of the human body response to vertical mechanical acceleration.

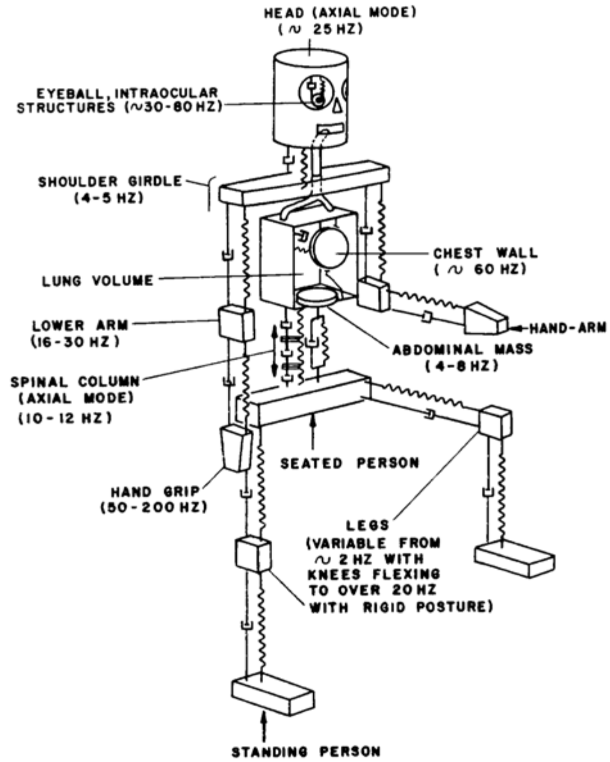

Figure 8 – From Chaffin et al., 1999
Adapted from Rasmussen, 1982, and von Gierke et al., 1975

Additionally, mechanical stimuli can directly and indirectly affect the biology of the human body. The biological response has been shown to be frequency-dependent. Natural frequencies occur within the body such as postural sway and peristalsis (the undulations in the gastrointestinal tract to move food during digestion.) Mechanical sources that introduce external frequencies into the system can cause different biological effects within each body system or components of a body system such as those shown in Figure 9.

