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Evaluation of Thoracic and Lumbar Accelerations of Volunteers in Vertical and Horizontal Loading Scenarios

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ABSTRACT

There are exposures of the body to accelerations in the lumbar and thoracic region on a regular basis with everyday activities and exercises. The purpose of this study was to evaluate the response of the thoracic and lumbar regions in human volunteers subjected to vigorous activities. A total of 181 tests include twenty volunteers subjected to four test scenarios: "plopping" down in a seat, a vertical jump, a vertical drop while in a supine position, and a vertical drop while seated upright in a swing. Each of the latter three activities included three severity levels with drop heights ranging from 25 mm to 900 mm. Volunteers selected represent the anthropometry of the general population including males and females at a wide range of weights (54 to 99 kg), heights (150 to 191 cm), and ages (26 to 58 years old). Instrumentation for each volunteer included tri-axial accelerometers attached to custom-fit mounts that were secured around the lumbar and upper thoracic regions. Subjects impacted an instrumented rigid force plate with forces ranging from 950 N to 14030 N. The time to peak load, peak values, and relative timing of the accelerations are reported. From the force and acceleration measurements approximate stiffness values are provided for the lumbar region with the initial loading up to 25% of peak force at close to 18 N/mm and reaching close to 90 N/mm in the stiffer region. Analyses of acceleration data as a function of drop height, subject variables, and activity level are also presented. Including a range of activities that produce accelerations from 0.6 G to 24.0 G, these 181 tests are beneficial in understanding the range of accelerations that do not cause injury. Moreover, a study of the parameters indicated activity level has the greatest influence on the magnitude of the accelerations of the spine compared to other variables in the study.

INTRODUCTION

The vast majority of volunteer research for thoracic accelerations has been completed using sleds with restraints. However, there are exposures of the body to accelerations in the lumbar and thoracic region on a regular basis with everyday activities and exercises. Several studies have already evaluated head accelerations in various activities and compared those values to the risk of injury. The focus of this study was to record accelerations at the thoracic and lumbar levels of volunteers to correlate with subject size, gender, and activity level. Recently in a study by Ng et al., 18 young volunteers were asked to perform seven daily activities [1]. These activities include sitting in a chair normally, sitting in a chair quickly, walking at 1.3 m/s, running at 2.7 m/s, jumping jacks, a standing vertical leap, and jumping off a step 200 mm high. The peak T1 resultant accelerations in that study were all less than 12 G with an average for each individual activity less than 6 G. Accelerations at L5 reported from that study were all less than 22 G with the average for each activity being less than 10 G. The results of that study indicated higher accelerations for the leap and jump activities and lower accelerations for sitting, walking, and running. Peak resultant accelerations at T1 and L5 were significantly different but there were not significant differences in peak accelerations based on gender and size. A more extensive study with a wider range of volunteers would substantiate previous findings and contribute to the number of tests available in the literature. The purpose of this study was to evaluate the response of the thoracic and lumbar spine in a wide range of human volunteers subjected to vigorous daily activities.

METHODS

Volunteers selected represent the general population anthropometrically including males and females at a wide range of weights, heights, and ages. Eight female and twelve male employees of Biodynamic Research Corporation participated in the study. Five of these individuals are co-authors on this research paper and have backgrounds in research testing. However the other 13 individuals were inexperienced in regards to impact testing. The results indicate no significant difference between the group of co-authors compared to the group of other employees. The entire group of individuals had an average age of 44 years (26 to 58), the average weight was 80 kg (54 to 99 kg) and the average height was 172 cm (150 to 191 cm). Body mass index was calculated using the weight in kilograms divided by the square of the height in meters (20.6 to 35.6, mean 27.1).

Each participant signed a written consent and was informed about risks and benefits and other appropriate disclosures. Each subject was made aware that he/she could withdraw from any test for any reason. The study protocol and consent form was approved for human use by an internal Research Review Board and an external Institutional Review Board. Imaging using a portable x-ray provided information to ensure subjects were negative for bony pathology which would increase their risk of injury. Single plain film lateral studies were obtained on each participant's cervical and lumber spine. Degrees of osteoporosis, disc space narrowing, end-plate sclerosis, facet joint arthrosis and osteophytosis were assessed by a board-certified radiologist. The grading of mild, moderate and severe was based on the subjective impression of the radiologist. Since the bony structure of the spine is most at risk from impact loading, the most important pathology to screen for was osteoporosis. None of the participants had this abnormality. In these studies, the severe abnormalities found were all disc related while several participants had moderate disc and facet joint changes. These were not felt to be important in assessing an individuals risk for injury considering the type and level of loading that they were subjected to. Four different activities were each repeated several times. All tests for one activity were completed in one session by that subject and at least one week was allowed before the subject performed the next activity. Any symptoms related to the testing were reported by the volunteer to a physician [CEB] [2]. The subjects were approached one day and one week after each activity to determine what symptoms each individual had experienced. All subjects were able to report symptoms up to any length of time after testing.

Instrumentation for each volunteer included tri-axial accelerometers (Endeavco 7596, 30g) attached to custom-fit mounts that were securely strapped around the lumbar and upper thoracic regions (Figure 1). Both lumbar and thoracic mounts consisted of a thermoplastic template that was heated and molded to fit the contours of each volunteer. The lumbar mount was then fitted with the tri-axial array and inserted into an elastic band which was strapped to the volunteer using Velcro at the attachment point. Additionally, two layers of gaffers tape was used to secure the elastic band and lumbar mount onto each volunteer. The upper thoracic mount was secured using a system of one inch thick straps that were firmly tightened without causing the volunteers discomfort. Vertebrae L1 and T1 were determined by the test administrators to be the closest vertebrae to the respective instrumentation.

Figure 1. Tri-axial accelerometers attached to custom-fit mounts were securely strapped around the lumbar and upper thoracic regions.

The reaction force at impact was recorded with an instrumented rigid force plate. Data were recorded at 2 kHz using a TDAS-PRO 32-channel rack (DTS) and filtered to CFC 180. Additionally high speed video (Phantom v7.1, Vision Research, Inc.) was collected at 1 kHz for optical tracking of the subjects. The time history of the angles of the lumbar and thoracic accelerometer mounts were recorded from the video using WINanlayze Tracking 3D Software (Mikromak, Inc.). Although subjects were also instrumented with a bite block accelerometer array, these data are not presented in this paper.

The desired test matrix included each participant “plopping” onto a rigid seat, jumping off a step, experiencing a vertical drop while seated upright in a swing, and being dropped vertically while in a supine position. The chair “plop” activity was chosen as an activity because the general population experiences this type of volunteer vertical and horizontal loading scenario regularly. The jumping is more vigorous than most people experience on a daily basis and it includes a vertical acceleration component that is dampened by the response of the lower body. A vertical drop while seated is a more controlled method of exposing volunteers to vertical loading directly through the buttocks. The chair tip activity was chosen to produce acceleration in the anterior-posterior direction. These activities were chosen because they include a range of intensity levels and directions of loading for analysis purposes. Some volunteers withdrew during an activity because of nervousness regarding the higher intensity levels. No subjects withdrew because of pain or physical injury.

While the subjects were instructed to vigorously perform the activities, the specific manner to sit or jump was not indicated. Each individual chose his or her own method to complete the activities. For the chair "plops", the volunteers were asked to aggressively sit down on a rigid seat and repeated the activity three times (Figure 2). Load cells were placed under the seat as well as behind the seat back. Portions of the back pieces were removed to provide ample clearance for the instrumentation. Eighteen individuals completed this activity for a total of 52 tests. The jumps were completed three times at each of the three heights: 300 mm, 600 mm, and 900 mm (Figure 3). Only the first attempt at each height was analyzed in this study because of time restrictions in processing data. Test data are reported for 17 individuals jumping off the 300 mm and 600 mm steps and 16 individuals jumped off the 900 mm step.

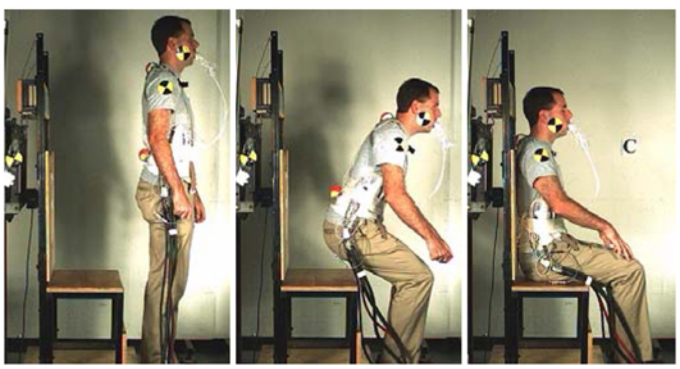

Figure 2. Video captures of a volunteer completing the chair "plop" activity.

