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Toddler Lower Extremity Posture in Child Restraint Systems

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16. Abstract

The postures of 28 toddlers 18 to 36 months old were analyzed in conditions simulating rear-facing and forward-facing child restraints. Rear-facing conditions included a narrow and wide child restraint configuration, while the forward-facing conditions used a shorter and longer cushion length. Data collected include 3D coordinates of key body landmarks as well as surface scans focusing on the lower extremities. In addition, standard anthropometry measures and full body scans in standing and seated postures were collected for each subject.
An overhead photo of each child's posture was taken at one-second intervals throughout the test session. The number of different postures for each subject was tabulated and categorized. For rear-facing test conditions, the most common lower-extremity postures were legs relaxed, feet together with knees bent outward, knees pulled back towards torso, and both legs straight and elevated. For the forward-facing test conditions, the most common lower-extremity postures were legs relaxed, feet together with knees bent and rotated outward, one leg bent and one leg straight, and legs crossed. There were no distinct trends with selected posture and the subjects' age or size.

Analysis of the measured subject postures showed variations in lower-extremity posture with child restraint condition. The narrow rear-facing condition more often had subjects with lower extremities in a relaxed posture, while the wide condition had more children with their feet flat together or their legs extended. For forward-facing, there was less variation in posture with the shorter cushion length; more children chose the frog leg or extended leg postures with the longer cushion length. Distribution of measured lower-extremity postures varied with age group.

An attempt was made to position the lower extremities of the HIII 3YO and 18MO ATDs in the most common rear-facing configurations chosen by the subjects. Although the more limited range of motion of the ATDs did not allow them to be placed in the most extreme positions chosen by subjects, the ATD posture could be adjusted to several postures commonly chosen by subjects without modifications to the ATD.

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INTRODUCTION

According to research studies, children up to 2 years old are safer in rear-facing than in forward-facing child restraint systems (CRS) (Jakobsson, Wiberg, Isaksson-Hellman, & Gustafsson, 2007; Isaksson-Hellman, Jakobsson, Gustafsson, & Norin, 1997). In 2011, the National Highway Traffic Safety Administration revised its recommendations for child restraint use to recommend that children travel rear-facing as long as possible, with the American Academy of Pediatrics advising that children should travel rear-facing at least through age 2 (AAP 2011). However, caregivers often express concern that the lower extremities of larger children sitting rear-facing may be at risk because of interaction with the rear seat back, although this has not been documented as a problem in the field. Two- and 3-year-olds sitting rear facing often must flex their knees and abduct or externally rotate their hips, and caregivers interpret these postures as uncomfortable or dangerous.

Although child restraint manufacturers have developed products that accommodate children rear-facing to 30, 35, or 40 pounds, procedures for evaluating their performance using the Hybrid III 3-year-old anthropomorphic test device (HIII 3YO ATD) have not been officially prescribed. Manufacturers have used a variety of techniques to position the lower extremities of the HIII 3YO during testing that may or may not be consistent with lower-extremity positions chosen by rear-facing occupants.

The purpose of the current study is to document the lower-extremity posture of toddlers while seated in rear-facing and forward-facing child restraints. The volunteer tests will provide data on the lower-extremity postures children choose while rear-facing, and provide guidance for developing rear-facing seating procedures for the H3YO ATD.

METHODS

Overview of Approach

The primary goal of the study was to document subject lower-extremity posture while seated in rear-facing and forward-facing child restraints. Basic anthropometry measures were collected for each subject. Posture data were collected with an Artec scanner (Figure 1, left) that captures surface contours. A FARO Arm 3D coordinate measurement system was used to collect key landmarks in each test condition (Figure 1, right). To collect a full-body surface geometry scan, each subject was measured in the Vitus scanner in one standing and one seated posture as shown in Figure 2.

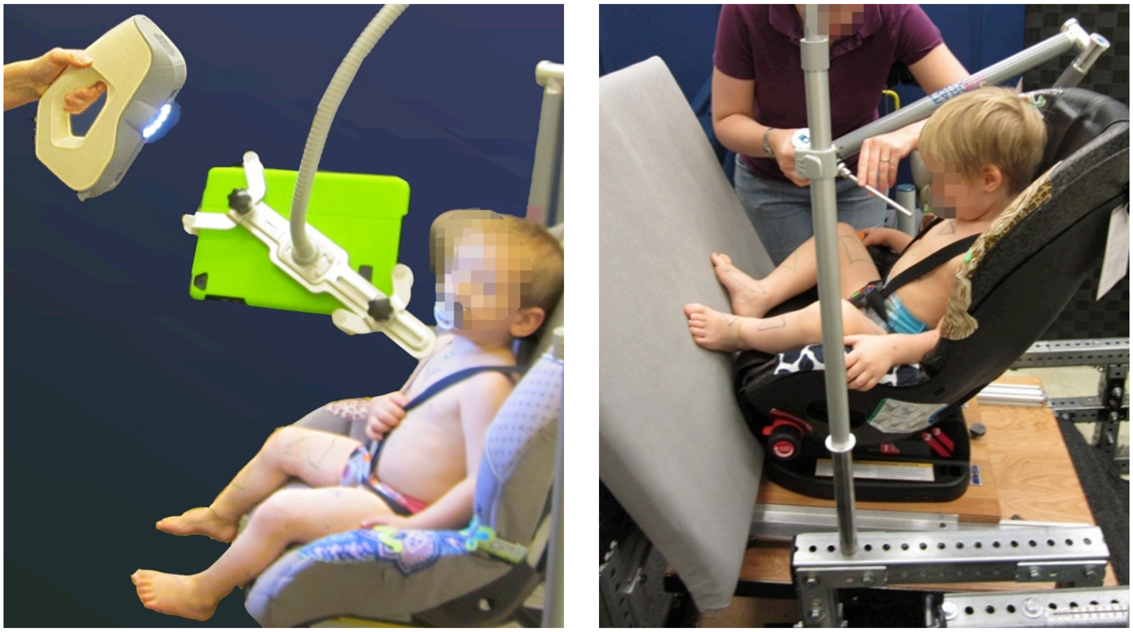


Figure 1. Subject being scanned with Artec scanner while distracted by tablet computer (left) and being measured with FARO Arm (right).

Figure 2. Subject in full-body scanner in seated posture.

Subject Recruitment

Thirty-one subjects 18 to 36 months old were recruited for this study. All test procedures and recruiting materials were approved by the University of Michigan Institutional Review Board (HUM00067147).

Reconfigurable Child Restraint Mockup

The test fixture developed to represent a vehicle seat is shown in Figure 3. To facilitate switching from rear-facing to forward-facing modes using different child restraints, a reconfigurable mock-up of a vehicle seat was used rather than an actual vehicle seat. A padded board was placed on the fixture during rear-facing tests to simulate the rear vehicle seat back that the child faces when traveling rear-facing. Most test conditions used a 19-degree back angle from vertical. This angle, which is more upright than the average rear seat back angle of about 23 degrees, was chosen to create a relatively constrained space for the lower extremities.

The CRS were mounted to boards that were secured to a sliding/locking plate on a tilt table. The rear-facing restraint seat back angle was set to 30 degrees (again to minimize child space), the most upright angle usually recommended for rear-facing use. The child restraint was moved forward so that the seat was tight against the vehicle seat back, simulating an installation with a vehicle seat belt or LATCH (lower anchors and tethers for children). To simulate a forward-facing test condition, the padded board representing the vehicle seat back was removed and the angle of the seat pan rotated to better replicate the more upright angles used with forward-facing child restraints. Simulating the forward-facing and rear-facing conditions with the child restraints in the same position increased the degree of condition repeatability and streamlined the testing and measurement, which is particularly important given the ages of the subjects.

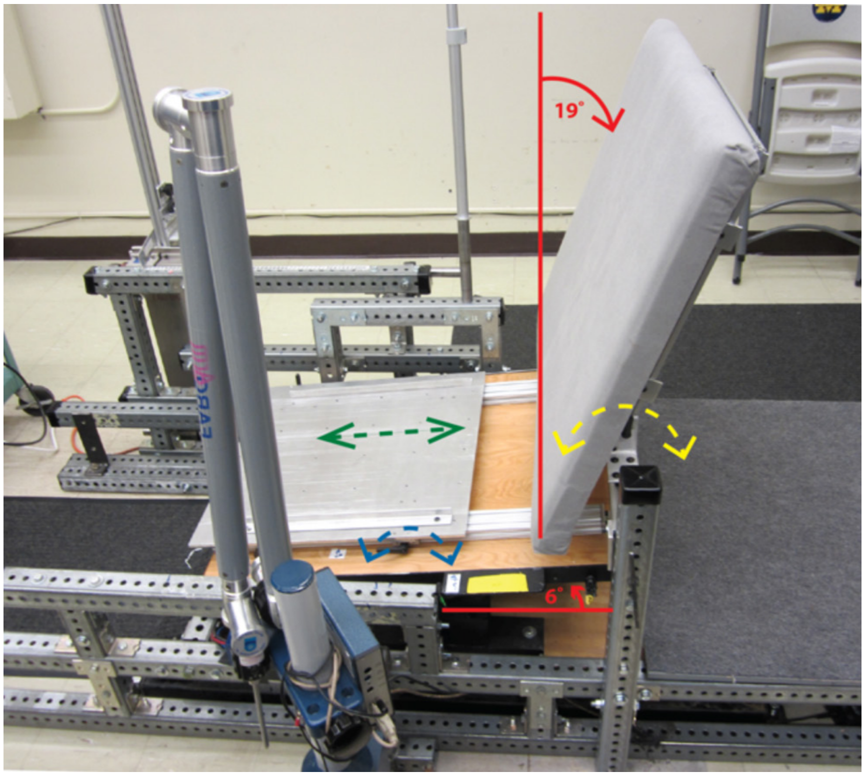


Figure 3. Reconfigurable mockup of vehicle seat.

Child Restraint Systems

Three production CRS were modified for use during testing. In all cases, the CRS were decorated with patterned material both to distract the child and to improve visibility on the scans.

The Evenflo Triumph 65 XL convertible car seat was used for rear-facing tests. The back angle was set to 30 degrees, which is a relatively upright angle in the range commonly recommended for use with older rear-facing children. Inserts were constructed that fit in the sides of the seat to simulate the effect on posture of a narrower child restraint.

Figure 4. Evenflo Triumph 65L in standard condition (left), with inserts to create a narrower seat width (right), and mounted to test fixture (below).

The Graco ComfortSport convertible was used for forward-facing test conditions as shown in Figure 5. With this seat, a foam insert was added to the seat back behind the cover for some conditions to simulate a seat with a shorter cushion depth.

Figure 5. Graco ComfortSport convertible attached to the mounting board (upper left), foam insert used to simulate shorter cushion length (upper right), in standard condition (lower left), in shorter seat cushion (lower mid), and installed on test fixture (lower right.)

In most of UMTRI studies using volunteer subjects, a set of 30 or more landmarks used to estimate joint locations and to characterize each individual's skeletal linkage is digitized with the subject seated in a rigid seat with access for documenting the spine and pelvis. Because the subjects in this study were younger than those previously tested (and less likely to sit still for measurement), a Cosco highback booster without its cover was modified to serve as the rigid seat for this study. As shown in Figure 6, the seat allowed subjects to be secured in with a 5-point harness restraint. The left side was partially cut away to allow visibility during scanning. A slot was cut in the back of the seat to allow access to spine and pelvis landmarks. An adjustable handle was added to allow the children to place their arms in a stable position. A foam insert between the legs helped to keep their lower extremities in position.

Figure 6. Modified Cosco highback booster used to seat subjects during anthropometry measures.

Subject Preparation

Upon arrival, the child was dressed in a disposable swim diaper. Then key landmarks and visual targets used to track body segments were designated on the child's skin with washable marker. Examples of subject preparation are shown in Figure 7.

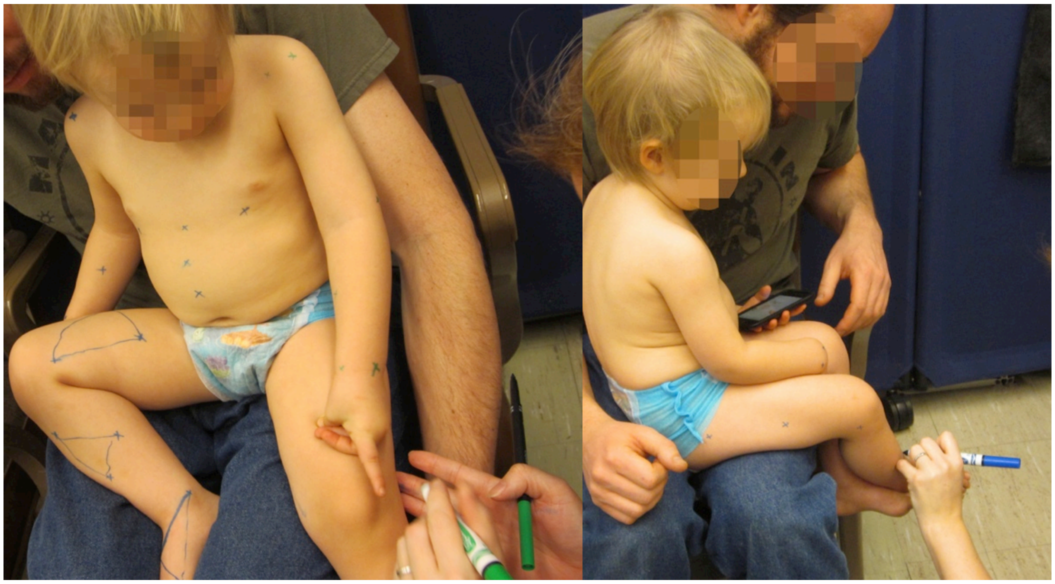


Figure 7. Marking landmarks on subjects.