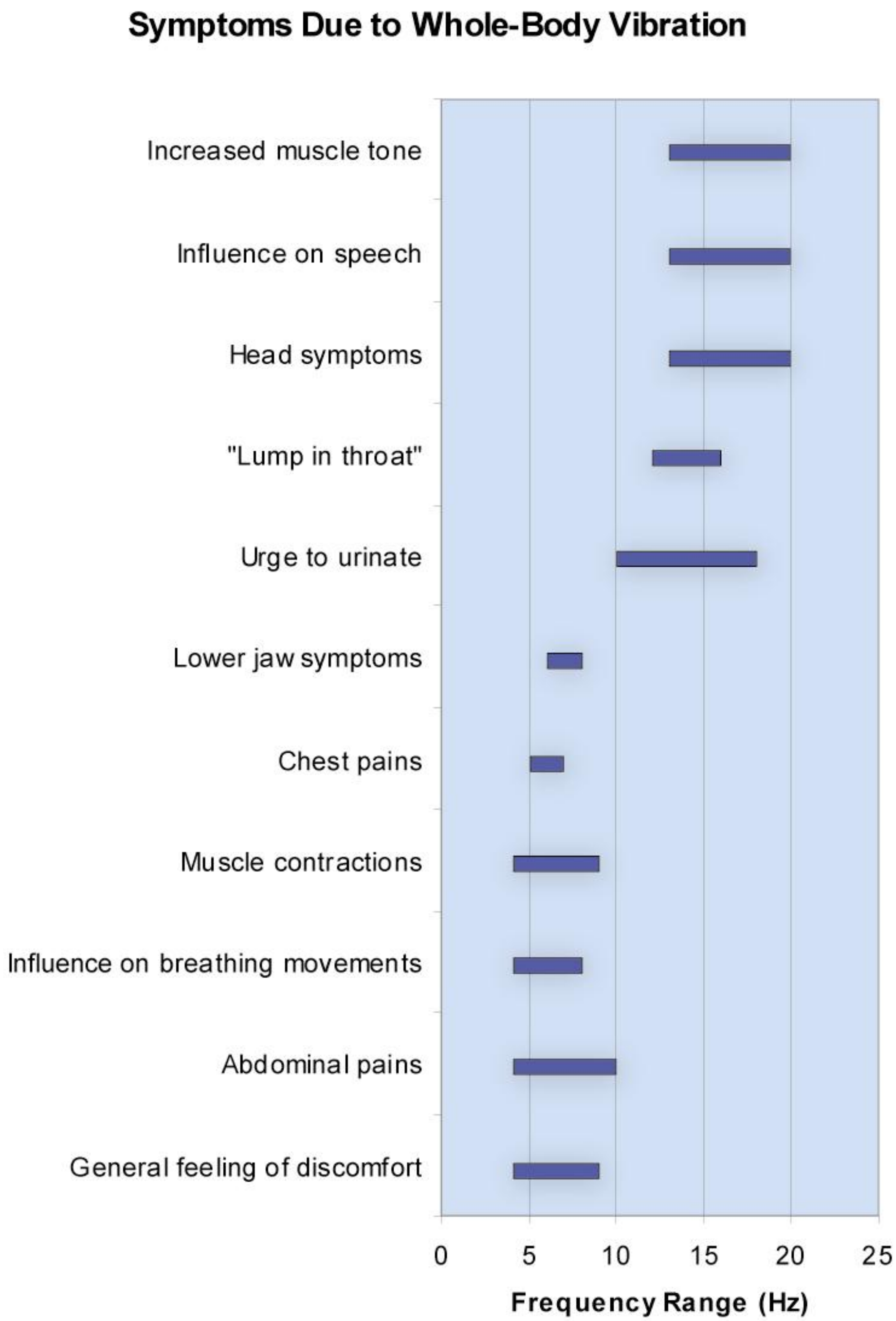

Figure 9 – Adapted from Chaffin et al., 1999, and Rasmussen, 1982

The human body is a complex, interlinked mechanical system that contains actuators (muscles) and a complex control system (nervous system). In response to a sudden mechanical input, the control system response takes time to develop. In the interim, the human body responds passively from its current state. For example, during a rapid lateral seat translation, the unrestrained human head is likely to stay in a relatively constant position and orientation until the passive stiffness of the body linkages translates force to the level of the head. This phenomenon is illustrated in the bumper car rider shown in Figure 10.