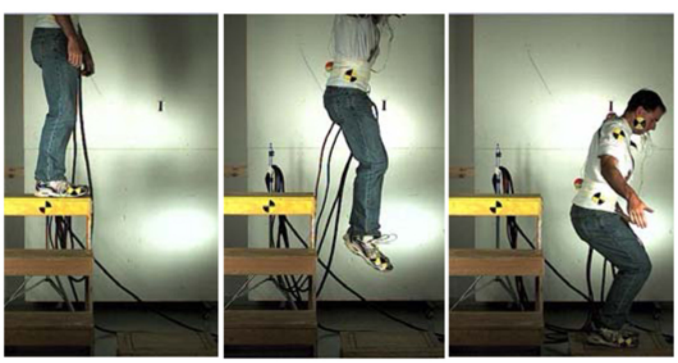

Figure 3. Video captures of a volunteer completing the jump activity from 3 ft.

The seated drops, where the subjects were sitting in a swing that was released, were completed with the bottom of the swing 50 mm, 75 mm, and 100 mm from the platform (Figure 4). There was no resistive force by the swing once the release was activated. The swing and the subject came to rest on the platform. This test series included 18 people dropped from 50 mm, 16 people dropped from 75 mm, and 15 people dropped from 100 mm. The chair tip activity had the subjects on their back with their knees up (Figure 5). Portions of the back pieces were removed to provide ample clearance for the instrumentation. The middle of the chair back platform was released from 50 mm, 100 mm, and 150 mm. Test data are presented for 9 volunteers at the 50 mm chair tip height and 10 volunteers at both the 100 and 150 mm heights. For this setup, there was no head or upper back support, so the subjects were asked to tense their neck muscles to hold their heads up against gravity. A padded headrest was placed on the chair to protect against hyperextension of the neck during testing, but no contact between the head and headrest occurred in any of the tests. For the activities with three intensity levels, the lowest intensity was performed first and then the intensity increased until the highest intensity level was completed. Not every subject completed every activity and for some individuals not all attempts at each activity were completed. Tests without complete video and instrumentation data are not reported here.

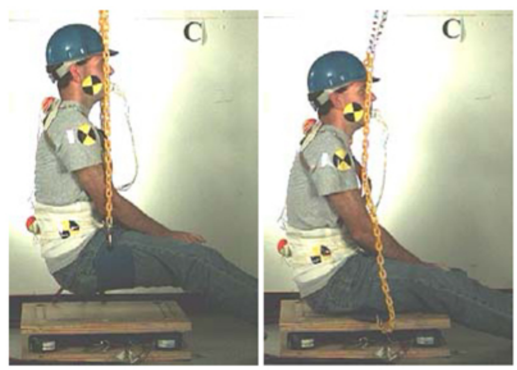

Figure 4. Video captures of a volunteer completing the seated drop activity from 100 mm.

<figure 5 here>

For all activities the video was used to track the angles of the thoracic and lumbar regions relative to the horizontal. The jump and seated drop activities provided views where the lumbar and thoracic mounts could be tracked optically for the position of the sensors for the duration of the event, with a few exceptions where individuals blocked the view for a short duration with a flailing arm. In the chair tip and chair "plop" activities, the lumbar region was blocked in part or in whole by the chair and the exact position of the mount was not attainable through video for the entire event. By differentiating and filtering the displacements from the video, velocities were obtained in the global Z coordinate system for the thoracic and lumbar regions. To the extent possible, test data were compared to video analysis for velocity and displacement. Although used as a subjective measure of ability of the instrumentation to correctly capture the event and the timing, the video analysis is inferior to the instrumentation due to the sensitivity and sampling rate of the measurement. The average scale for the videos was 4 mm/pixel and the data had to be filtered at CFC 60 to differentiate from displacement to velocity.

Accelerations in the X and Z directions from the instrumentation were analyzed for the lumbar and thoracic mounts. For the seated drop, chair “plop”, and jumps, the angle of L1 was generally close to 90 degrees with respect to the horizontal. However, even in a sitting position such as for the seated drop, T1 was generally at 45 degrees. Therefore local X and Z measurements were different than global X and Z. The raw data were filtered to CFC 180 and the angles of the sensor mounts from the video analysis were used to transform the data to global X and Z values and remove the effect of gravity. In order to present the accelerations along the spine, the data were then transformed back into the X and Z values representing the local coordinate systems at the mounts for T1 and L1 respectively (Figure 6). The acceleration values were integrated to obtain velocity and displacement values for the events. All of the values reported are from the instrumentation at the T1 and L1 regions and the platform load cells. The peak accelerations, velocities, platform force, and time to peak are reported for each test (Appendix A). In the figures the resultant accelerations are reported.

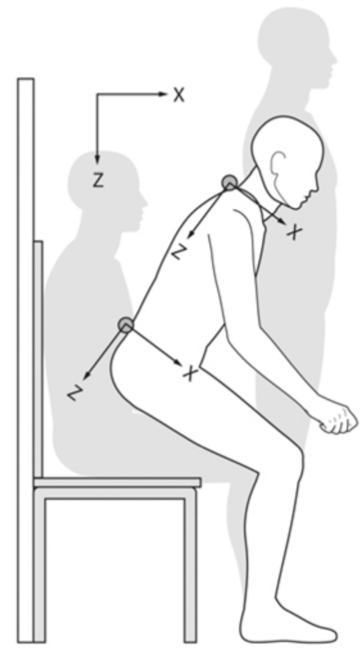

Figure 6. Global and local coordinate systems.

Using a threshold of 44N (10 lbs), the time to peak load was calculated as the time from crossing the threshold until the peak force on the platform occurred. Additionally for the chair “plop” tests, the peak force on the seat back is also reported. In the seated drop tests, stiffness values are reported. Displacement was determined from the time the load crossed the threshold until the peak acceleration occurred. This was calculated separately using the Z accelerometers for the thoracic and lumbar regions. Using the force and displacement data for the loading events, two stiffness values were determined for these tests. The first slope is representative of the displacement until 25% of the peak force and the second slope used the displacement from 25% to 75% of the peak load. By calculating two slopes, the stiffness can be modeled in a piecewise linear manner. These stiffnesses can be utilized in future work with comparison to a Hybrid III response or multibody modeling programs.

Statistical analyses were performed on the data gathered during this study using SAS (SAS Institute, Cary, NC). Descriptive statistics were calculated to demonstrate the influence of severity descriptors (drop height, jump height, etc.) on the dependent variables (lumbar and thoracic acceleration). Pearson's correlation coefficients were determined to evaluate the potential correlation between subject descriptors (gender, BMI, etc.) and the measured response. For cases in which one subject was exposed to multiple events, a linear model was created to account for inter-subject variability. This model was used to assess differences between drop heights.

RESULTS

A total of 181 tests were analyzed including four different activity scenarios. The data are reported by the activity performed and then grouped by drop height. For all of the activities, the acceleration directions conform to SAE J211. In the figures, the absolute values are plotted and the direction is indicated in the legend with a (−) or (+).

SEATED DROPS

The seated drop event in general was a very controlled activity. Volunteers were released onto the platform from a standard height. The position of the subjects' legs were such that they were extended with heels resting on the floor. An example of the time history for the lumbar acceleration, thoracic acceleration and platform force is provided for volunteer 6 and a drop height of 100 mm (Figure 7). In this example it is noted that the peak acceleration lags in time behind the peak force. The subject is falling at 1 G and impacts the platform and then comes to rest. The corresponding video analysis for displacement and velocity are also shown (Figure 8 and Figure 9). These support the data obtained by the instrumentation.

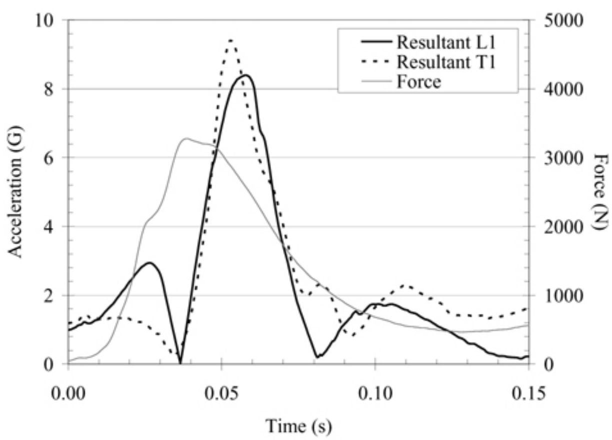

Figure 7. Time history of lumbar acceleration, thoracic acceleration, and corresponding platform force for a seated drop.