Test Conditions

The test conditions using the child restraint are listed in Table 1. Subjects began with the two rear-facing postures, starting with the narrow seat width followed by the wider seat cushion condition. (In some cases, if there was a concern about the quality of the data collection in the first two trials, and the child was cooperative, the rear-facing trials were repeated). For the third trial the child restraint was reclined, and the initial posture of the subject was recorded. Then the caregiver was asked to rotate the child's legs toward the child's head (about the laboratory y-axis) to simulate the lower-extremity motion that might occur in a frontal crash with a rear-facing child. The maximum condition was recorded. The parent then repeated the movement of the child's legs while the investigator recorded the action with the scanner.

Table 1. Child Restraint System Testing Conditions

Code	Condition	Description
RFN	Rear facing narrow	Side pieces in to narrow the seat pan
RFW	Rear facing wide	Side pieces removed to widen seat pan
RMS	Range of motion *start*	Posture before range of motion
RMM	Range of motion *max*	Maximum hip range of motion
RMA	Range of motion *action*	Moving through hip range of motion
HHS	Hard seat *side*	Scan focusing on side of child
HSF	Hard seat *front*	Scan focusing on front of child
FFS	Forward facing *short*	Spacer added to back of child restraint to shorten seat pan length
FFL	Forward facing *long*	Spacer removed from back of child restraint to increase seat pan length

Following the range of motion tests, the hard seat was installed and a scan of the side of the child in a child restraint was taken, followed by a scan measuring the front of the child. The final two tests in the vehicle mockup used the forward-facing restraint with the simulated shorter seat pan length, followed by the longer seat pan condition with the insert removed. Again, if the child was cooperative and there were concerns about data quality, the forward-facing trials were repeated with some subjects.

Anthropometric data were also gathered from each child to characterize overall body size and shape. Body shapes were recorded using a Vitronic Vitus XXL full-body laser scanner and AnthroScan software (Human Solutions). The VITUS XXL records hundreds of thousands of data points on the surface of the body in about 12 seconds. Examples of two scans are in Figure 8. The standard anthropometry measures listed in Table 2 were obtained using manual measurements following the procedures in Snyder et al 1977. Figure 9 shows examples of these measurements.

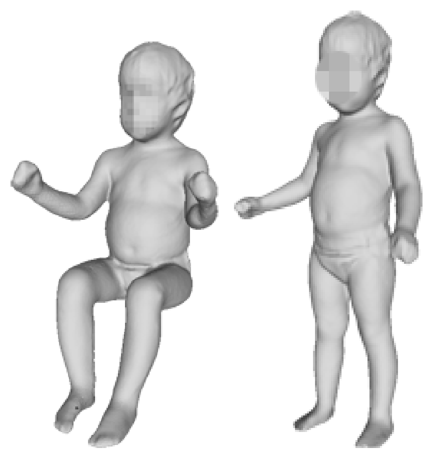


Figure 8. Sitting and standing postures recorded in Vitus scanner

Table 2. List of Anthropometry

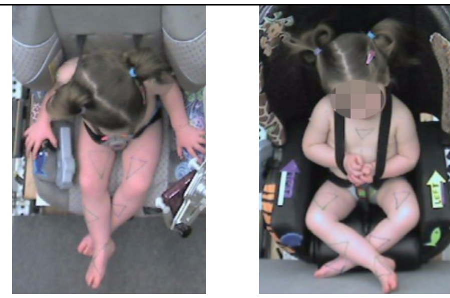
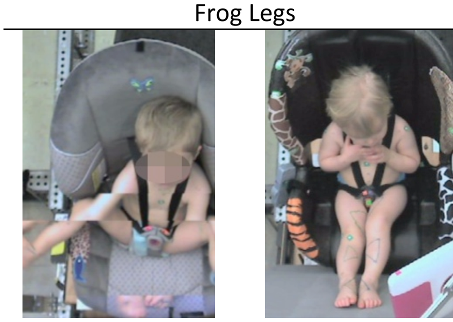
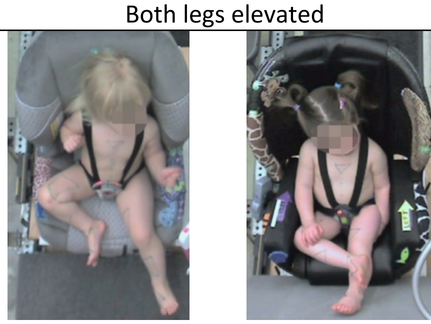
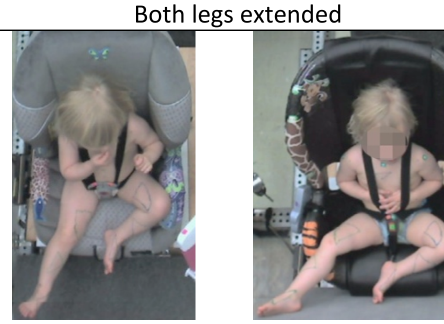
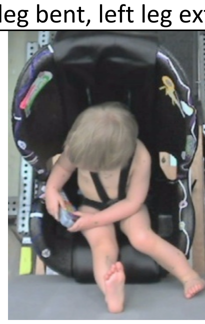
Date of Birth	Erect Sitting Height
Weight	Eye Height (Sitting)
BiASIS Breadth	Acromial Height (Sitting)
Biacromial Breadth	Knee Height
Shoulder Breadth	Tragion to Top of Head
Chest Depth (Scapula)	Head Length
Chest Depth (Spine)	Head Breadth
Stature	Shoulder-Elbow Length
Chest Circumference (Axilla)	Elbow-Hand Length
Waist Circumference	Maximum Hip Breadth
Hip Circumference (Buttocks)	Buttock-Knee Length
Upper Thigh Circumference	Buttock-Popliteal Length

Figure 9. Examples of knee height, erect sitting height, stature and waist circumference measurements

Time-Lapse Images

A time-lapse camera was mounted above the testing fixture and recorded the child participants seated in the different restraint systems once per second. One research assistant reviewed the images and classified the child's posture each time it changed. A set of 10 distinct postures were identified. Table 3 lists these postures with example frames. The investigator first considered the position of the feet as crossed or feet flat, then considered the overall placement of the thigh and leg. The number of times each posture was selected by a child was also tabulated, but the duration spent in each posture was not.

Table 3. Lower Extremity Positions Recorded

 Relaxed Legs	 Legs Crossed
 Frog Legs	 Feet flat against each other
 Both legs elevated	 Both legs extended
 Right leg bent, left leg extended	 Left leg bent, right leg extended
 Right leg elevated, left leg not elevated	 Left leg elevated, right leg not elevated

Scan Processing

The Artec scans were cleaned and converted from points to polygonal meshes using the Artec Studio (version 8) software. The scan data were aligned to the landmarks digitized with the FARO Arm using reference points on the child restraints common to both sets of data. Screen shots of some processed Artec scans are in Figure 10.

Figure 10. Examples of processed Artec scans of children in rear-facing conditions

Research assistants used Meshlab software version 1.31 (meshlab.org) to manually extract the landmark and marker locations shown in Figure 11 and Figure 12. Leg position data from the scan was combined with the coordinated measurement pelvis and hard seat joint and linkage information to identify the hip joint locations of the subjects in each posture.

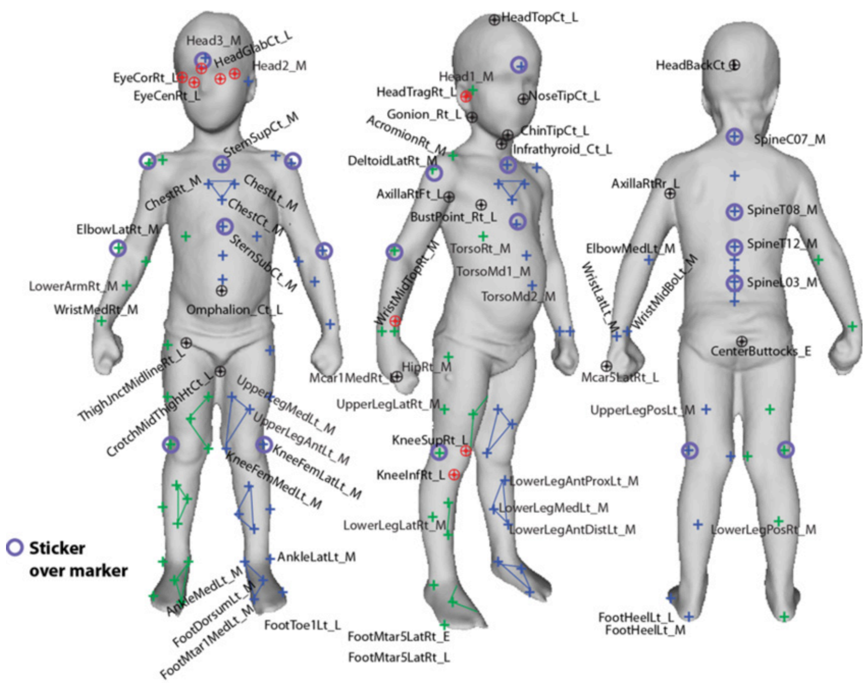


Figure 11. Illustration of points recorded on Artec and/or Vitus scans

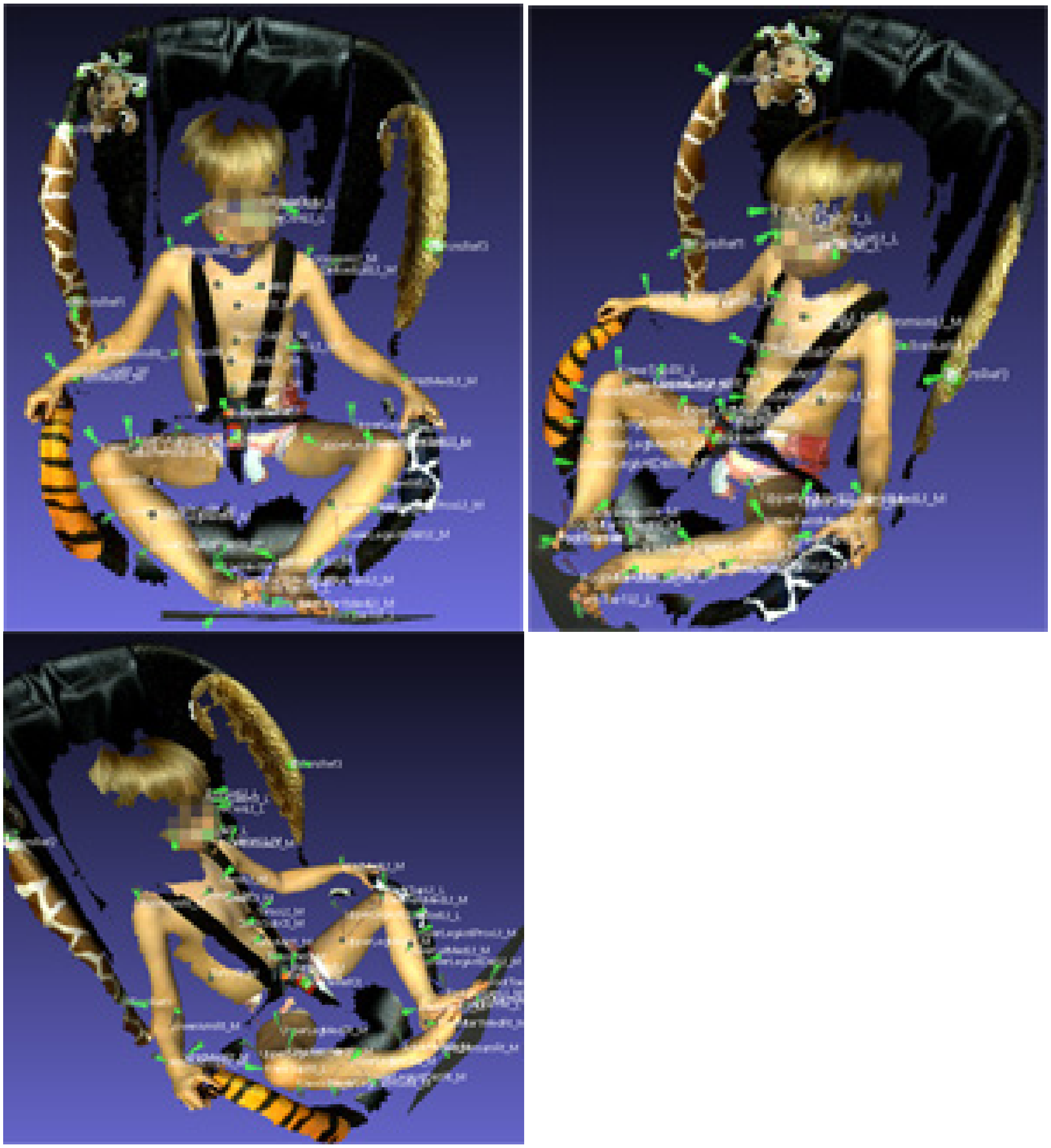


Figure 12. Example scan with landmarks and reference points digitized as seen from 3 perspectives