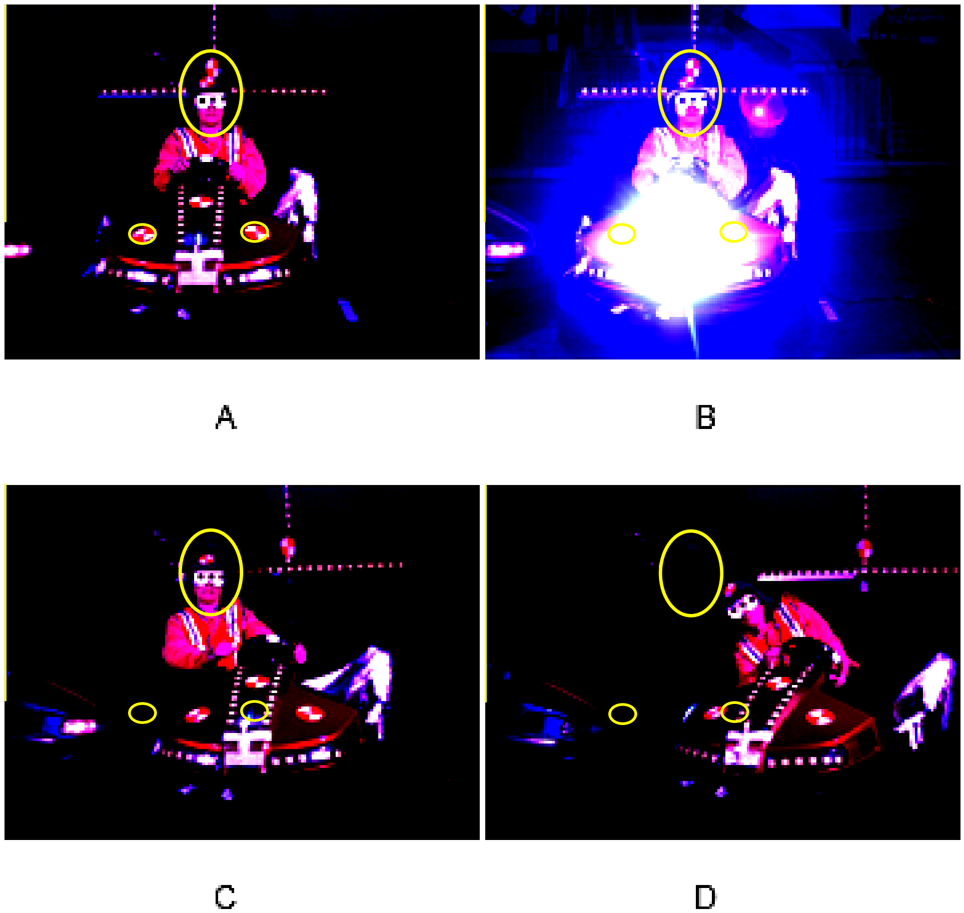

Figure 10

Depending on the geometry of the vehicle and a person's ability to react to sudden movements, a sudden acceleration could result in a rider contacting part of the vehicle with their head or another body part. For this reason, ASTM F 2291 requires that padding be considered and amusement rides are typically padded where contact may occur. The relative distance, acceleration direction and magnitude, and reaction time play a role in determining the severity of the contact or if a contact occurs at all. Figure 11 shows typical head and trunk movements caused by sideways and front-to-back accelerations as observed by Vibert and colleagues (2006). The values below each schematic drawing are the average values (± Standard deviation) for 108 subjects. In the figure, LTM is the latency of the initial trunk movement in space, LHM is the latency of the initial head movement in space, LPHT is the latency to the peak of the initial head translation in the direction opposite to the sled, and LPHR is the latency to the peak of the initial head roll.