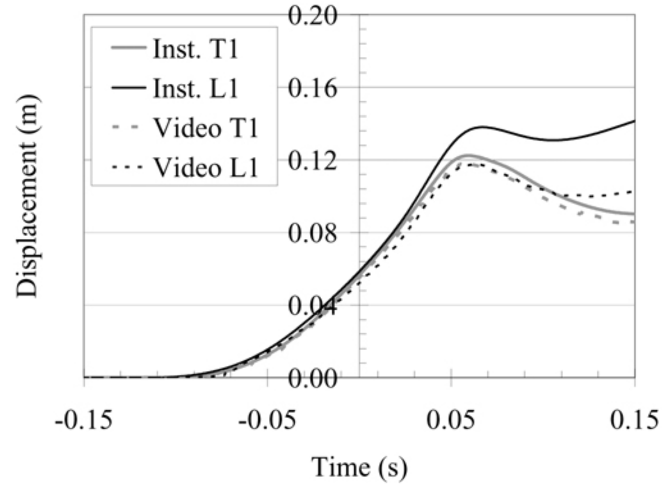

Figure 8. Video analysis of displacement for a seated drop.

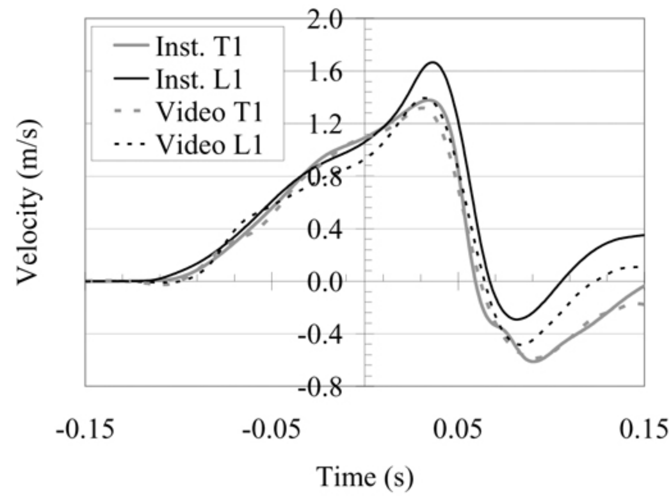

Figure 9. Video analysis of velocity for a seated drop.

For the seated drop test series, the average peak accelerations in the Z direction for the upper thoracic region are −5.2 ± 2.2 G, −6.0 ± 1.9 G, and −7.3 ± 3.1 G for increasing drop heights (Figure 10). These are similar to the average peak accelerations of −4.5 ± 1.6 G, −6.0 ± 2.2 G, and −7.6 ± 2.5 G for the lumbar region in the Z direction for a 50, 75 and 100 mm drop. The L1 Z acceleration peaks are significantly different at the three drop heights ($p<0.05$). However, the T1 Z acceleration peaks are not significantly different from one another at the 75 and 100 mm drop heights ($p>0.05$). In the local X direction, the thoracic average peak accelerations have values of −5.3 ± 2.1 G, −5.5 ± 2.2 G, and −6.6 ± 3.1 G (Figure 11). As a consequence of the mount angle, these are greater in absolute value than those at the lumbar region of 2.5 ± 1.1 G, 2.8 ± 1.1 G, and 2.7 ± 1.1 G respectively.

The peak force of the platform and the time duration from crossing the threshold of 44 N until peak was recorded. As the drop height increased the average peak load was 2387 N in 0.064s, 2725 N in 0.054s, and 3010 N in 0.052 s (Figure 12). When compared to the time until peak acceleration of the lumbar and thoracic regions in the Z direction, on average the peak force occurred first and the peak thoracic acceleration occurred last. The average time to peak for the lumbar region was 0.072 s, 0.065 s, and 0.064 s with the thoracic acceleration peak occurring 0.009 s, 0.006 s, and 0.002 s on average afterwards. For the entire set of seated drops, the velocities for L1 are approximately what would be expected with free fall at 0.9 m/s, 1.1 m/s, and 1.3 m/s for the 50, 75 and 100 mm drop heights. The velocities of T1 are lower because of the orientation of the accelerometer mount during the event with values 0.8 m/s, 1.0 m/s, and 1.0 m/s for the respective drop heights.

Using the force data and displacements determined from the T1 Z and L1 Z axis accelerometers, two slopes were determined. The first slope was calculated until 25% of the peak force was reached. The second slope reflected the higher stiffness from 25% to 75% of the loading. When analyzed by drop height, there was no significant difference between the higher stiffness values so all of the data is grouped together. At L1 the average stiffness from 25% to 75% of the peak load for all tests was 92 ± 56 N/mm (Figure 13). The toe region of this loading curve had an average stiffness of 18 ± 8 N/mm. T1 stiffness values were higher with a toe region stiffness of 26 ± 14 N/mm and a slope of 113 ± 46 N/mm at the part of the curve between 25% and 75% of the peak load. This stiffness does not represent the spinal column individually but rather the response of the whole region.

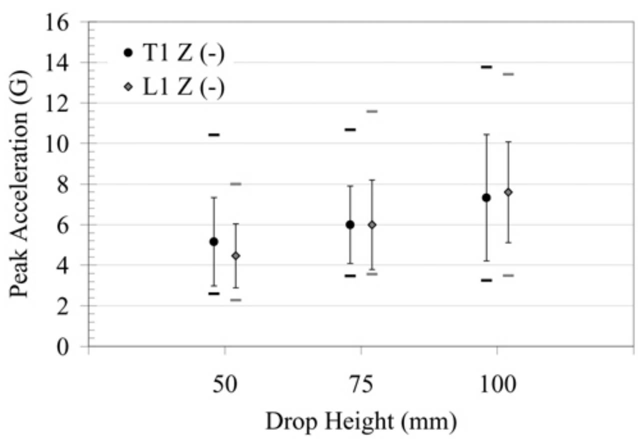

Figure 10. The average, standard deviation, maximum and minimum accelerations are reported for the Z axis accelerometers at T1 and L1 for the seated drop activity.

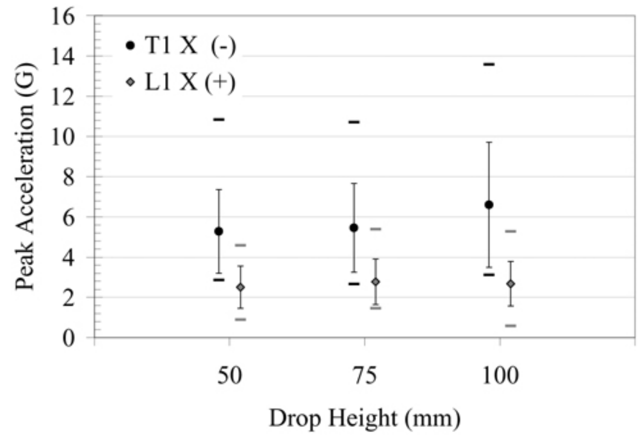

Figure 11. The average, standard deviation, maximum and minimum accelerations are reported for the X axis accelerometers at T1 and L1 for the seated drop activity.

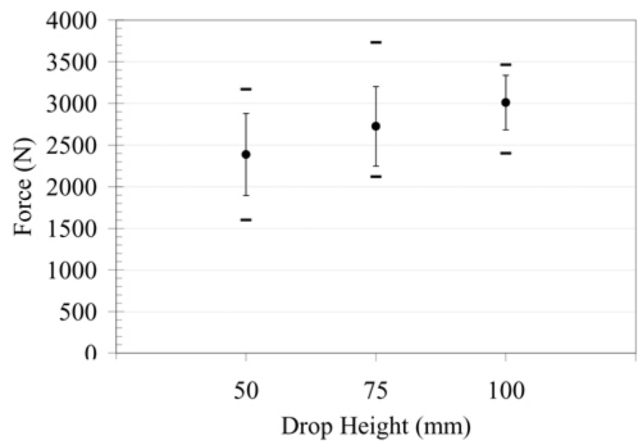

Figure 12. The average, standard deviation, maximum and minimum platform forces are reported for the seated drop activity.

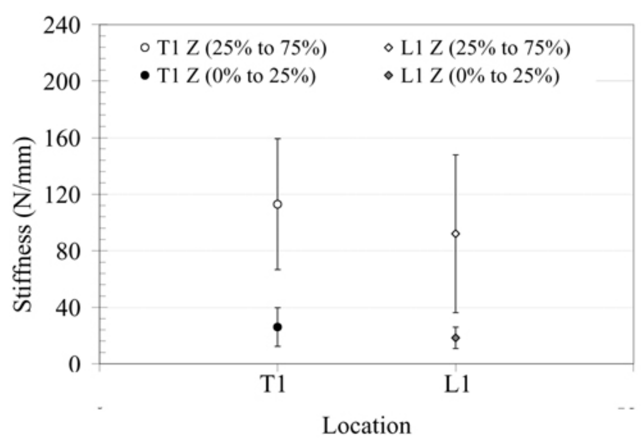

Figure 13. The average and standard deviation stiffness values for T1 and L1 in the Z direction are reported for the seated drop activity.

JUMPS

The kinematics for the jumps were not as consistent as for the seated drops. Individuals had various methods of stepping off the platform and landing. A time history of the data shows the ground force and the accelerations at the lumbar and thoracic acceleration mount locations (Figure 14). The angles of the lumbar and thoracic regions with respect to the ground at landing varied by individual.