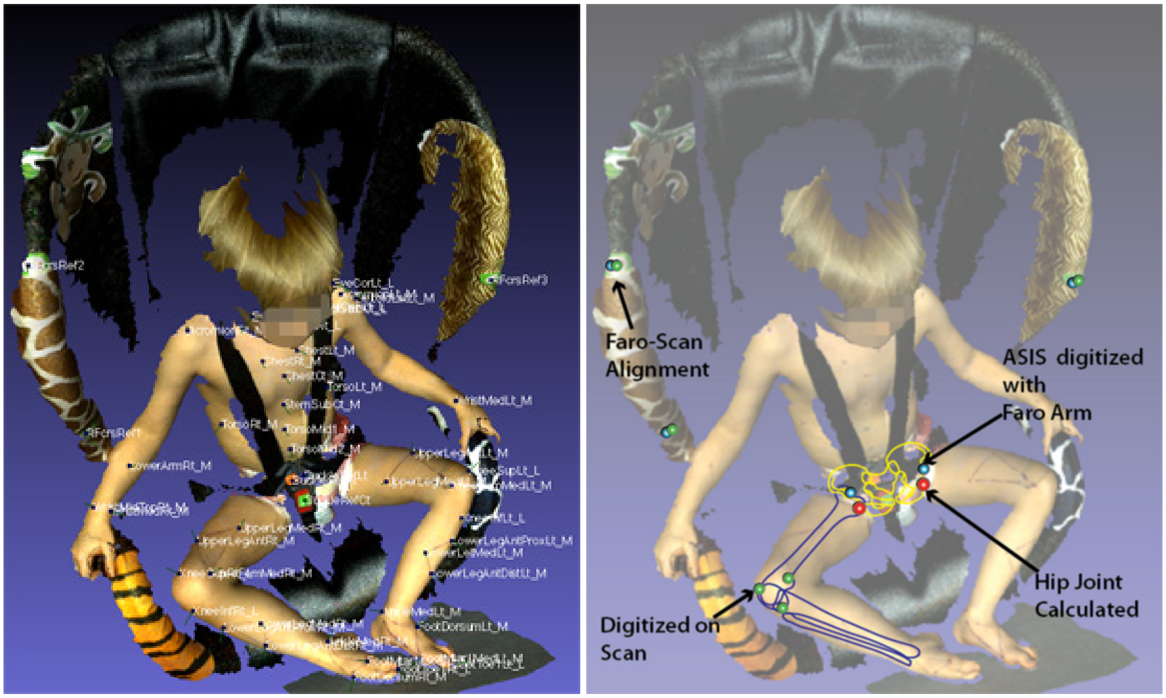


Figure 13. Example of Artec scan digitized in Meshlab software (left) and combined with FARO Arm data to calculated hip joint location (right). The joint data (including the hips) are calculated from scan points using the marker-joint relationships measured in the hard seat.

Joint Angle Calculations

Several different angles were used to describe the posture of the lower extremities, as illustrated in Figure 14. The hip, knee, and ankle joint were used to describe the length and position of the thigh and leg. A segment from the hip joint to the ASIS was used to characterize the location of the pelvis. From these four points, the hip angle is considered the included angle in the plane formed by the ASIS, hip joint, and knee joint locations, while the knee angle is the included angle in the plane formed by the hip joint, knee joint, and ankle joint locations.

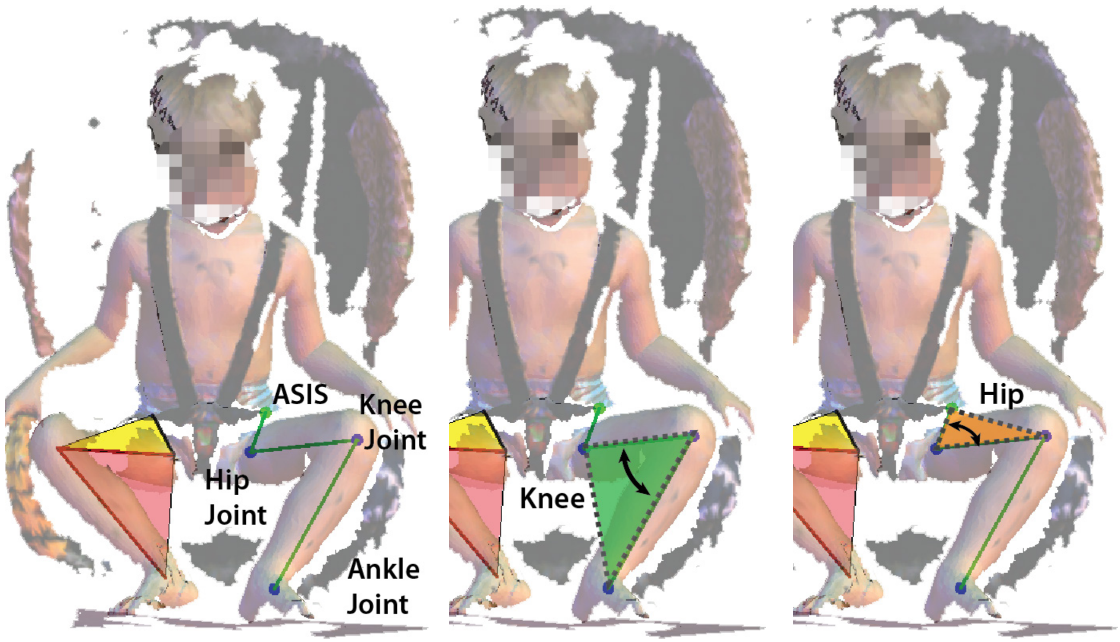


Figure 14. Definition of key joint landmarks and planar angles

Joint angles were also described orthogonally with the hip joint set as the origin with the positive axes as follows: X axis to the rear, Y axis to the right, and Z axis up. Figure 15 shows the XZ plane from the left while Figure 16 shows the YZ plane from the back. Both orientations have the positive axis going to the right side of the image. The angles are reported from 0 to 359 degrees in the XZ and YZ planes relative to the positive horizontal axis. The ASIS to hip angle defines the pelvis orientation. The angles in the XZ and YZ planes, from horizontal to the hip joint define the thigh orientation.

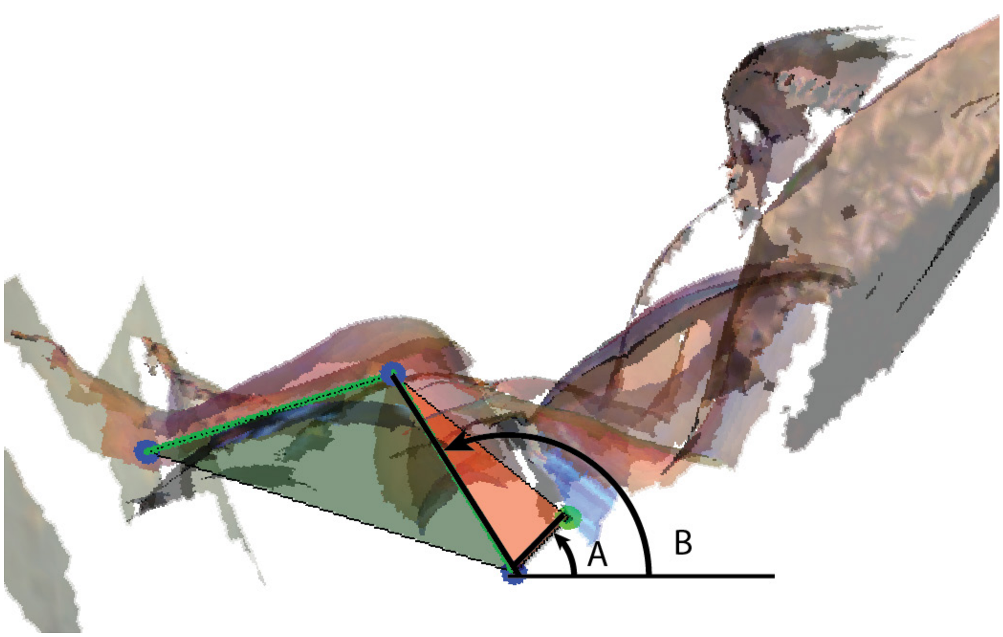


Figure 15. Pelvis angle (A) and thigh angle (B) in XZ plane, viewed from the subject's left, and reported in 360 degrees so that the included angles can easily be calculated.

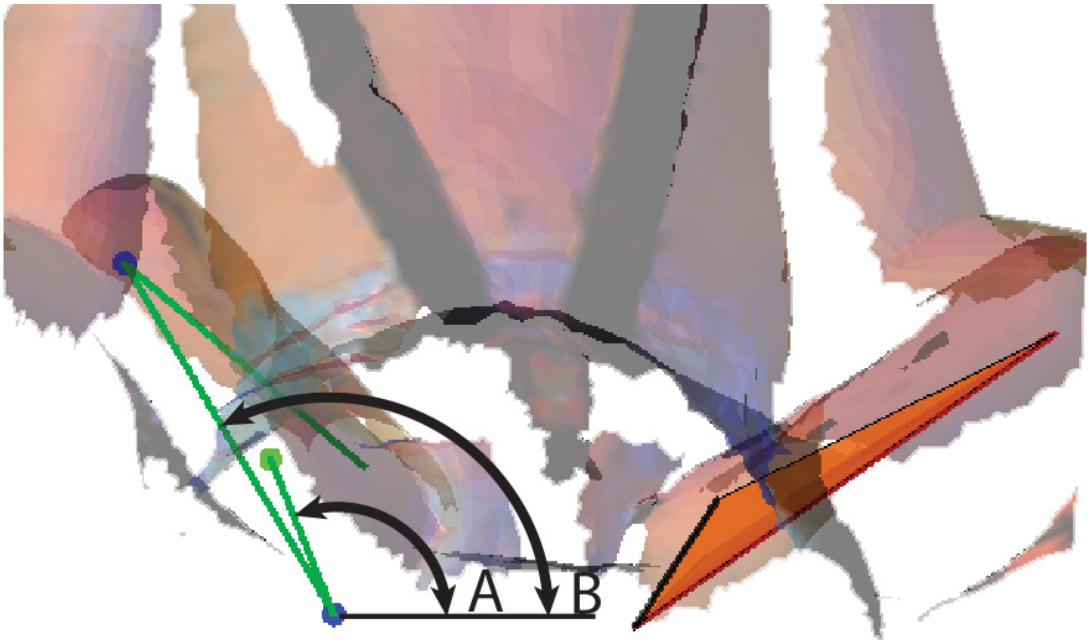


Figure 16. Pelvis angle (A) and thigh angle (B) in YZ plane, viewed from the subject's posterior, and reported in 360 degrees so that the included angles can easily be calculated.

The orientation of the upper and lower leg segments combined can be represented by a plane formed by the hip, knee and ankle joints and a vector normal to this plane as the knee motion is primarily flexion-extension (little rotation, abduction, or adduction). This is illustrated in Figure 17 by the red triangle and the perpendicular vector at the knee. To relate this information to the other orthogonal angles, the normal to the plane as viewed in the YZ plane from the posterior was used to characterize another aspect of leg posture.

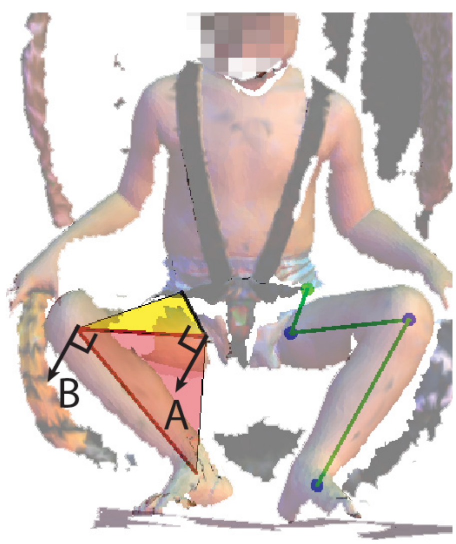


Figure 17. Left image: the plane of the leg (red triangle) and the vector normal to it (B); right image the same vector B as view in YZ plane as viewed from behind the subject.

Foot position was categorized by determining if any points measured on the left foot were to the right of any points measured on the right foot, and vice versa or if points measured on either foot crossed the midsagittal plane of the child. A qualitative assessment of the subjects' measured postures was also made by the same research assistant who classified the subjects' postures on the time-lapse images. This allowed comparison of selected posture trends between the measured conditions and observed positions.