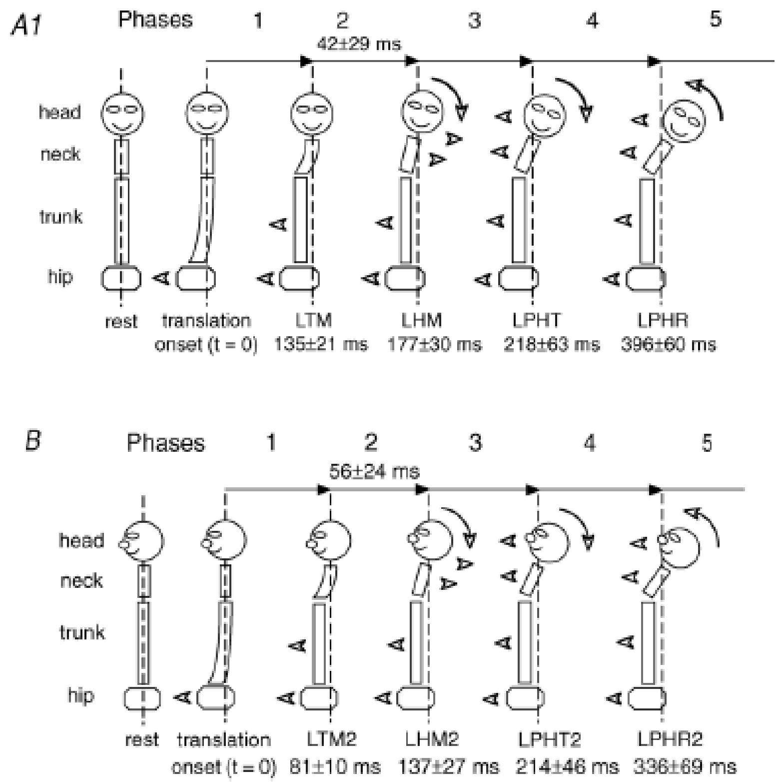

Figure 11 – From Vibert et al., 2006

Human response to a given stimulus, such as a ride's acceleration, generally demonstrates a range of responses that fall within a predictable envelope. Specific rider acceleration and motion in response to a given ride acceleration will depend on the rider and their state at a given instant. Their individual characteristics determine where in the human range they will fall. Because of this, the rider response envelope must be modeled or measured. Ride measurements cannot account for rider action or rider response, such as contact with the restraints or with another rider, without an understanding of the rider response envelope. For example, testing on amusement bumper cars indicates that rider head acceleration can vary in magnitude from the vehicle acceleration.

Human Tolerance and Everyday Events

Humans can, and do, tolerate linear head accelerations exceeding 100G[1] and angular head accelerations exceeding 10,000 rad/s^2. The average non-injurious head impact in a Division I collegiate football practice or game is 32G, with a maximum recorded value of 200G. The injury assessment reference value for side impacts is 180G for a 50th percentile adult male. Most current head injury research focuses on acceleration tolerance of the brain.

Much research is done on the 50th percentile adult male. Due to the continuum of age, weight, height, and differences in gender, the tolerances of other members of the population may vary from these standard values. To estimate values for these populations, various scaling techniques have been applied. A method to assess sub-tolerance, normal exposure for a wide segment of the population is to document the accelerations associated with everyday events.

Research on everyday events has found that the daily exposure to linear and angular accelerations for people aged 20 to 50 years old is up to approximately 10G and 1000 rad/s^2. These accelerations typically last for approximately 0.15 seconds and are not influenced by height, weight, age, or handedness. Some studies have found that males demonstrate slightly larger accelerations, whereas others have found that the difference due to gender is negligible. The accelerations found in everyday events are far below reported injury thresholds. For most activities, measured accelerations are higher in lower positions of the spine.

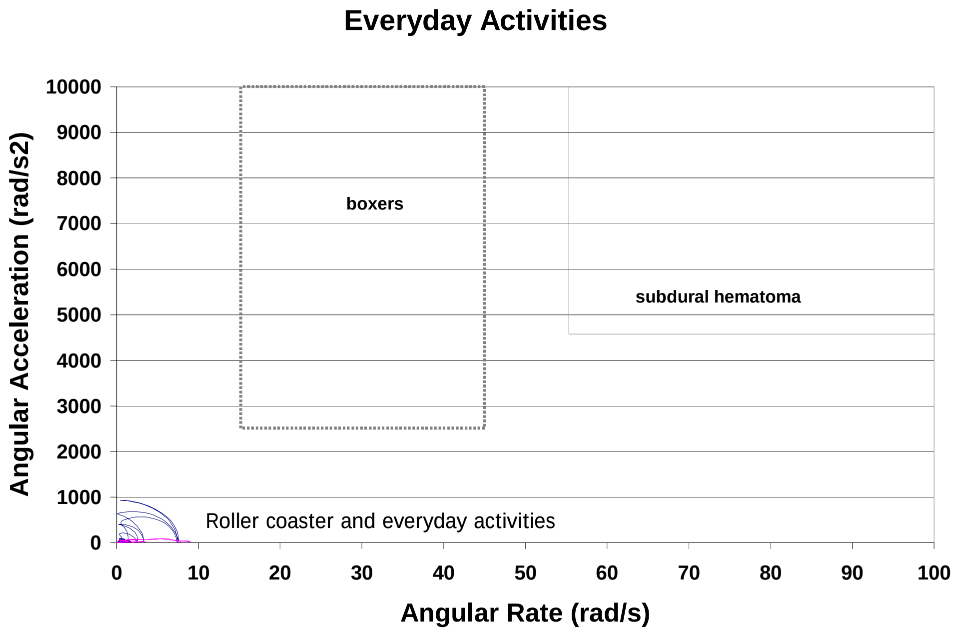

Figure 12 – Roller coaster and everyday activities shown on the same scale as other tolerance data

[1] 1G is equivalent in magnitude to the acceleration due to gravity: 9.8 m/s^2 (32.2 ft/s^2).