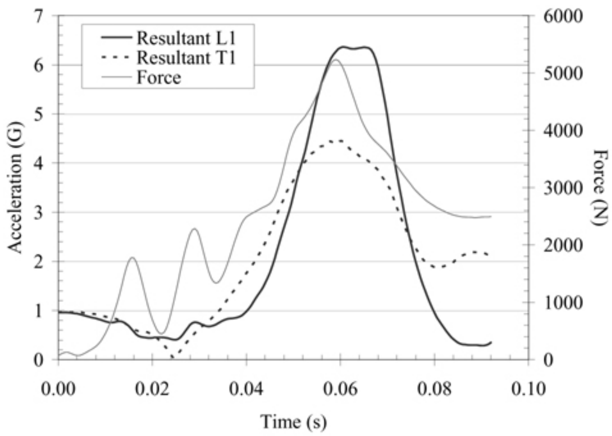

Figure 14. Time history of lumbar acceleration, thoracic acceleration, and corresponding platform force for a jump.

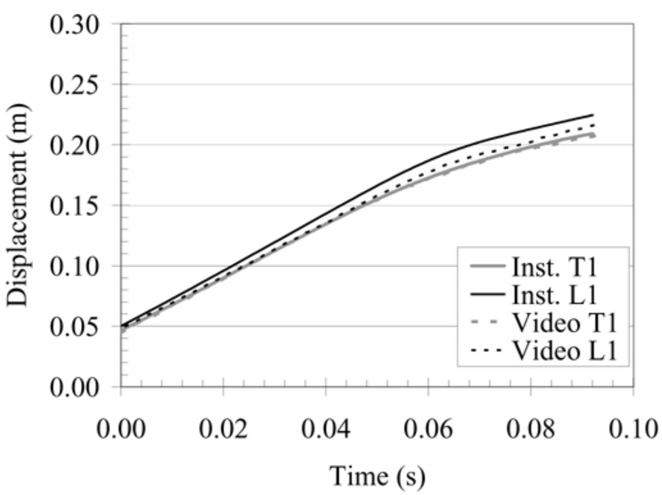

Figure 15. Video analysis of displacement for a jump.

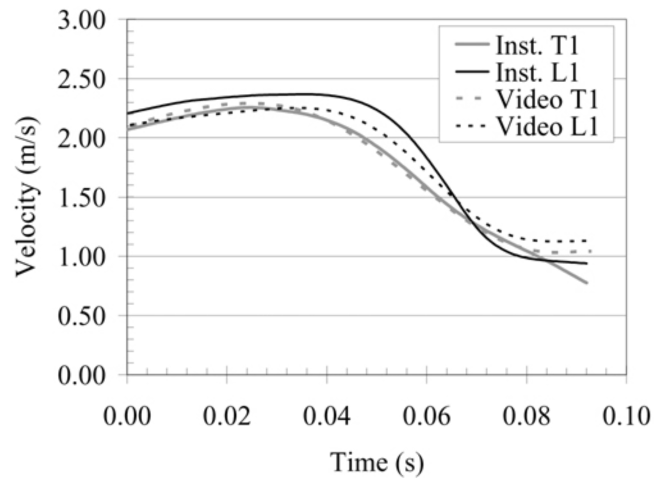

Figure 16. Video analysis of velocity for a jump.

The peak accelerations for the jumps were greater at L1 than T1. The average peak acceleration in the Z direction for L1 was −5.7 ± 1.9 G, −10.4 ±2.9 G, and −13.2 ± 5.3 G (Figure 17). In the region of T1, the Z accelerations had an average peak value of −4.3 ± 1.6 G, −5.9 ± 2.2 G, and −6.3 ± 3.6 G. The Z accelerations between all three jump heights were significantly different for the lumbar region ($p<0.05$). However, T1 Z accelerations were only significantly different between the lowest and highest drop heights ($p<0.05$). When volunteers jumped off the steps at 300 mm, 600 mm, and 900 mm the X accelerations were −3.2 ± 1.7 G, −4.4 ± 1.8 G, and −6.4 ± 3.7 G for the T1 mount and −3.9 ± 2.0 G, −6.0 ± 2.0 G, and −9.5 ± 3.7 G for the L1 mount (Figure 18). The average platform force that resulted from the volunteer landing after the jump was 3912 N, 6480 N, and 8493 N (Figure 19). The average time to reach the peak force after crossing the load threshold ranged from 0.025 s to 0.083 s. Generally the peak platform force occurred before the lumbar acceleration peak and the thoracic acceleration peak occurred last. The average velocities for the jumps were higher in the Z direction than the X direction although similar for both the T1 and L1 regions (Figure 20). The velocities at L1 in the Z direction were close to the predicted velocity from free fall but varied slightly since people left the platform in different manners.

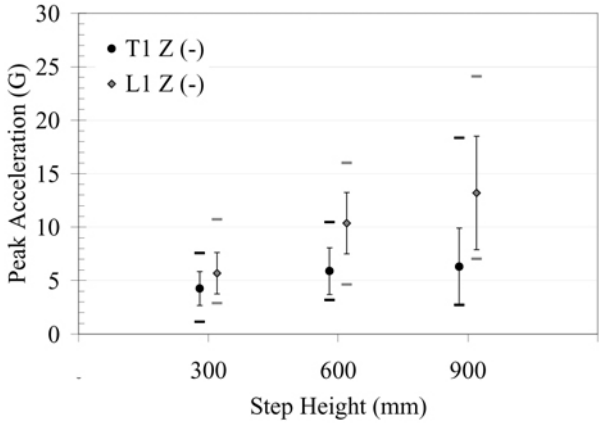

Figure 17. The average, standard deviation, maximum and minimum accelerations are reported for the Z axis accelerometers at T1 and L1 for the jump activity.

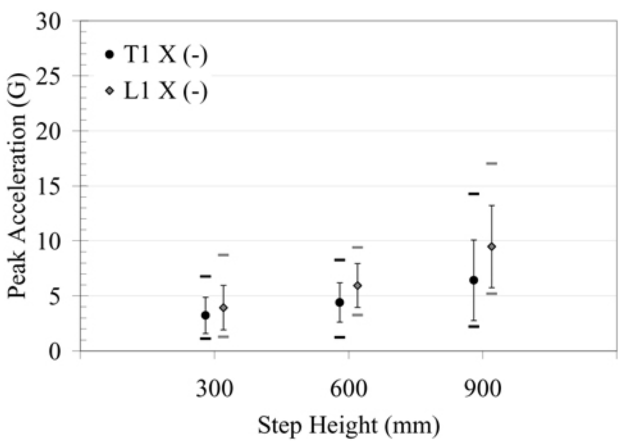

Figure 18. The average, standard deviation, maximum and minimum accelerations are reported for the X axis accelerometers at T1 and L1 for the jump activity.

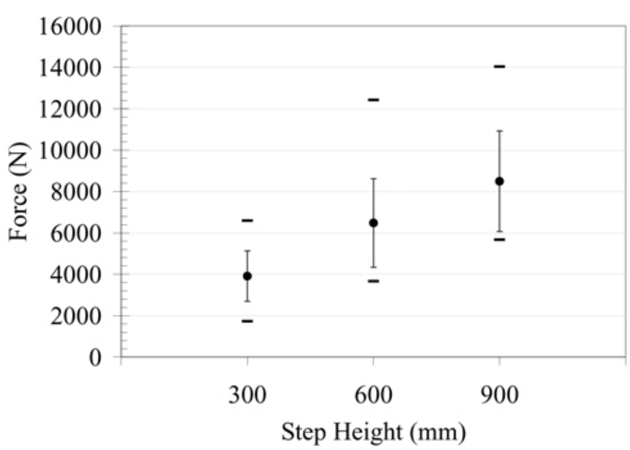

Figure 19. The average, standard deviation, maximum and minimum platform forces are reported for the jump activity.

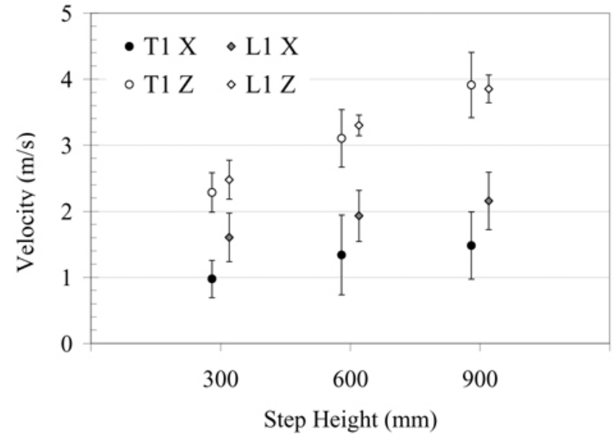

Figure 20. The average and standard deviation velocities for T1 and L1 in the Z and X directions are reported for the jump activity.