Range of Motion

Recording child lower-extremity range of motion with the Artec scanner and FARO Arm system had two shortcomings. First, most of the children and caregivers could not maintain a position with the legs elevated for more than a few seconds without some leg movement and this was not sufficient time to collect enough surface data to locate the knee position reliably. Second, the ASIS landmarks were recorded before the legs were lifted, as they were hard to reach with the leg raised. Therefore, it was difficult to determine if the pelvis was lifted off the seat or rotated during the movement. Data from a trial with likely pelvis movement is shown in Figure 18. Due to the incomplete knee data and potential for error with the pelvis, these range-of-motion data were not included in the results.

Figure 18. Example of a trial with forward pelvis movement during lower-extremity rotation.

Subject Categories

To evaluate trends with occupant age and size, each subject was grouped according to age, stature, sitting height, and weight as indicated in Table 4. The stature and sitting height ranges were divided into three ordinal bins. For weight, an increment of 2.5 kg was used to provide a more even distribution of subjects.

Table 4. Ranges used to categorize occupants.

Subject factor	Group range		
	1	2	3
Age (months)	< 24	24-30	30+
Stature (cm)	760-832	833-904	905-976
Sitting height (mm)	480-515	516-550	551-585
Weight (kg)	9-11.49	11.5-13.99	14-16.5

For each of the measured postures, the subject's left and right lower-extremity posture was classified using the same method used to characterize the postures recorded in the time lapse video. Categories include relaxed, feet flat, crossed, frog leg, extended, and elevated.

Comparison to ATD Posture

The CRABI 18MO and HIII 3YO ATDs were measured and scanned under the same test conditions used with child volunteers. The ATDs' lower extremities were placed in several of the more common postures found in test subjects, some of which have also been used by child restraint manufacturers for testing.

RESULTS

Subject Characteristics

Thirty-one subjects were tested in this study, 19 girls and 12 boys. Data from 28 subjects were suitable for numerical analysis, although results from the other three subjects were included in the observed posture analysis when their data were usable. The distribution of subjects' weight versus stature and weight versus sitting height are shown in Figure 19 and Figure 20, respectively. Points to designate the size of the 18MO and 3YO ATDs are also included on each plot (Irwin & Mertz, 1997). Two points from the 1977 UMTRI anthropometry study are also shown on the plots (Snyder, 1977), representing the 5th percentile of 19- to 24-month-old subjects and the 95th percentile of 31- to 36-month-old subjects.

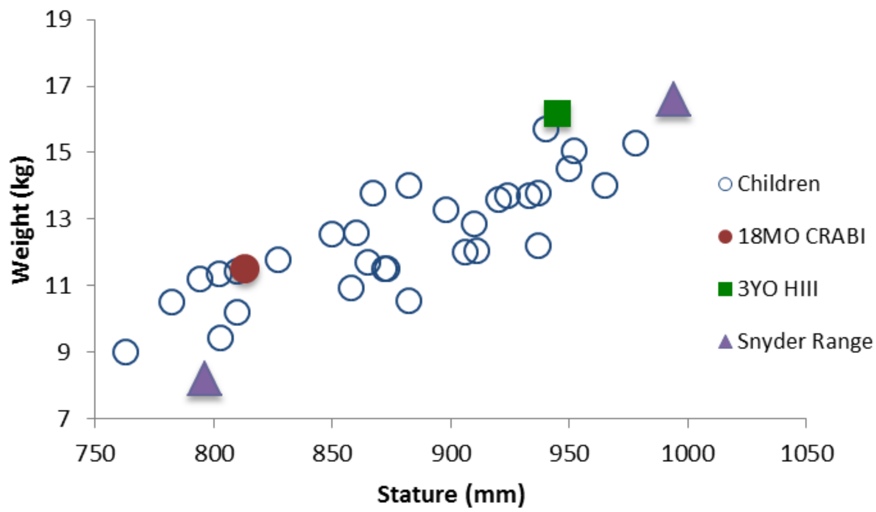


Figure 19. Distribution of subjects by weight versus stature.

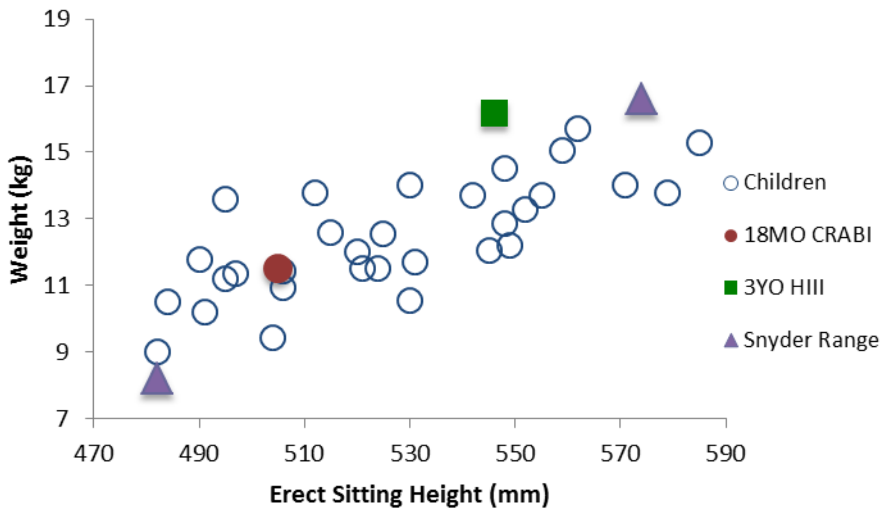


Figure 20. Distribution of subjects by weight versus erect sitting height.

The distribution of subjects by age and size category is shown in Table 5. Use of age for categorical analysis provides the most even distribution of subjects in each category. For the analyses involving measured posture distribution and comparisons of means, preliminary analyses have been performed using age, stature, sitting height, and weight group as a potential predictor. No analyses showed significant effects of these subject covariates, so most results are presented using age categories.

Table 5. Distribution of subjects by age and size categories.

Subject factor	Number of subjects in group		
	1	2	3
Age (months)	8	7	13
Stature (cm)	6	9	13
Sitting height (cm)	10	12	6
Weight (kg)	8	14	6

Frequency of Postures Throughout Test Session

Rear-Facing

The distribution of subjects by the number of rear-facing posture changes is shown in Figure 21. Most subjects had between 50 and 125 posture changes in the rear-facing test sessions, which took less than an hour but varied with each subject. The two subjects with the fewest were 19 months old, and the two with the highest were 19 and 28 months old, achieving 1,013 and 797 different postures, respectively.

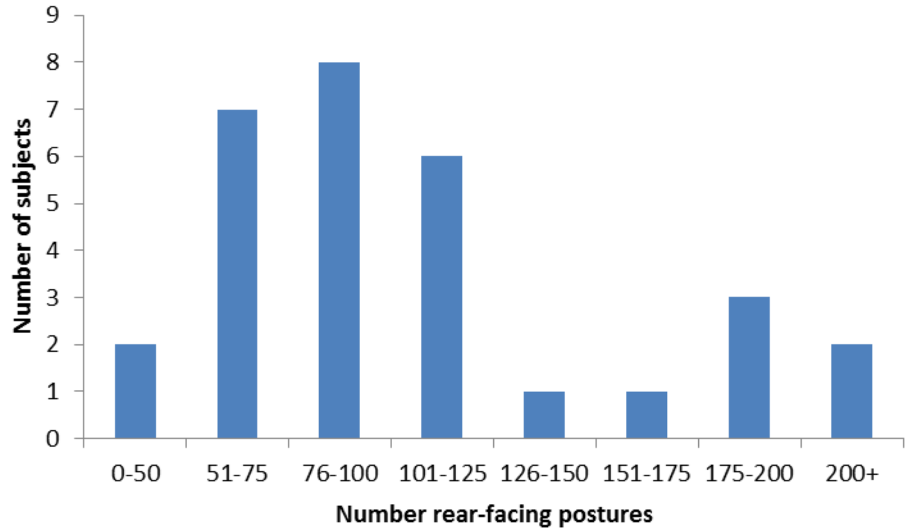


Figure 21. Distribution of subjects by the number of rear-facing postures in test session.

The rear-facing postures selected by each child are shown in Figure 22, expressed as the proportion of all postures tabulated for that child and arranged by age from youngest on the left to oldest on the right. The colors in each bar are arranged with the most common postures across all subjects on the bottom, and the least common postures near the top. For the four most common rear-facing postures, the percentage of selected postures in each one is shown in Figure 26, arranged by subject stature. Taller children spent more time in the knees out (feet flat against each other) or knees back (frog legs) posture than shorter children. Four children selected the legs elevated posture 20 percent more frequently than other postures, but they cover a range of statures. Most children selected the relaxed posture at least 25 percent of the time.

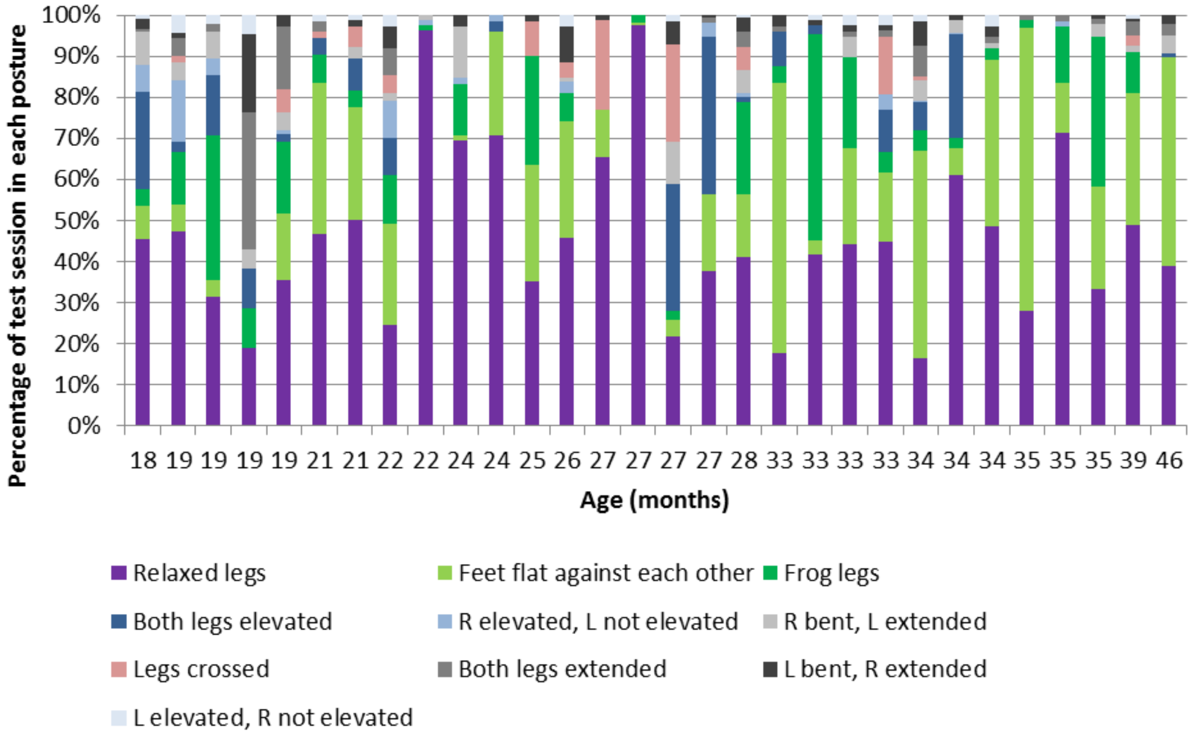


Figure 22. Percentage of rear-facing test conditions in each posture for each subject.

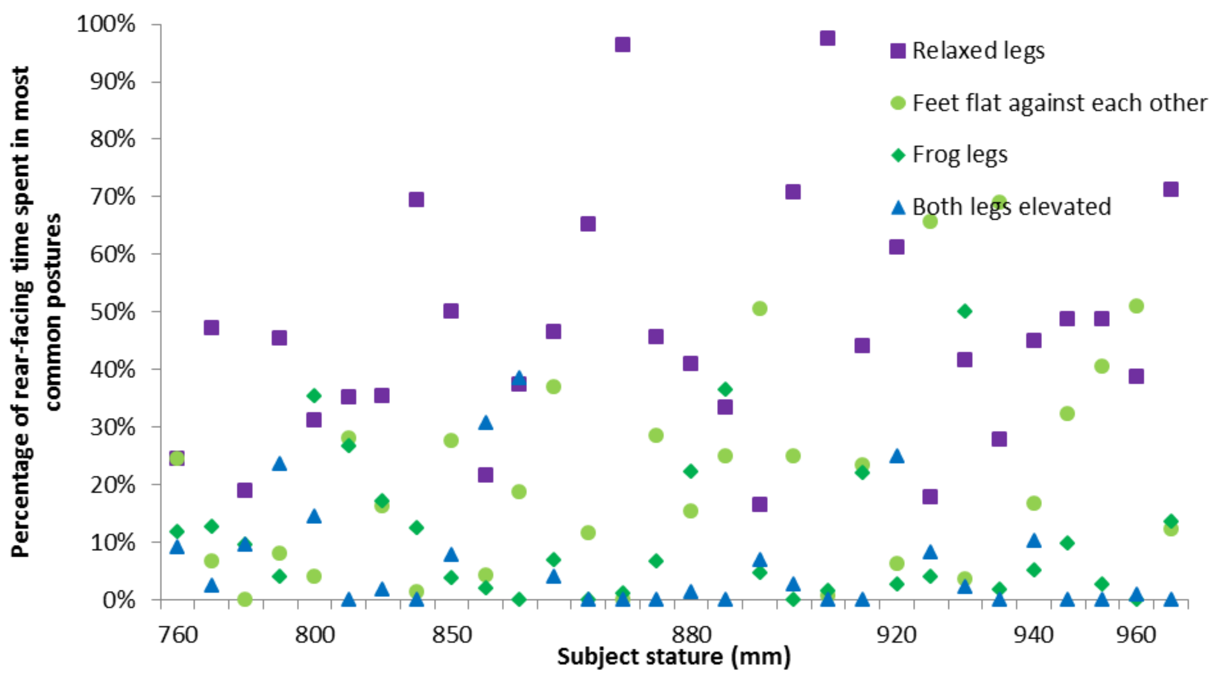


Figure 23. Most common postures selected by each subject in rearward-facing test conditions (as a percentage of all tabulated postures).