Figure 12 illustrates the relative magnitudes of the head angular rates and head angular accelerations associated with roller coaster and everyday activities compared to those values in boxing and human tolerance levels. The everyday activities are represented by the blue and pink curves in the lower left corner of the figure.

Everyday events are usually non-contact accelerations. Contact accelerations, such as being struck in the head with a pillow, tend to be larger in magnitude but smaller in duration than non-contact accelerations, thus indicating higher levels of jerk. Examples of everyday, non-contact peak resultant head acceleration are shown in Figure 13.

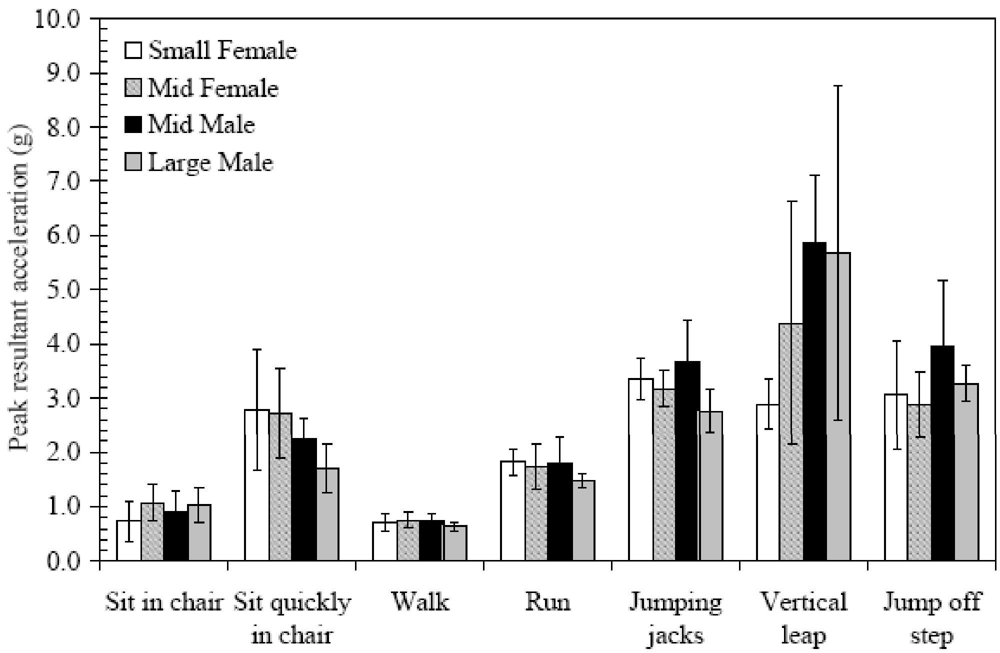

Figure 13 – From Ng et al., 2006a

The human body is a complex, interlinked mechanical system. As such, the angular and linear accelerations of the head are kinematically related. Figure 14 presents the relationship between the peak angular and linear head accelerations for volunteers performing vigorous activities of daily living. For comparison, the single axis maximum acceleration of 6G permitted in ASTM F 2291 is shown by a vertical line on this figure. Note that for some axes and durations, the maximum acceleration is substantially less than this value.