SEAT "PLOPS"

The kinematics for seat "plops", like the jumps, were based on the individual's method of "plopping" onto the seat. Differences included whether the feet left the ground, if the seat back was loaded, when the seat back was loaded, angles of the lumbar and thoracic regions during the event, vertical and horizontal distances to the seat bottom and the rate at which the volunteer accelerated himself. Data from the chair "plops" were not compared between video and instrumentation. There was difficulty in tracking the accelerometer mount accurately for position when it passed behind the chair. Only the angle of the lumbar region was recorded when the accelerometer mount was not within view of the video. An example of the time history of the force, thoracic acceleration, and lumbar acceleration is provided (Figure 21).

<figure 21 here>

When the volunteers "plopped" down onto a wooden chair, the Z axis accelerations were greater than the X axis accelerations. Then the subjects would often lean back and load the seat back. During this second loading, the X accelerations were positive and there was generally a second peak at T1 Z that was equal to or larger than the first peak. The peaks presented are the negative peak in the Z direction and the positive peak in the X direction. The average peak Z acceleration for the upper thoracic region was −4.1 ± 1.8 G and for the lumbar region it was −3.3 ± 2.2 G. In the X direction, the average peak accelerations were 1.9 ± 0.8 G and 3.2 ± 2.9 G for the thoracic and lumbar regions respectively (Figure 22). At the time the subject loaded the seat, the velocities were greater in the Z direction with an average peak of 0.7 m/s and 0.9 m/s for the T1 and L1 mount locations. The X direction velocities were 0.4 m/s and 0.1 m/s with the thoracic velocity in the X direction being greater than that of the lumbar region (Figure 23). The peak force on the seat bottom had an average value of 1568 ± 387 N and peaked around 0.12 s compared to the seat back which had an average peak value of 1362 ± 702 N and peaked at approximately 0.27 s (Figure 24). In comparison, the L1 Z acceleration peaked at 0.18 s on average and the T1 Z acceleration peaked at 0.27 s on average (Figure 25).

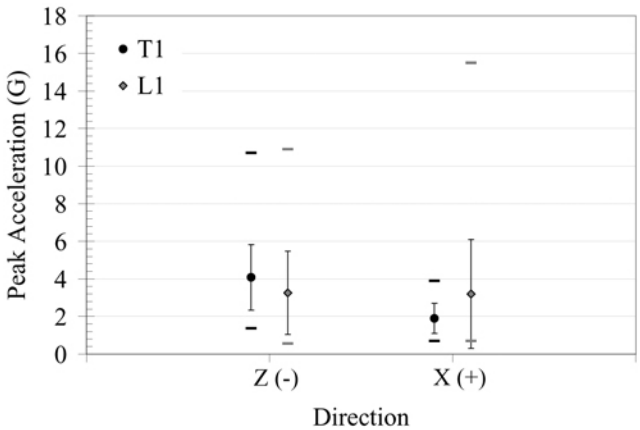

Figure 22. The average, standard deviation, maximum and minimum accelerations are reported for the Z and X axis accelerometers at T1 and L1 for the chair "plop" activity.

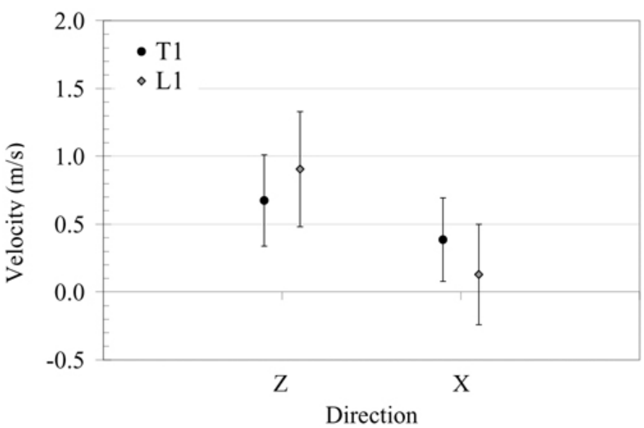

Figure 23. The average and standard deviation velocities for T1 and L1 in the Z and X directions are reported for the chair "plop" activity.

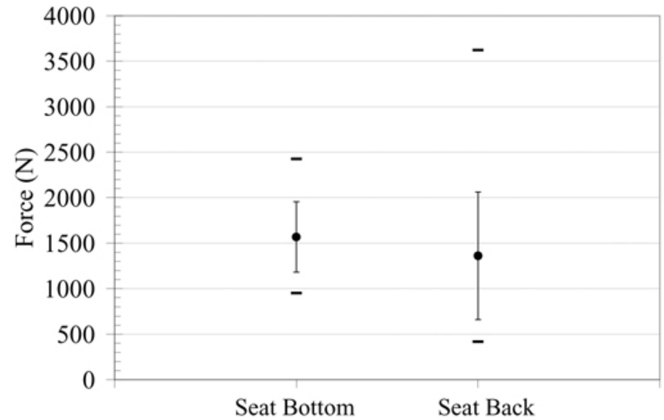

Figure 24. The average, standard deviation, maximum and minimum seat bottom and seat back forces are reported for the chair "plop" activity.

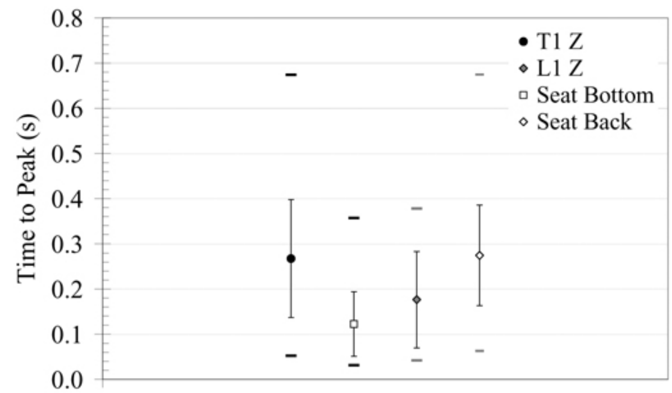

Figure 25. The average, standard deviation, maximum and minimum time to peak acceleration and force are reported for the chair "plop" activity.

CHAIR TIPS

During the chair tip activity, the lumbar region position was consistent for the subjects. Their knees were at approximately a 90 degree angle with their feet elevated above their torso. However, each subject was instructed to keep his/her head elevated against gravity. When the chair was released, some volunteers let the head drop as well and others flexed so that the head position actually moved further away from the chair. Individuals had different methods of bracing themselves during the release and impact for the chair tip in the upper thoracic and head region. Because the lumbar accelerometer mount was blocked from the video view, only the angle of the lumbar region was recorded and not the position of the mount. The chair tip activity is different from the other three activities reported because the primary load is in the X direction rather than the Z direction. A typical acceleration and force profile from the highest drop height for subject 19 is provided (Figure 26). The peak lumbar acceleration occurs slightly before the peak force value.

<figure 26 here>

The X accelerations for the lumbar region are greater than those at the upper thoracic region. For the lumbar region average peak X acceleration values are 7.2 ±1.1 G, 12.7 ±2.2 G, and 13.2 ±2.7 G (Figure 27). The upper thoracic accelerations with an increase in drop height reach 4.0 ± 2.0 G, 4.3 ± 1.5 G, and 3.6 ± 1.5 G. For the Z direction peak accelerations are −7.6 ± 2.0 G, −9.0 ± 3.4 G, and −7.6 ±2.7 G for the T1 accelerometer mount and −3.6 ± 1.3 G, −8.3 ± 2.6 G, and −8.8 ± 3.0 G for the L1 accelerometer mount (Figure 28). T1 accelerations in the X direction were not significantly different for any of the drop heights ($p>0.05$). The L1 X axis accelerations did have an increase that was significant when comparing the larger two drop heights to the lowest ($p<0.05$), but not between the 100 mm and 150 mm release heights ($p>0.05$). The peak platform force on average for the lowest drop height of 50 mm was 5916 N. At 100 mm the average maximum was 9244 N and at 150 mm the average maximum was 10365 N (Figure 29). From the time the force reached 44 N it took 0.020 s to reach the peak force at the lowest drop height and 0.018 s to reach the peak force at the higher two drop heights. During the chair tips, the peak X acceleration at the upper thoracic region occurred after the peak force and peak L1 X acceleration on average. The velocities calculated from the accelerometers indicated peak velocities of 0.5 m/s, 0.9 m/s, and 1.1 m/s for the upper thoracic region and 0.8 m/s, 1.2 m/s, and 1.3 m/s for the lumbar region with an increase in drop height respectively (Figure 30).