Forward-Facing

The distribution of subjects by the number of forward-facing posture changes during the test session is shown in Figure 24. Subjects had fewer posture changes forward-facing compared to rear-facing. Of the two subjects with more than 200 postures, subject L16 had 418, and was the same subject who had 1,013 postures rear-facing. However, this subject seemed to shift back and forth between legs relaxed and left leg bent, right extended but did not use any other postures forward-facing.

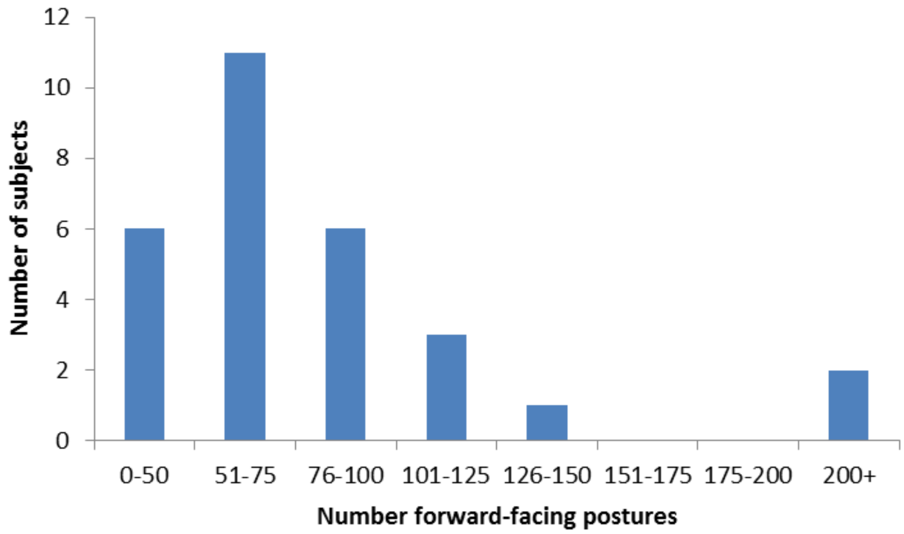


Figure 24. Distribution of subjects by the number of forward-facing postures in test session.

The percentages of each forward-facing posture for each subject are shown in Figure 25, arranged from youngest to oldest. (Two subjects withdrew from testing and did not complete the forward-facing session.) Like the rear-facing test conditions, the most common postures are relaxed legs followed by feet against each other. The next most common postures were legs crossed, right leg bent and left extended, and left leg bent and right extended. The five most common postures, expressed as a percentage of all selected postures, are shown for each subject in Figure 26.

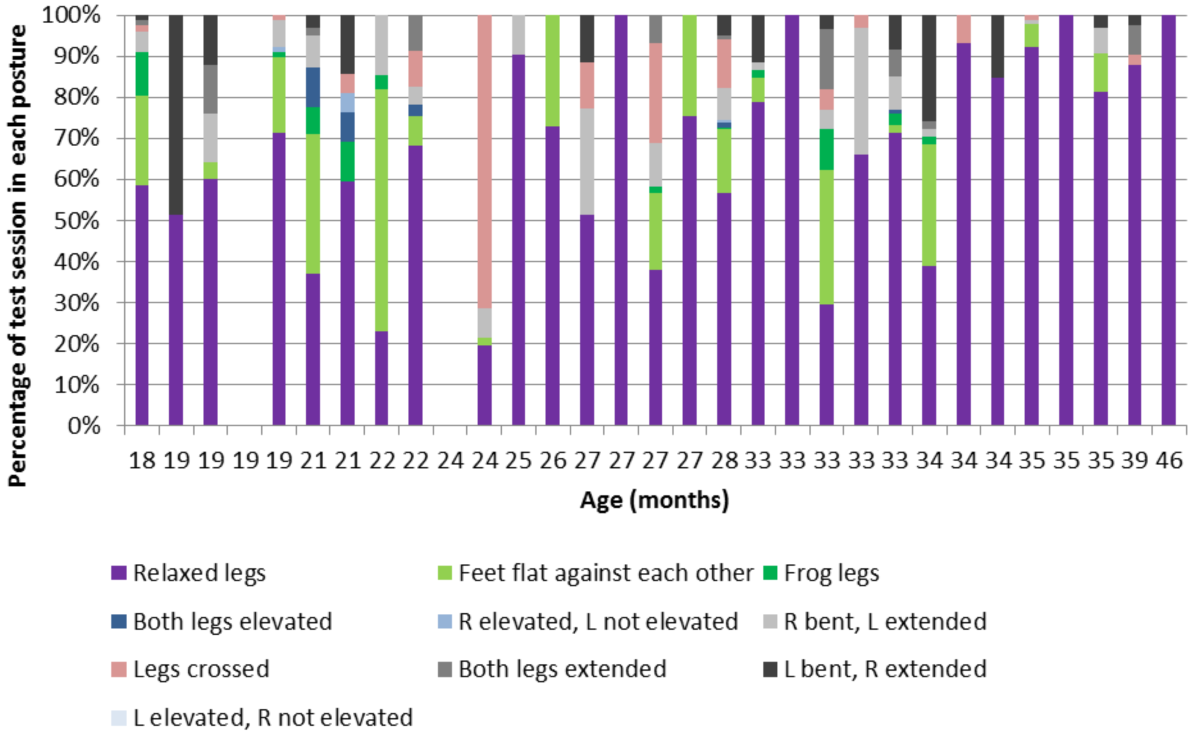


Figure 25. Percentage of forward-facing test conditions spent in each posture.

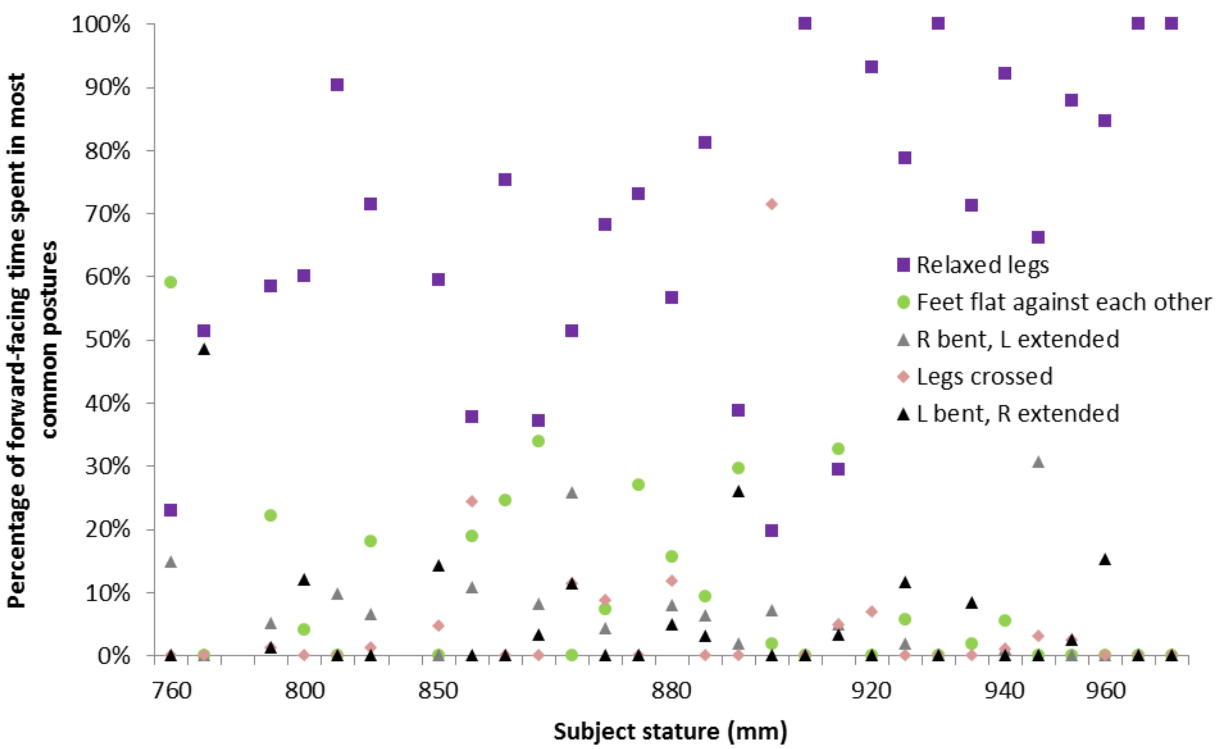


Figure 26. Most common postures selected by each subject in forward-facing test conditions (as a percentage of all tabulated postures).

Distribution of Measured Postures

Table 6 describes the subjects' orientation of the left and right lower extremity in the conditions where they were measured using the FARO arm. Some subjects were measured more than once, so the total is greater than 29 x 2. For the forward-facing postures, the frequency of each measured category is consistent with the observed categories throughout the test sessions. For the rear-facing postures, more children were observed in the legs crossed position, and fewer in the extended and frog positions, than might be expected based on the frequencies observed on time-lapse images throughout the session.

Table 6. Distribution of subjects by measured posture.

Posture	Forward-Facing		Rear-Facing	
	Left	Right	Left	Right
Crossed	5	6	6	4
Elevated			8	7
Extended	1	1	2	1
Flat	5	8	19	22
Frog	3	2	5	5
Relaxed	46	43	30	31
Total	60	60	70	70

Quantitative Postures

Rear-Facing

The following plots depict the lower-extremity postures drawn from the hip joint to the knee joint to the ankle joint. In all of these plots, orange depicts children less than 24 months, green shows children 24 to 30 months, and purple shows children older than 30 months. Two different representations are used to show the XZ orientation. For each pair of plots, the left one uses the lab coordinate system (CS), while the right one shows the plane of the lower extremity.

In Figure 27, the top row shows the rear-facing postures by age group in the narrow seat configuration while the second row shows the wider seat configuration. The oldest group seems most likely to have knees pulled towards chest. Figure 28 and Figure 29 show the differences between the wide and narrow seat pans (described under "Child Restraint Systems" in Methods). The narrower seat pan leads to less variation in lateral lower-extremity posture.

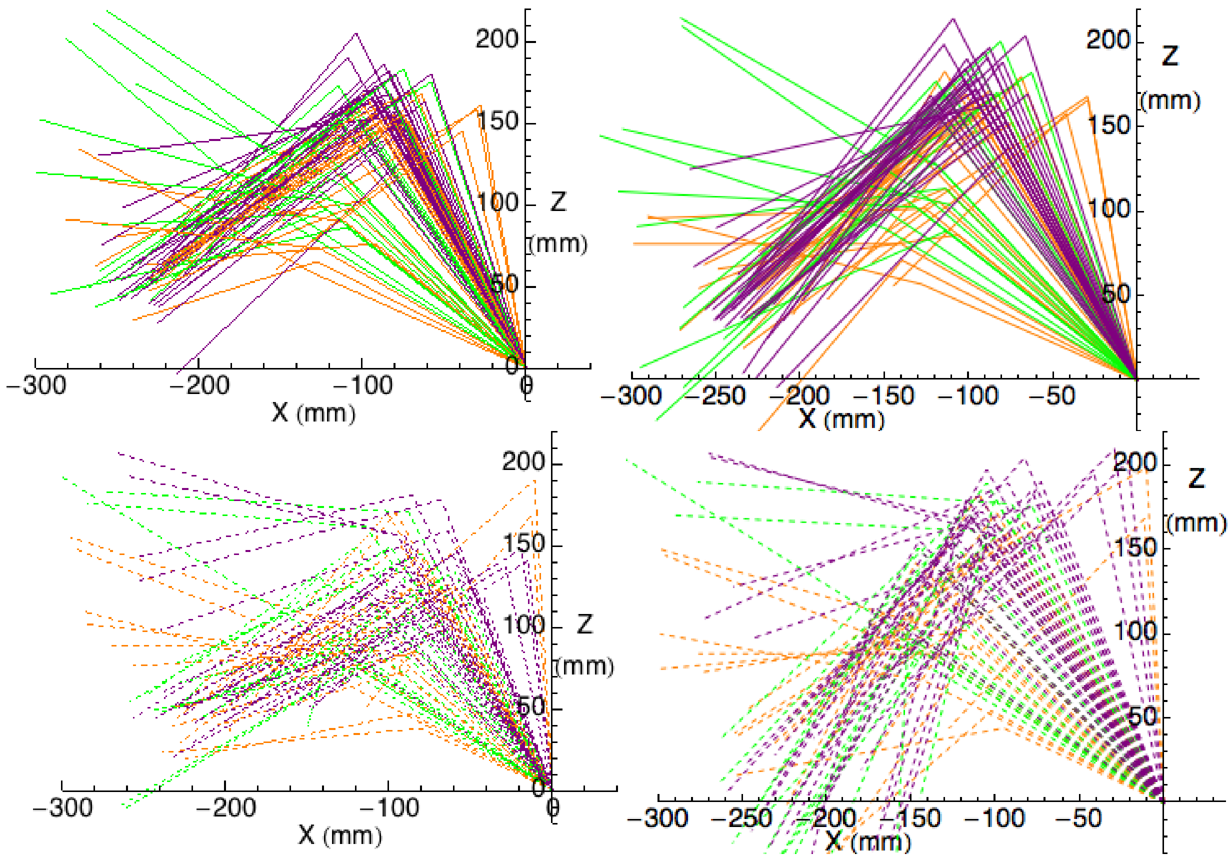


Figure 27. Rear-facing lower-extremity posture in narrower seat pan (top) and wider seat pan (bottom); (lab CS on left and in- plane of leg on right). Orange < 24 months, green 24-30 months, purple > 30 months.