Peak Resultant Linear Acceleration and Angular Accelerations for Each Subject by Gender

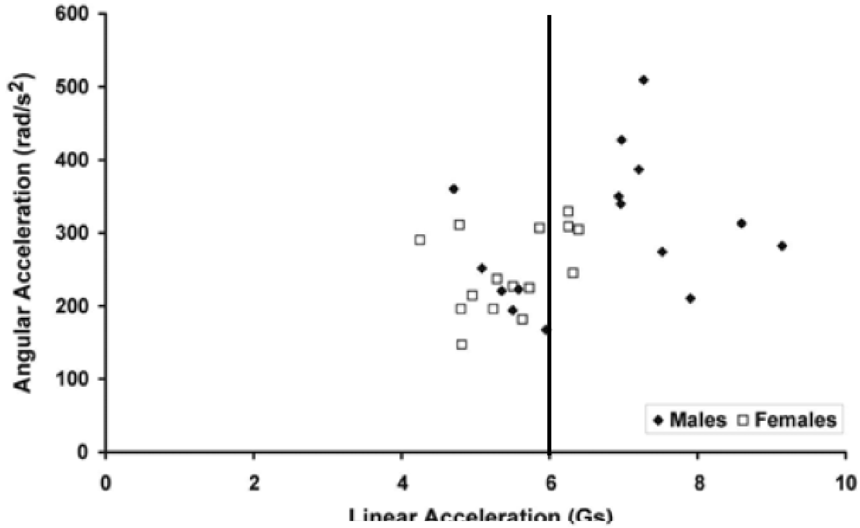

Figure 14 – Adapted from Scher et al., 2005

Spectral analysis, a study of the acceleration frequencies, of everyday events shows that the accelerations are within the range of 0-5 Hz (cycles per second) and tend to peak at 2 Hz for most activities studied. These results are shown in Figures 15 and 16.

Compiled PSD of head acceleration while skipping rope (30 subjects).

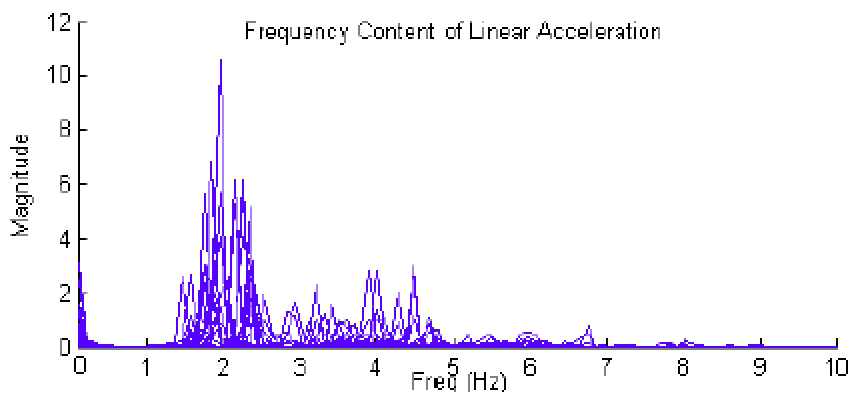

Figure 15 – From Richards et al., 2005

Peak frequency response (mean ± standard error)

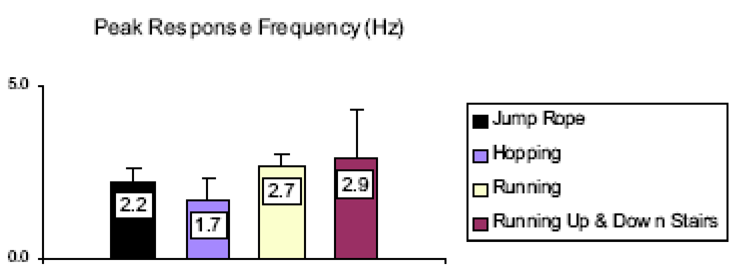

Figure 16 – From Richards et al., 2005

Bumper Cars

The rotational and linear head accelerations, as well as neck forces and moments, are similar between bumper cars and everyday events. For lateral bumper car impacts (side-impacts), lateral head accelerations were slightly higher than for everyday events. Results from other types of amusement rides appear to be similar. Ride accelerations are comparable to everyday accelerations such as those shown in Figure 17.