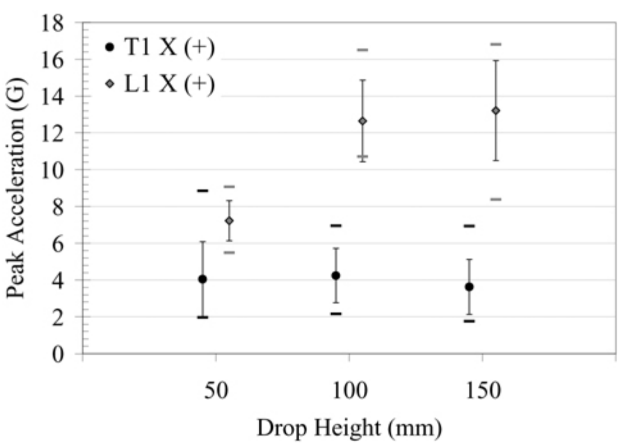

Figure 27. The average, standard deviation, maximum and minimum accelerations are reported for the X axis accelerometers at T1 and L1 for the chair tip activity.

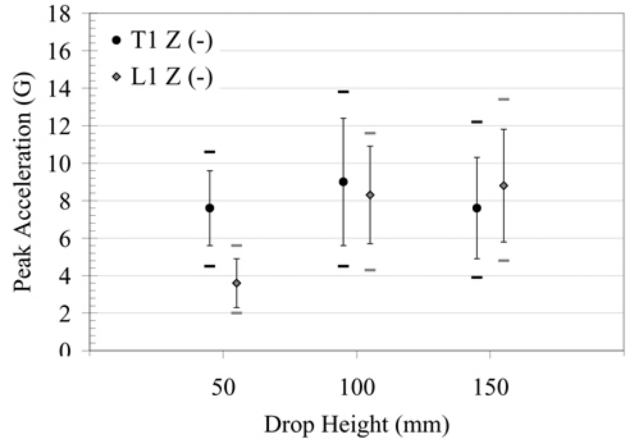

Figure 28. The average, standard deviation, maximum and minimum accelerations are reported for the Z axis accelerometers at T1 and L1 for the chair tip activity.

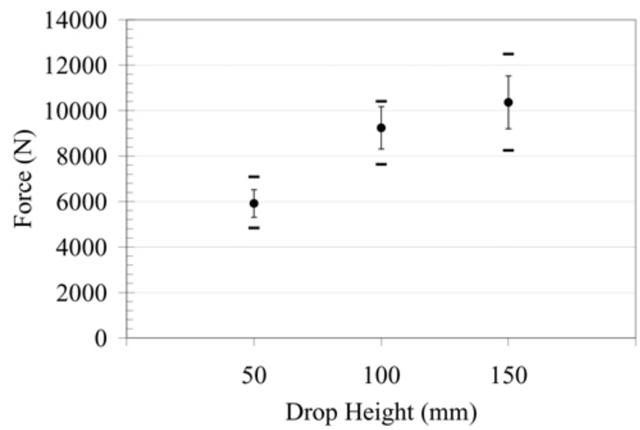

Figure 29. The average, standard deviation, maximum and minimum platform forces are reported for the chair tip activity.

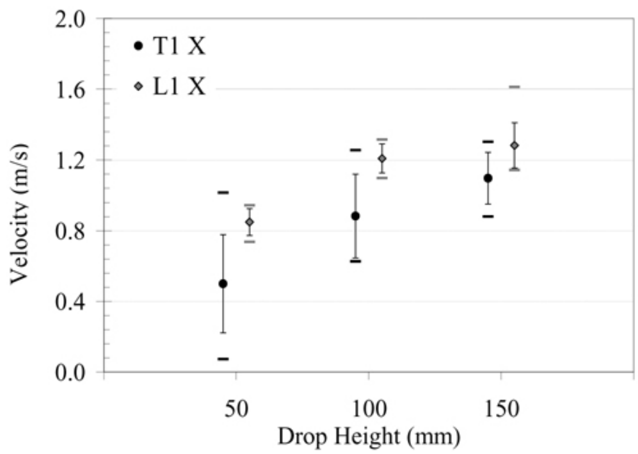

Figure 30. The average, standard deviation, maximum and minimum velocities for T1 and L1 in the X direction are reported for the chair tip activity.

The time duration from crossing the threshold until the time of the peak force and acceleration varied for the four different activities. The chair tip had the shortest average time to peak force of 0.019 s and the chair "plops" had the longest duration with an average of 0.123 s. Typically the force peaked before the acceleration at L1 and the acceleration at T1 peaked last (Figure 31).

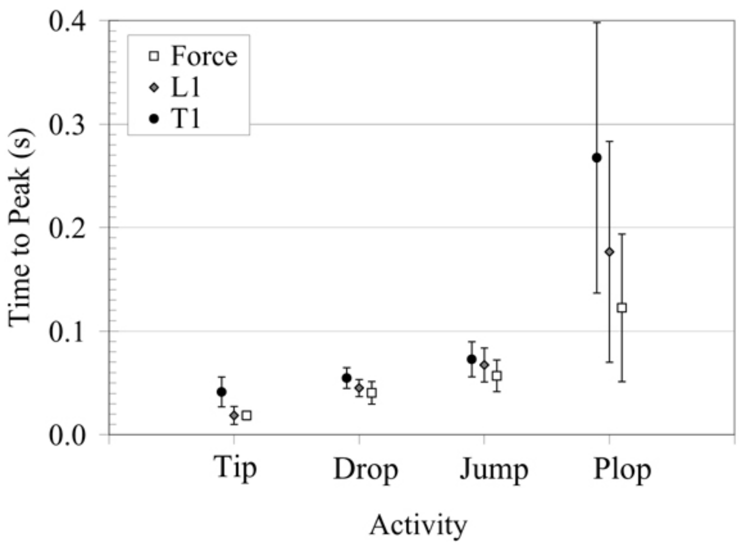

Figure 31. Average time from 44N until the peak force and acceleration values for the four activities.

For all of the activities, there was no correlation between BMI and accelerations in the primary loading direction for the thoracic or lumbar regions. The only correlation between gender and acceleration response in the primary loading direction was the tallest jump height for T1. Although only 5 females completed this level of the activity, the ones who did had an average acceleration of 9.4 ± 5.1 G compared to the 11 men who averaged 4.9 ± 1.4 G at T1 in the Z direction.

From the data that were collected and reported in this study, 6 volunteers reported symptoms of temporary pain (Table 1). All of these lasted less than 2 days. Because subjects completed all levels of an activity in one session, the symptoms correspond to an activity but not the specific level of the activity. No subject had more than discomfort or soreness as a result of these activities which produced up to 17.0 G and 24.0 G on the lumbar region in the X and Z directions and 14.3 G and 18.4 G in the X and Z directions on the upper thoracic region. Imaging of the thoracic and lumbar spines prior to testing indicated subjects had a range of degenerative changes from none to severe. Subjects with complaints had a lower level of degenerative changes on average than subjects without complaints.

<table 1 here>

DISCUSSION

The instrumentation was mounted to the subjects to obtain accelerations at the thoracic and lumbar levels. Through video analysis and data processing, the response of the instrumentation was evaluated thoroughly. There were no perceivable differences between the instrumentation and body motion during the videos of the events. When comparing the displacements and velocities obtained through the instrumentation and the video, the data were similar for the jumps and seated drops. Although video tracking was not completed for the "plops" and chair tips, the distances and velocities obtained from the instrumentation were within reason given the experimental setup. Moreover, there were not signs of high frequency vibrations in the data as a product of mounting the instrumentation around the soft tissue. The instrumentation values are sampled at a higher rate and a higher accuracy level and are the basis for the data presented in this study.

The data collected for each activity were affected by the position for the subject. For instance, the seated drops had volunteers in a swing without a back support. Therefore many people sat with their torso flexed so that T1 was closer to 45 degrees with respect to the horizontal rather than 90 degrees. As a result, it was observed in the data that the T1 X peak was greater than that for L1 in the X direction. The time to peak acceleration or load was slightly quicker for the higher drop heights. In general for the activities, the jumps had the subject falling from the greatest height and corresponded to the largest acceleration values in the lumbar region for the Z direction. Often the upper thoracic region would keep moving downward and forward producing a lower peak acceleration at a later time in the event. This difference is more exaggerated at the higher jump heights when subjects absorbed the landing differently, some subjects bent their knees and others landed with straighter legs. The seat "plops" had the lowest peak Z accelerations overall due to control of the seat impact by the legs. The time duration from crossing the load threshold until peak load was much longer for the chair "plops" than the other activities.