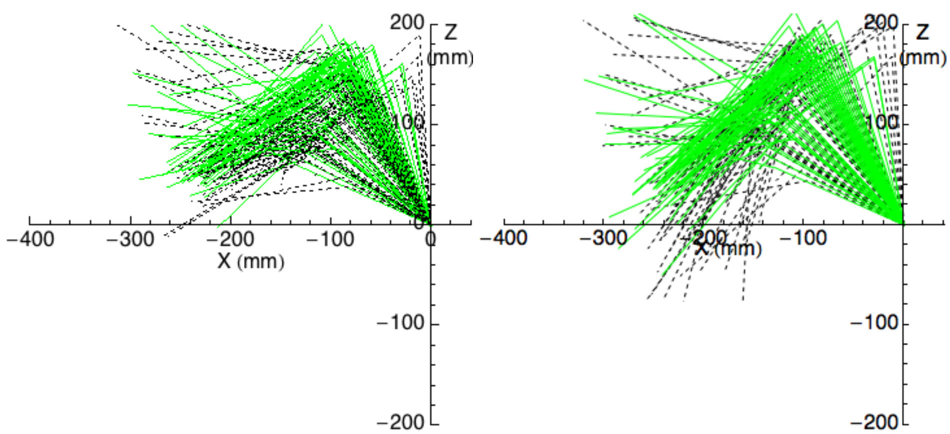


Figure 28. Rear-facing lower-extremity posture with narrower (solid green) and wider (dashed black) seat pans (in lab CS on left and in plane of leg on right)

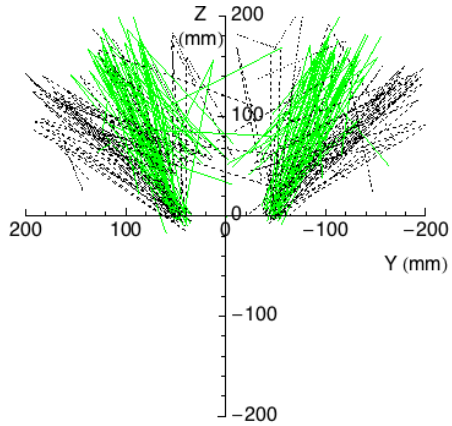


Figure 29. Rear-facing posture with narrower (solid green) and wider (dashed black) seat pans.

Figure 30 through Figure 33 depict the measured femur and knee angles by qualitative posture description. The femur YZ angle is the position of the femur when viewed from the front, while the femur XZ angle is the position of the femur when viewed from the side. The knee angle is the in-plane ASIS knee ankle angle. Because these three dimensions do not describe the orientation of the feet that was considered in the qualitative categorization, a gray circle around a data point indicates a "crossed posture," where any digitized points on the right foot are to the left of any left foot digitized points (and vice versa).

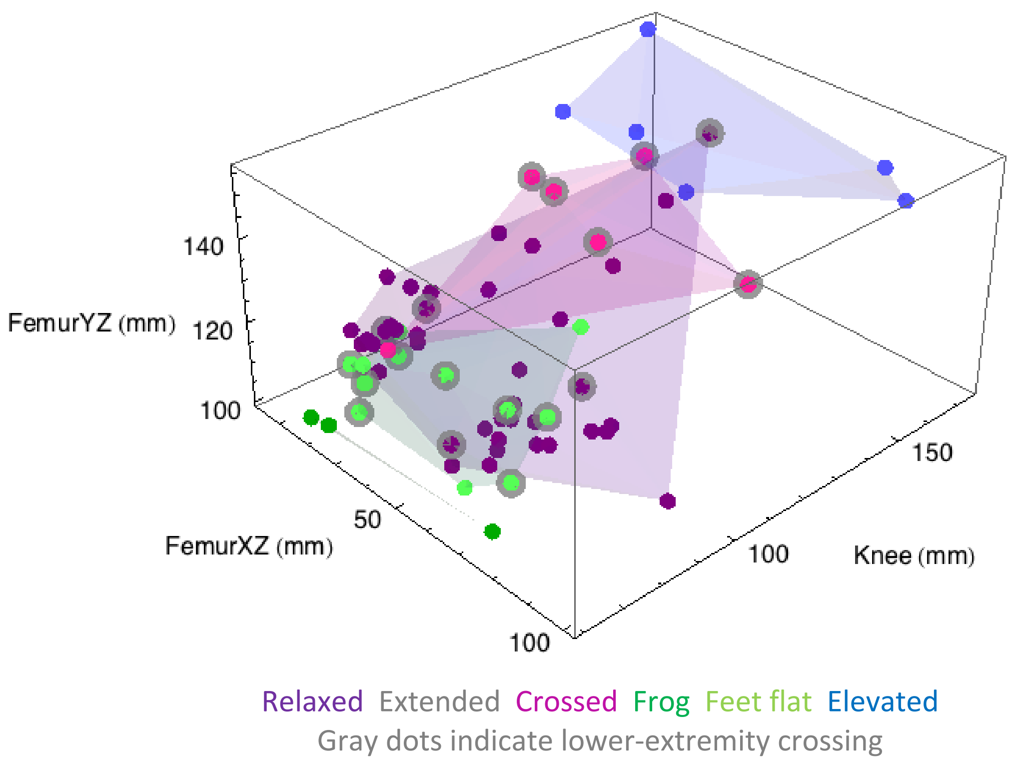


Figure 30. Isometric view of YZ and XZ femur angles (deg) versus in-plane knee angle (deg) for rear-facing postures.

The qualitative categorization is associated with the numerical groupings shown in these plots, although there is some overlap. The elevated and crossed postures have the largest values of in-plane knee angle, while the frog postures generally have the smallest. The elevated and crossed postures also have the highest values of femur YZ angle. Some of the relaxed postures also have higher values of femur YZ and in-plane knee angle, but do not have their feet crossing (gray dots). The feet flat postures have in-plane knee angles that overlap with the lower range of knee angles in the relaxed postures, but usually have a different foot positions. When considering the femur XZ angles shown in Figure 31 and Figure 32, most of the data points for each posture fall into two groups that are associated with the narrow and wide seat configurations.

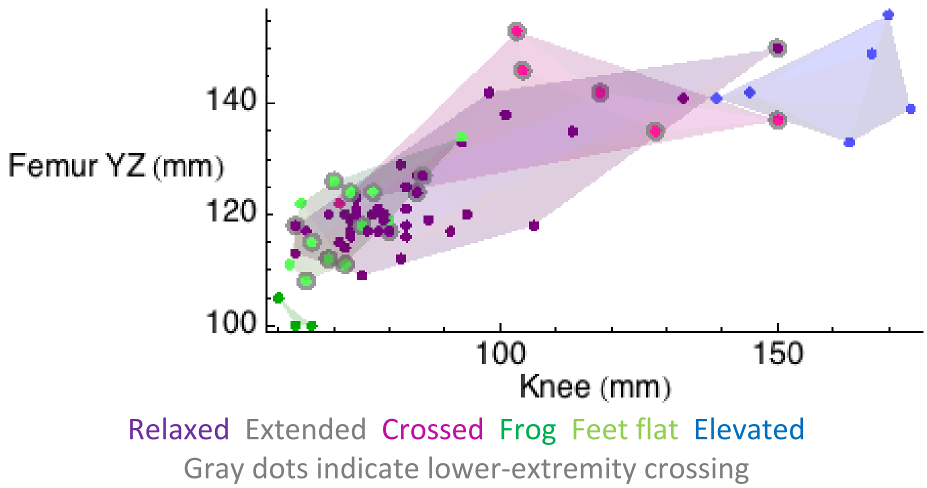


Figure 31. Femur YZ angle (deg) versus in-plane knee angle for rear-facing postures.

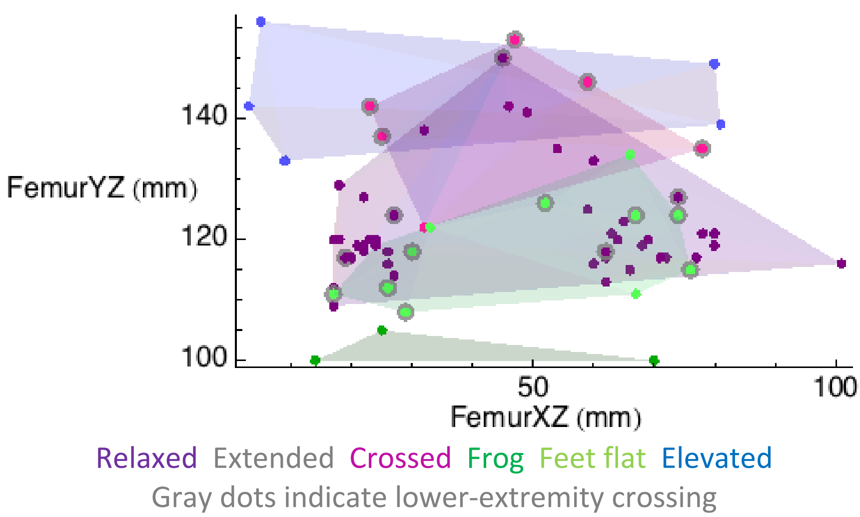


Figure 32. Femur YZ angle (deg) versus femur XZ angle (deg) for rear-facing postures.

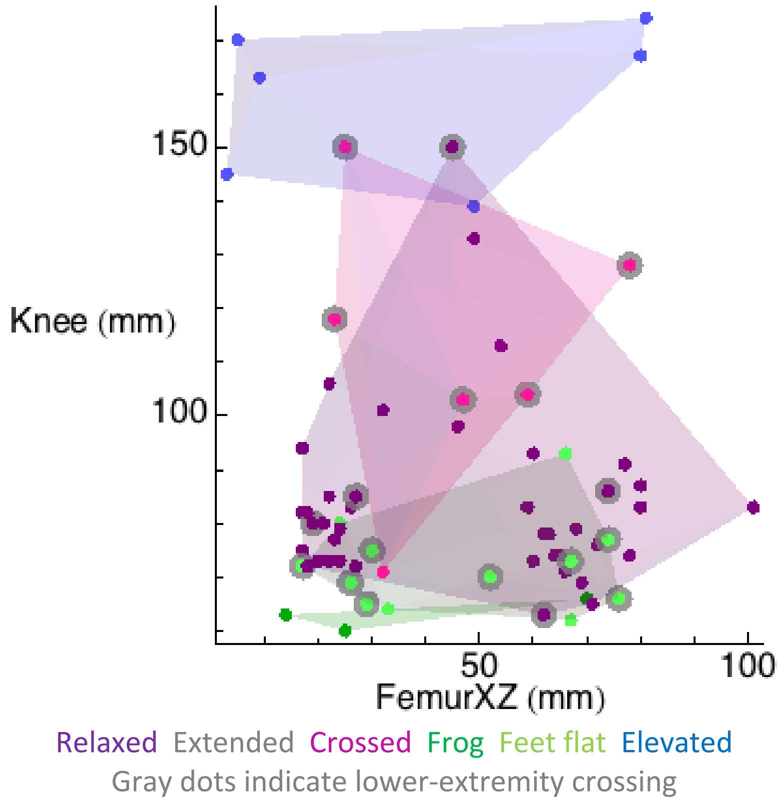


Figure 33. Femur in-plane knee angle (deg) versus femur XZ angle (deg) for rear-facing postures.