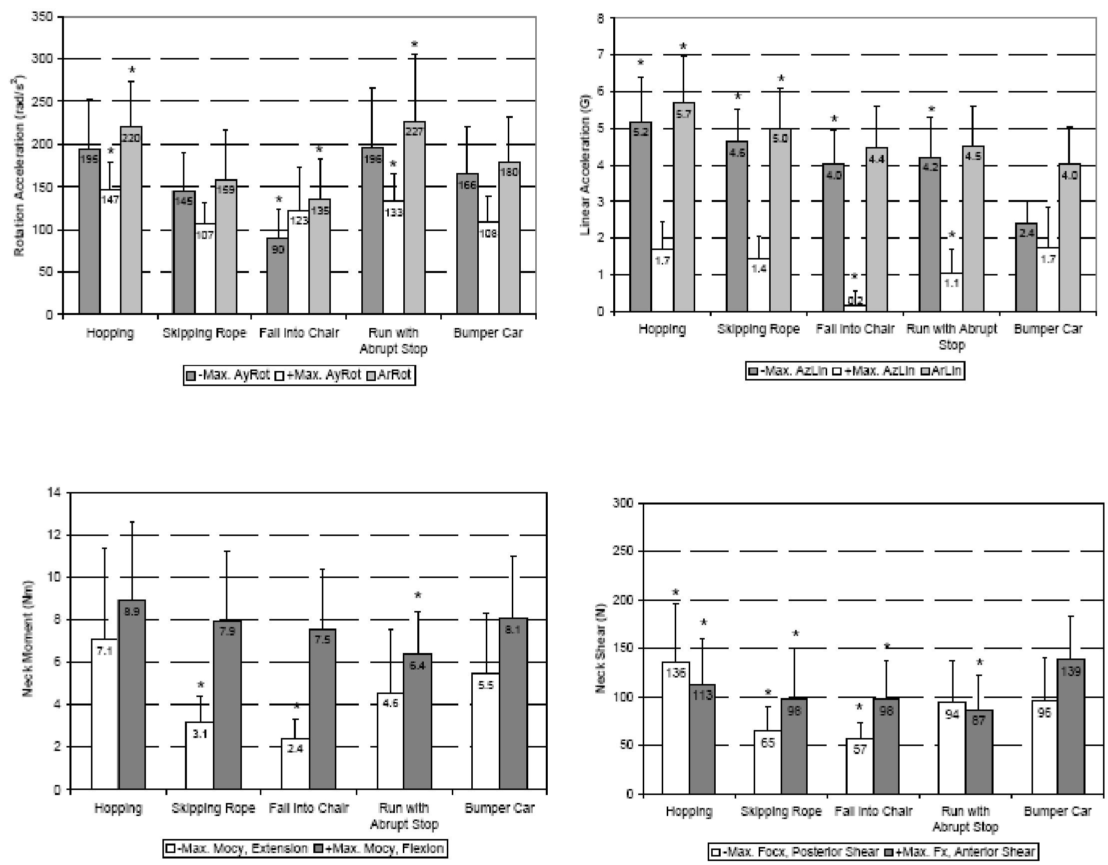

Figure 17 – From Vijayakumar et al., 2006

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Authors and contact information

Robert S. Cargill II, Ph.D., P.E.
3401 Market Street, Suite 300
Philadelphia, PA 19104
215-594-8833
rcargill@exponent.com

Irving Scher, Ph.D., P.E.
5401 McConnell Avenue
Los Angeles, CA 90066
310-754-2756
ischer@exponent.com

William Bussone, M.S.
3401 Market Street, Suite 300
Philadelphia, PA 19104
215-594-8894
wbussone@exponent.com

Michelle F. Heller, Ph.D.
3401 Market Street, Suite 300
Philadelphia, PA 19104
215-594-8876
mheller@exponent.com

www.exponent.com

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