The chair tips are a set of volunteer data with accelerations in the X direction that reach almost 17 Gs in the lumbar region and 8.8 Gs in the T1 region. The majority of volunteer research with accelerations in the sagittal plane has been rear impact testing. Rear impact tests using human subjects have indicated acceleration values at T1 of less than 6 G with an 8 km/h change in velocity [3, 4, 7]. Neilsen et al. indicated a remote potential for strain with a normally positioned healthy occupant in a rear impact with a delta V of 8km/h or less [8]. The T1 acceleration values were less than 2.6 G with a corresponding 4 km/h change in velocity [3]. For a 9.5 km/h delta V, the average human volunteer acceleration data for T1 had a peak of less than 8 G for men and women [5, 6]. The peak resultant lumbar acceleration in human subject research was less than 7.5 G in tests with up to a 10 km/h change in velocity [7, 9,10]. These tests mentioned for human subjects tested had peak accelerations in the thoracic and lumbar regions in the X direction lower than the maximum values measured in the chair tip tests performed in the current study. Although the seats can be different as well as the global orientation of the volunteer in the laboratory, the non-injurious levels of acceleration in the anterior-posterior direction from the chair tip tests can be compared to the accelerations measured in these rear impact scenarios. Additional research has been performed on frontal and lateral collisions with human volunteers. With delta V's up to 11 km/h in the frontal collisions, there were no pain symptoms reported by the volunteers [11]. Expanding beyond the everyday exposure range measured in this study, a higher range of impact severities have been considered by researchers using sleds and multipoint restraint systems [11].

The peak forces and accelerations experienced for all four activities can be compared to the limited previous data available for similar activities. The peak accelerations presented are generally higher than those previously reported by Ng et al. The jumps performed in the current study were from a higher platform and the subjects were generally heavier. The data from Ng did show that the accelerations at T1 were lower than those at L5 just as was noticed in the current study [1]. That study included a younger population and reported no pain or discomfort for any of the tests performed. The pain or discomfort that was related with any of the activities in the current study was not long term and resolved itself within 1 to 2 days of the subject performing the activity. From 20 subjects in a total of 181 volunteer tests, only one subject complained of back soreness and two mentioned neck soreness. A wide range of subjects have completed a variety of activities and contributed to a set of data that are non injurious accelerations of the thoracic and lumbar spines. Additionally, the corresponding load, time to peak and velocities are known for the events. Although primarily peak acceleration was reported, it is important to consider duration and change in velocity when considering injury potential from impact loading.

Robertson [12] has defined injury as "physical damage occurring to an individual due to an acute exposure to energy levels outside the normal tolerance bands for human tissue". The American Medical Association [13] in their book "Guides to the Evaluation of permanent Impairment" define injury as "A sudden traumatic event producing immediate or prompt symptoms and/or signs due to physical and/or psychological pathology". Acute damage is manifested through tissue deformation which will result in mechanical nocioceptor stimulation. This stimulation is typically interpreted by the individual as pain. In medicine, when an individual is subjected to a force or acceleration and remains symptom free it is concluded that they have not been acutely injured. Therefore this study has reported the data that correspond to events which do not produce lasting pain or injury.

SUMMARY

In summary, acceleration data have been collected for 181 tests on 20 volunteer subjects. The test series includes a range of intensity levels and types of volunteers. All of the symptoms, which only included soreness or discomfort, were resolved within at least 2 days of completing the activity. Lumbar and upper thoracic acceleration values from 0.6 G to 24.0 G were recorded in non-injurious events. The durations, peak loads, and velocities that correspond with these values are also described for drop heights from 25 mm to 900 mm. The most significant factor in determining the level of acceleration that was present was the intensity of the drop that the subject sustained. If this was a self-controlled drop such as a "plop" into the seat the accelerations were in general lower than if the subject was not controlling themselves and falling freely onto the platform or seat. Moreover, for the highly controlled series of tests, the stiffness was measured and reported in a piecewise linear manner for future modeling of the thoracic and lumbar regions in response to a given input. This study contributes to the useful set of volunteer data that exists in the biomechanical literature.

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APPENDIX

Table 2. Seated drop data averages, standard deviations, maximums, and minimums. Data are presented from the instrumentation in the local coordinate system for the activity.

Description	Height (mm)	N	Mean	Std	Min	Max
T1 Z Acceleration (G)	50	18	5.2	2.2	2.6	10.4
	75	16	6.0	1.9	3.5	10.7
	100	15	7.3	3.1	3.3	13.8
Time Max T1 Acceleration (s)	50	18	0.081	0.015	0.060	0.114
	75	16	0.071	0.014	0.048	0.096
	100	15	0.066	0.019	0.043	0.108
T1 Z Velocity (m/s)	50	18	0.8	0.3	0.4	1.5
	75	16	1.0	0.2	0.6	1.3
	100	15	1.0	0.3	0.6	1.8
L1 Z Acceleration (G)	50	18	4.5	1.6	2.3	8.0
	75	16	6.0	2.2	3.6	11.6
	100	15	7.6	2.5	3.5	13.4
Time Max L1 Acceleration (s)	50	18	0.072	0.013	0.055	0.106
	75	16	0.065	0.015	0.046	0.105
	100	15	0.064	0.021	0.043	0.114
L1 Z Velocity (m/s)	50	18	0.9	0.2	0.4	1.3
	75	16	1.1	0.2	0.7	1.4
	100	15	1.3	0.3	0.6	1.7
T1 X Acceleration (G)	50	18	5.3	2.1	2.9	10.8
	75	16	5.5	2.2	2.7	10.7
	100	15	6.6	3.1	3.1	13.6
L1 X Acceleration (G)	50	18	2.5	1.1	0.9	4.6
	75	16	2.8	1.1	1.5	5.4
	100	15	2.7	1.1	0.6	5.3
Peak Platform Force (N)	50	18	2387	492	1599	3168
	75	16	2725	478	2120	3732
	100	15	3010	326	2402	3464
Time to Peak Platform Force (s)	50	18	0.064	0.012	0.049	0.086
	75	16	0.054	0.010	0.041	0.072
	100	15	0.052	0.020	0.037	0.111
T1 Stiffness 1 (N/mm)	all	49	26.0	13.6	10.0	71.8
T1 Stiffness 2 (N/mm)	all	49	112.9	46.3	28.9	317.4
L1 Stiffness 1 (N/mm)	all	49	18.4	7.6	7.4	44.0
L1 Stiffness 2 (N/mm)	all	49	92.0	55.8	35.1	307.8

Table 3. Jump data averages, standard deviations, maximums, and minimums. Data are presented from the instrumentation in the local coordinate system for the activity.

Description	Height (mm)	N	Mean	Std	Min	Max
T1 Z Acceleration (G)	300	17	4.3	1.6	1.1	7.6
	600	17	5.9	2.2	3.2	10.5
	900	16	6.3	3.6	2.7	18.3
Time Max T1 Acceleration (s)	300	12	0.057	0.013	0.042	0.091
	600	12	0.055	0.010	0.041	0.070
	900	13	0.051	0.009	0.038	0.066
T1 Z Velocity (m/s)	300	17	2.3	0.3	1.6	2.8
	600	17	3.1	0.4	1.9	3.5
	900	16	3.9	0.5	3.2	4.8
L1 Z Acceleration (G)	300	17	5.7	1.9	2.9	10.7
	600	17	10.4	2.9	4.6	16.0
	900	16	13.2	5.3	7.0	24.1
Time Max L1 Acceleration (s)	300	17	0.050	0.011	0.035	0.074
	600	17	0.045	0.006	0.035	0.054
	900	16	0.040	0.003	0.036	0.045
L1 Z Velocity (m/s)	300	17	2.5	0.3	1.8	3.0
	600	17	3.3	0.2	3.0	3.5
	900	16	3.9	0.2	3.4	4.2
T1 X Acceleration (G)	300	17	3.2	1.6	1.1	6.8
	600	17	4.4	1.8	1.2	8.3
	900	16	6.4	3.7	2.2	14.3
T1 X Velocity (m/s)	300	17	1.0	0.3	0.5	1.5
	600	17	1.3	0.6	0.0	2.7
	900	16	1.5	0.5	0.6	2.3
L1 X Acceleration (G)	300	17	3.9	2.0	1.3	8.7
	600	17	6.0	2.0	3.3	9.4
	900	16	9.5	3.7	5.2	17.0
L1 X Velocity (m/s)	300	17	1.6	0.4	1.1	2.3
	600	17	1.9	0.4	1.1	2.5
	900	16	2.2	0.4	1.4	3.1
Peak Platform Force (N)	300	17	3912	1216	1730	6593
	600	17	6480	2141	3665	12425
	900	16	8493	2434	5666	14033
Time to Peak Platform Force (s)	300	17	0.045	0.015	0.025	0.083
	600	17	0.041	0.007	0.028	0.055
	900	16	0.034	0.005	0.028	0.045

Table 4. Chair "plop" data averages, standard deviations, maximums, and minimums. Data are presented from the instrumentation in the local coordinate system for the activity.