Figure 34 shows the distribution of rear-facing measured postures, considering left and right legs separately, according to age group. The frequencies of all of the measured postures were significantly different across age group (using chi-squared tests with $p<0.05$). The middle age group was most likely to choose the legs crossed position compared to the younger and older age groups. The 24- to 30MO age group was more likely to choose the elevated posture than the >30 MO age group. The <24MO age group was more likely to choose the extended posture than the other two age groups. The oldest age group was most likely to choose the feet flat posture, while the youngest age group was most likely to choose the frog posture. The middle age group was least likely to choose the relaxed posture.

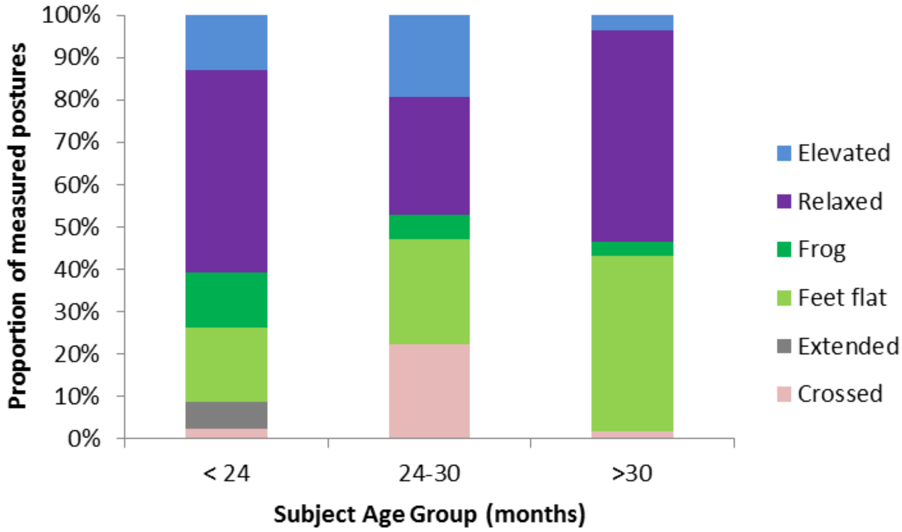


Figure 34. Distribution of rear-facing measured postures (left and right separately) by subject age group.

The distribution of rear-facing measured postures by category and seat pan condition, considering left and right postures separately, is shown in Figure 35. Legend entries marked with an asterisk are significantly different ($p<0.005$) between seat conditions. The narrow condition more often had subjects with lower extremities in a relaxed posture, while the wide condition had more children with their feet flat together or their legs extended.

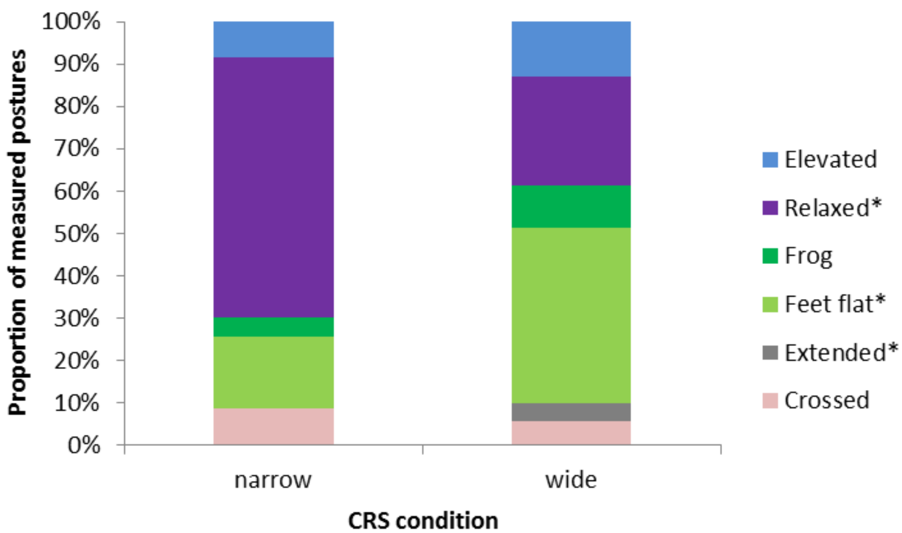


Figure 35. Distribution of measured postures (left and right separately) by rear-facing CRS condition. (* significantly different values between CRS condition)

The mean values of relevant angles by age group are shown in Table 7, as well as the number of subject extremities, standard deviation, minimum and maximum values. The shaded cells indicate a statistically significant difference with age group ($p<0.05$).

Table 7. Mean, N, standard deviation, minimum, and maximum angles (deg) by age group (shading indicates significant difference at $p<0.05$).

Age Group		Hip Knee Ankle Angle In Plane	ASIS Hip Knee Angle In Plane	Femur XZ 360 Ang From Left	Femur YZ 360 Ang From Rear	Pelvis XZ 360 Ang From Left	Pelvis YZ 360 Ang From LRear	ASIS Hip Angle XZ 360 Ang From Left	ASIS Hip Angle YZ 360 Ang From Rear	Thigh Plane YZ Angle 360 From Rear
1	Mean	97	65	128	89	178	137	55	88	198
	N	46	46	46	46	38	42	46	46	46
	SD	33	28	17	33	65	170	27	37	148
	Min	47	10	93	34	110	1	3	4	12
	Max	170	120	156	146	309	359	122	151	360
2	Mean	98	70	132	89	210	257	53	87	188
	N	36	36	36	36	36	36	36	36	36
	SD	35	22	12	34	64	159	23	37	141
	Min	43	30	109	37	96	1	9	11	12
	Max	179	109	150	151	285	359	100	153	356
3	Mean	73	58	120	91	203	234	69	95	186
	N	58	58	58	58	58	58	58	58	58
	SD	17	19	8	36	87	168	57	49	147
	Min	48	30	96	29	29	0	5	36	12
	Max	137	121	146	149	342	359	357	308	358
All	Mean	87	63	125	90	198	210	60	91	191
	N	140	140	140	140	132	136	140	140	140
	SD	30	23	14	34	76	172	42	42	145
	Min	43	10	93	29	29	0	3	4	12
	Max	179	121	156	151	342	359	357	308	360

For the same measures calculated for each seating condition, the only statistically significant measure was the in-plane ASIS-knee-ankle angle, which was 58 degrees (SD 25 deg) for the narrow seating condition and 68 degrees (SD 21 deg) for the wide seating condition.

Forward-Facing

The same conventions used for the rear-facing plots are also used for the following forward-facing plots. Orange depicts children less than 24 months old, green shows children 24 to 30 months old, and purple shows children older than 30 months. Segments represent the hip joint to the knee joint to the ankle joint. For each pair of plots, the left one uses the lab coordinate system, while the right one shows the plane of the lower extremity.

Figure 36 shows children seated in the longer seat cushion in the top two plots and in the shorter seat cushion on the bottom two plots. With the longer seat cushion, more children have their knees pulled closer to their chests, probably because the seat cushion is too long to accommodate their thigh length, especially for the youngest children shown in orange. With the shorter seat cushion, more children have their lower extremities in the relaxed posture. The shorter seat pan leads to less variation in lower-extremity posture.

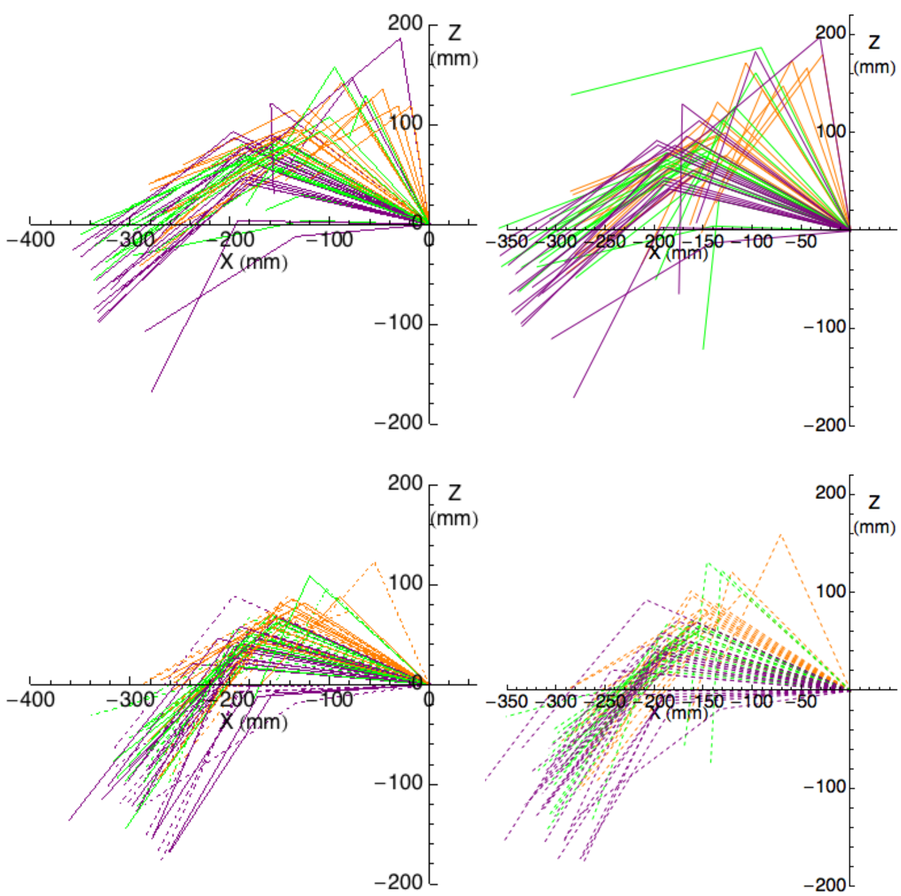


Figure 36. Forward-facing lower-extremity posture with longer seat cushion (top) and shorter seat cushion (bottom) (lab CS on left and in- plane of leg on right). Orange < 24 months, green 24-30 months, purple > 30 months.

Figure 37 and Figure 38 compare the postures in the longer (red) and shorter (blue) seat pans. More children choose the relaxed posture while forward-facing in the shorter condition compared to the longer condition.

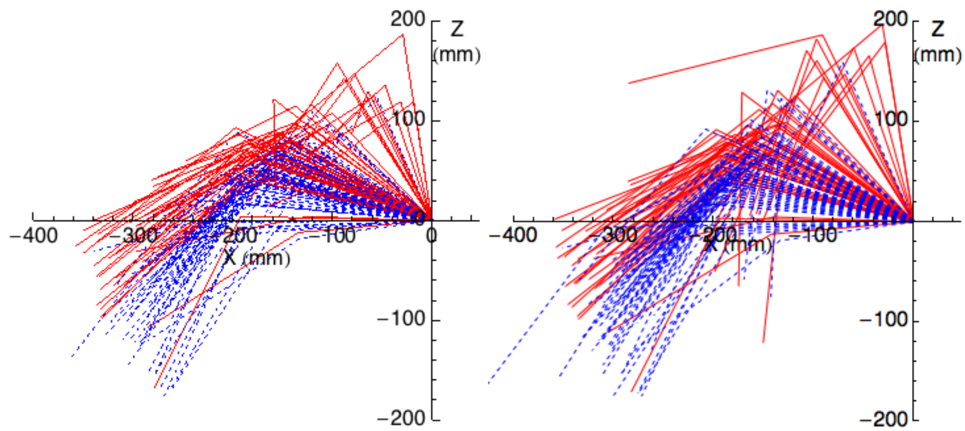


Figure 37. Forward-facing postures with longer (solid red) and shorter (dashed blue) seat pans in orthogonal XZ view on left and in plane of leg on the right.