Description	Height (mm)	N	Mean	Std	Min	Max
T1 Z Acceleration (G)	n/a	52	4.1	1.7	1.4	10.7
T1 X Acceleration (G)	n/a	52	1.9	0.8	0.7	3.9
Time Max T1 Acceleration (s)	n/a	52	0.267	0.131	0.053	0.674
L1 Z Acceleration (G)	n/a	52	3.3	2.2	0.6	10.9
L1 X Acceleration (G)	n/a	52	3.2	2.9	0.7	15.5
Time Max L1 Acceleration (s)	n/a	52	0.177	0.107	0.042	0.378
T1 Z Velocity (m/s)	n/a	52	0.7	0.3	-0.1	1.5
T1 X Velocity (m/s)	n/a	52	0.4	0.3	0.0	1.1
L1 Z Velocity (m/s)	n/a	52	0.9	0.4	-0.2	2.0
L1 X Velocity (m/s)	n/a	52	0.1	0.4	0.0	2.4
Peak Force Seat Bottom (N)	n/a	52	1568	387	953	2427
Peak Force Seat Back (N)	n/a	52	1362	702	418	3624
Time to Peak Force Seat Bottom (N)	n/a	52	0.123	0.071	0.032	0.357
Time to Peak Force Seat Back (N)	n/a	52	0.274	0.111	0.063	0.675

Table 5. Chair tip data averages, standard deviations, maximums, and minimums. Data are presented from the instrumentation in the local coordinate system for the activity.

Description	Height (mm)	N	Mean	Std	Min	Max
T1 X Acceleration (G)	50	9	4.1	2.0	2.0	8.8
	100	10	4.2	1.5	2.2	7.0
	150	10	3.6	1.5	1.8	6.9
Time Max T1 Acceleration (s)	50	9	0.043	0.010	0.030	0.056
	100	10	0.043	0.018	0.027	0.088
	150	10	0.039	0.015	0.017	0.063
T1 X Velocity (m/s)	50	9	0.5	0.3	0.1	1.0
	100	10	0.9	0.2	0.6	1.3
	150	10	1.1	0.1	0.9	1.3
L1 X Acceleration (G)	50	9	7.2	1.1	5.5	9.1
	100	10	12.6	2.2	10.7	16.5
	150	10	13.2	2.7	8.4	16.8
Time Max L1 Acceleration (s)	50	9	0.027	0.004	0.021	0.033
	100	10	0.017	0.008	0.008	0.037
	150	10	0.012	0.006	0.004	0.027
L1 X Velocity (m/s)	50	9	0.8	0.1	0.7	0.9
	100	10	1.2	0.1	1.1	1.3
	150	10	1.3	0.1	1.1	1.6
T1 Z Acceleration (G)	50	9	7.6	2.0	4.5	10.6
	100	10	9.0	3.4	4.5	13.8
	150	10	7.6	2.7	3.9	12.2
L1 Z Acceleration (G)	50	9	3.6	1.3	2.0	5.6
	100	10	8.3	2.6	4.3	11.6
	150	10	8.8	3.0	4.8	13.4
Peak Platform Force (N)	50	9	5916	609	4836	7086
	100	10	9244	931	7638	10413
	150	10	10365	1165	8256	12489
Time to Peak Platform Force (s)	50	9	0.020	0.004	0.016	0.027
	100	10	0.018	0.004	0.016	0.030
	150	10	0.018	0.004	0.016	0.029

Figure 5. Video captures of a volunteer completing the chair tip activity from 150 mm.

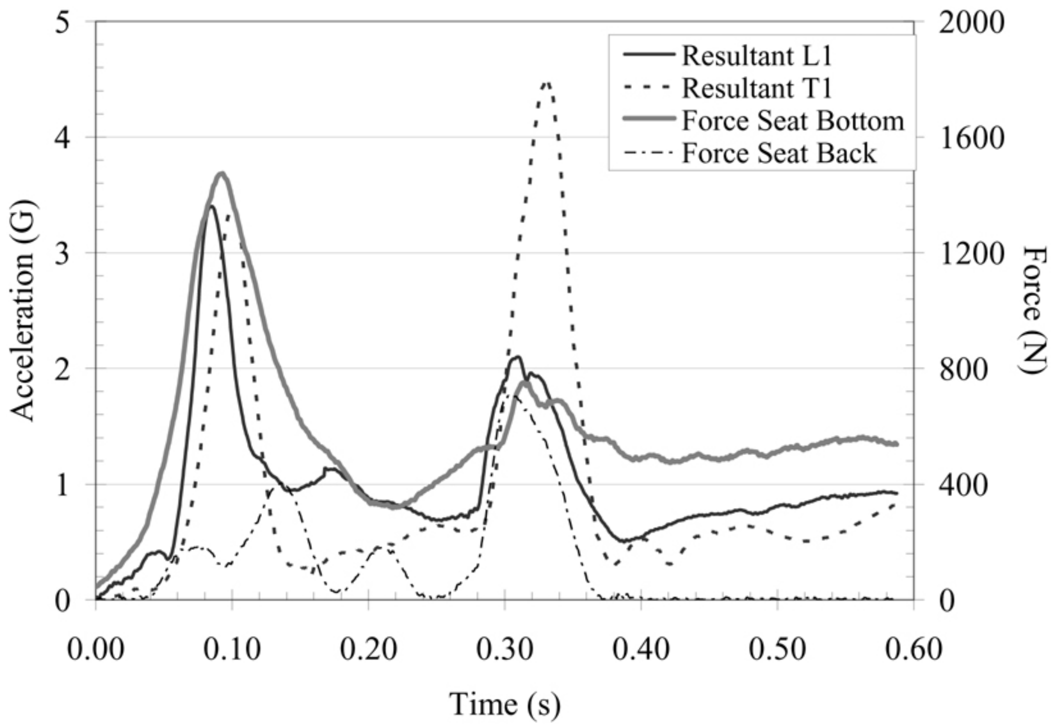

Figure 21. Time history of lumbar acceleration, thoracic acceleration, and corresponding seat bottom force for a seat "plop".

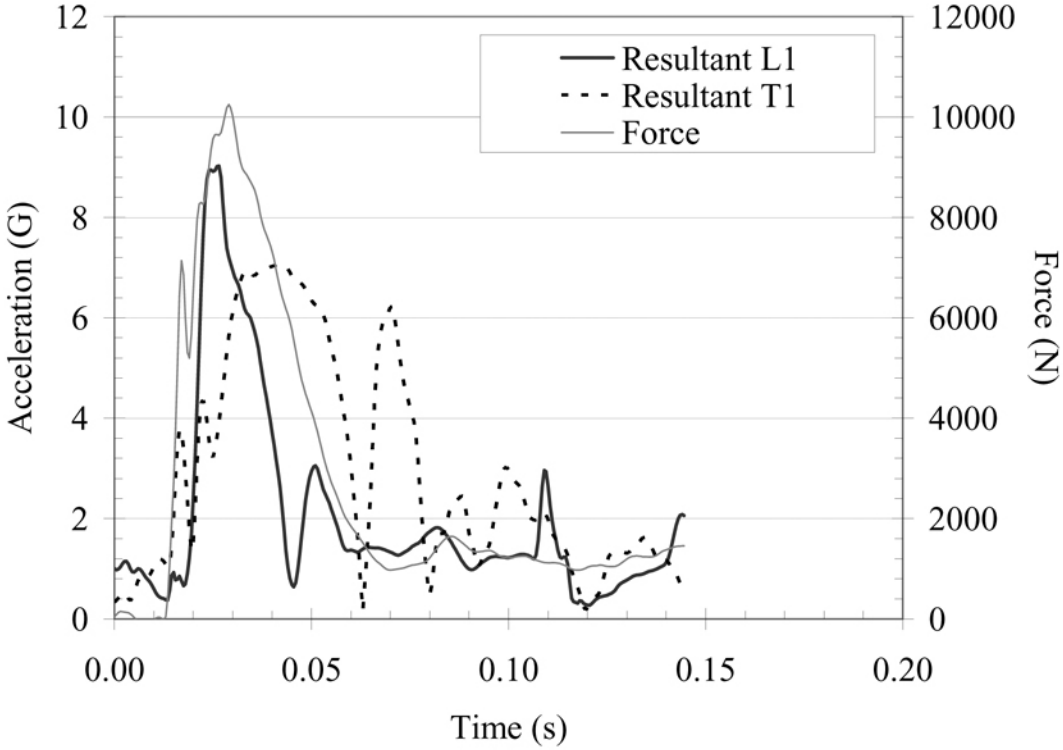

Figure 26. Time history of lumbar acceleration, thoracic acceleration and corresponding platform force for a chair tip.

Table 1. Subjects who had pain or discomfort and the duration of the symptom following the tests.

Event	*Volunteer ID*	*Symptoms*	*Length*
Chair Tip	24	neck stiffness	< 6 hours
Chair Tip	19	minor neck soreness the next AM	< 1 day
Jump	3	subtle quadriceps soreness	< 1 day
Jump	23	foot discomfort	< 1 day
Jump	12	lower back soreness	< 2 day
Seated drop	18	quadriceps soreness	< 1 day

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