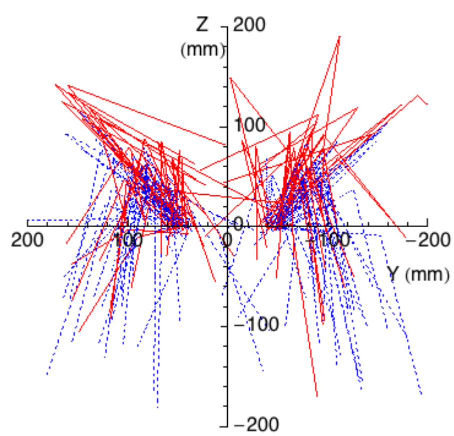
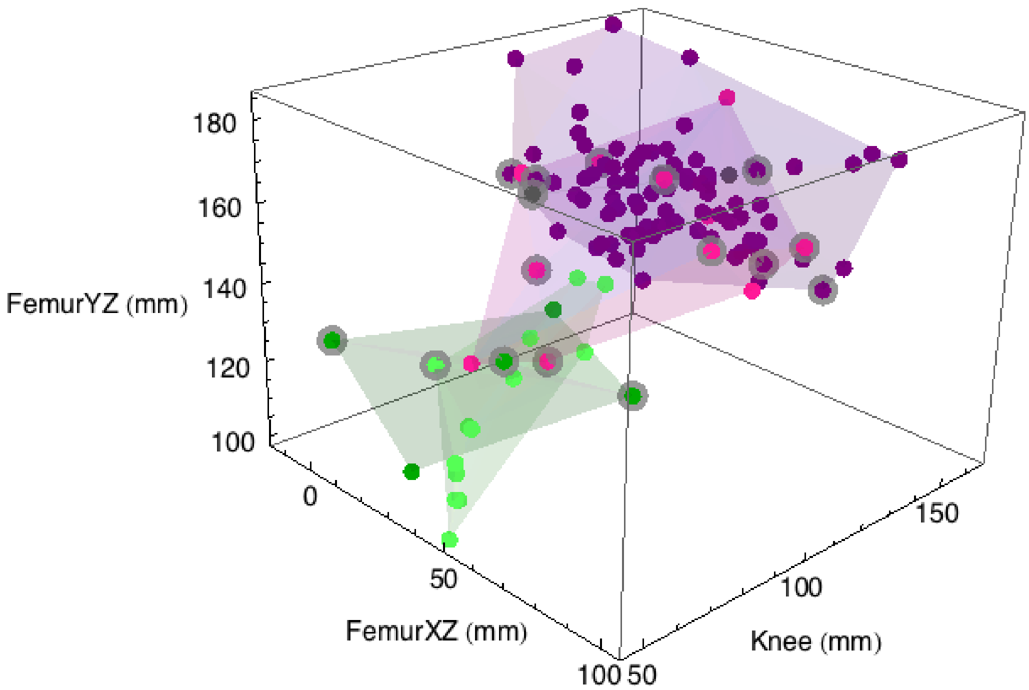


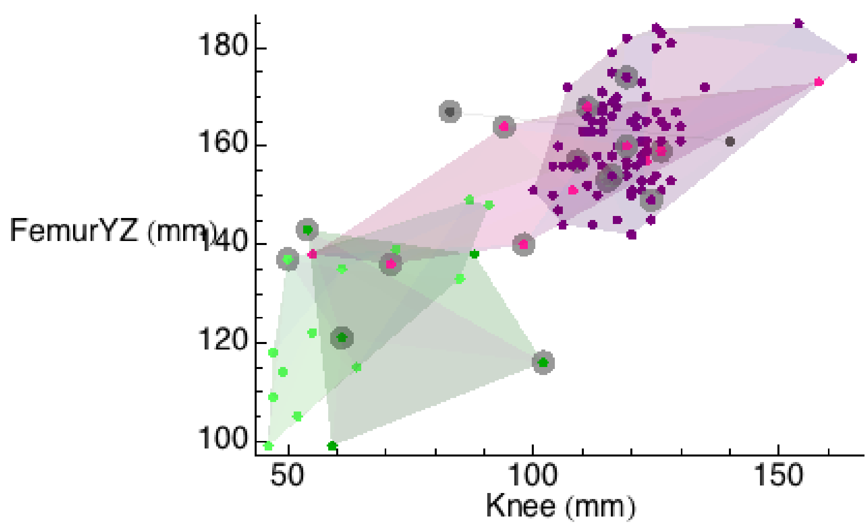
Figure 38. Forward-facing postures with longer (solid red) and shorter (dashed blue) seat pans in orthogonal YZ viewed from the front of subjects.

The femur XZ angle, femur YZ angle, and in-plane knee angle are compared in Figure 39 through Figure 42 by categorized posture for the forward-facing trials. Compared to the rear-facing postures, the range of values for each posture using these angles has less overlap. The frog and feet flat postures have smaller in-plane knee angles and femur YZ angles than the relaxed postures. The crossed posture overlaps among the relaxed and frog/feet flat zones.



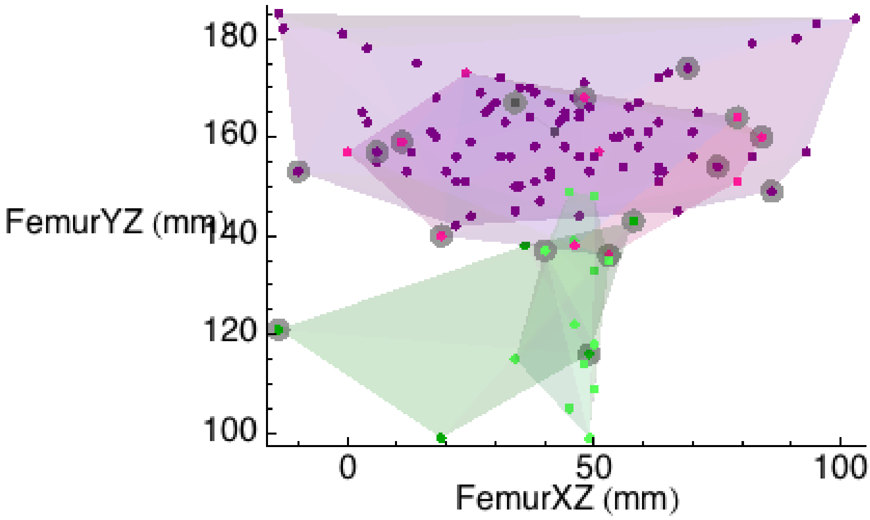
Relaxed Extended Crossed Frog Feet flat Elevated
Gray dots indicate lower-extremity crossing

Figure 39. Isometric view of YZ and XZ femur angles (deg) versus in-plane knee angle (deg) for forward-facing postures.



Relaxed Extended Crossed Frog Feet flat Elevated
Gray dots indicate lower-extremity crossing

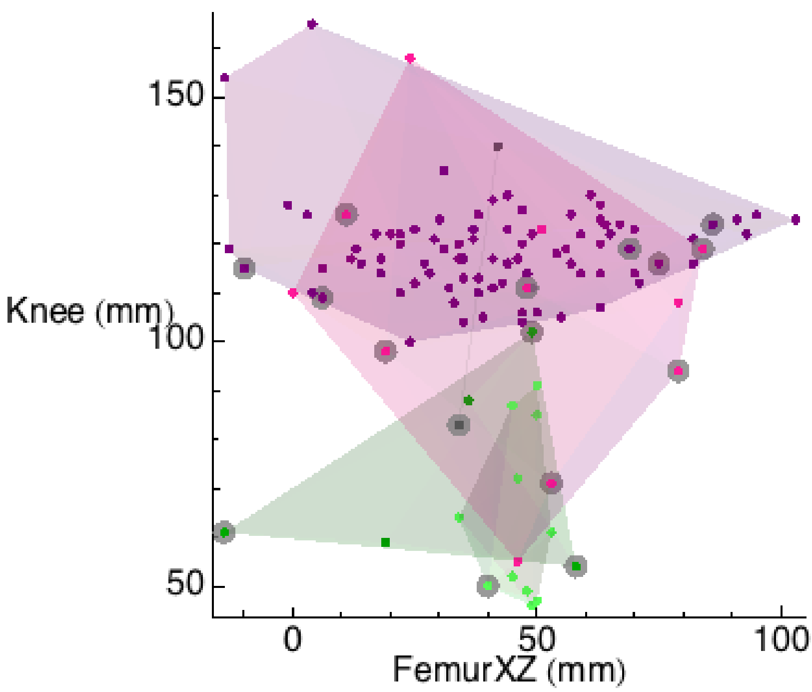
Figure 40. Femur YZ angle (deg) versus in-plane knee angle for forward-facing postures.



Relaxed Extended Crossed Frog Feet flat Elevated

Gray dots indicate lower-extremity crossing

Figure 41. Femur YZ angle (deg) versus femur XZ angle for forward-facing postures.



Relaxed Extended Crossed Frog Feet flat Elevated

Gray dots indicate lower-extremity crossing

Figure 42. In-plane knee angle versus femur XZ angle (deg) for forward-facing postures.

The distribution of measured forward-facing postures, considering left and right legs separately, is shown in Figure 43 according to age group. Except for the frog postures, each measured posture had statistically different frequencies* across age group ($p<0.05$). As in the rear-facing condition, the middle age group was most likely to choose the legs crossed position compared to the younger and older age groups. The middle group was also most likely to choose the extended posture. The youngest group was most likely to choose the feet flat posture. The oldest group was most likely to choose the relaxed posture.

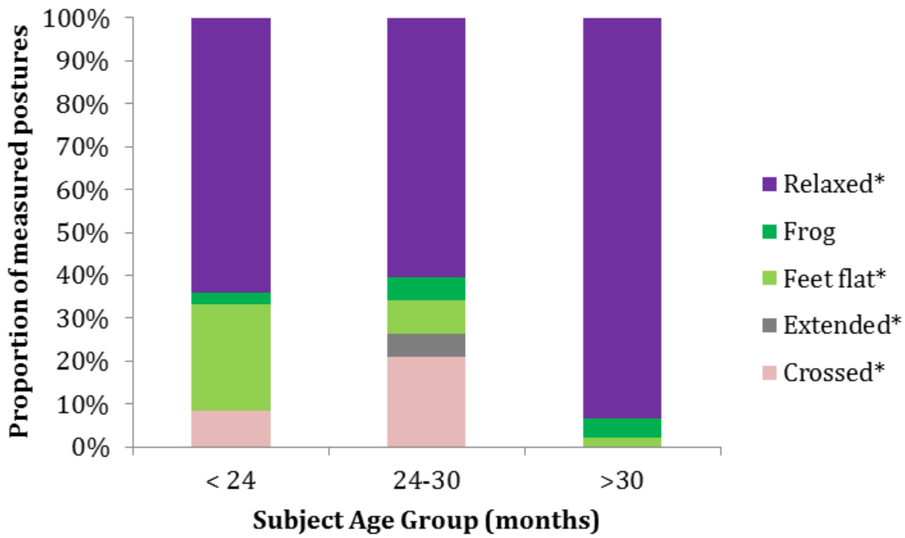


Figure 43. Distribution of measured forward-facing postures (left and right separately) by subject age group. (* significantly different values between CRS condition, $p<0.05$)

Figure 44 shows the distribution of measured forward-facing postures by category and seat pan condition, considering left and right postures separately. Only the frog and extended postures had a significant difference with seat condition at a $p<0.05$ level. The long condition had a higher likelihood of frog or extended postures.

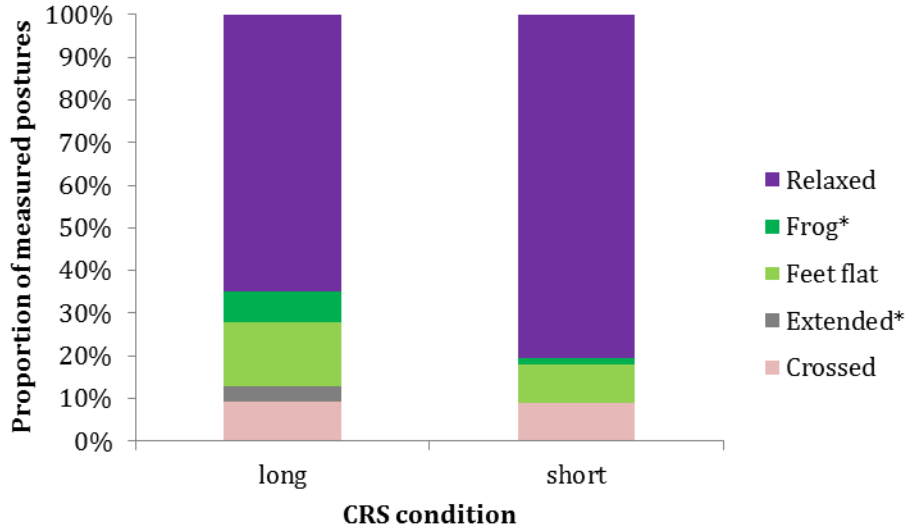


Figure 44. Distribution of measured postures (left and right separately) by forward-facing CRS condition. (* significantly different values between CRS condition, $p<0.05$)

Table 8 shows for each age group the mean values of relevant angles, the number of subject extremities, plus the standard deviation, minimum and maximum values. The shaded cells indicate a statistically significant difference with age group ($p<0.05$).

Table 8. Mean, N, standard deviation, minimum, and maximum angles by age group (shading indicates significant difference at p<0.05).

Age Group		Hip Knee Ankle Angle In Plane	ASIS Hip Knee Angle In Plane	Femur XZ 360 Ang From Left	Femur YZ 360 Ang From Rear	Pelvis XZ 360 Ang From Left	Pelvis YZ 360 Ang From LRear	ASIS Hip Angle XZ 360 Ang From Left	ASIS Hip Angle YZ 360 Ang From Rear	Thigh Plane YZ Angle 360 From Rear
1.0	Mean	99	75	144	86	191	199	63	87	217
	N	36	36	36	36	36	36	36	36	36
	SD	26	29	17	35	116	176	26	34	152
	Minimum	46	6	99	36	21	0	22	32	1
	Maximum	130	130	166	143	326	359	147	151	360
2.0	Mean	113	90	156	87	194	180	76	107	186
	N	38	38	38	38	32	36	38	38	38
	SD	24	17	13	40	94	178	67	64	164
	Minimum	50	56	116	4	55	0	25	36	1
	Maximum	165	136	178	159	346	359	354	351	360
3.0	Mean	115	90	164	119	230	282	68	87	201
	N	46	46	46	46	42	38	46	46	46
	SD	19	26	16	90	93	144	24	25	171
	Minimum	47	37	99	14	31	3	22	40	0
	Maximum	154	152	188	359	346	360	133	134	359
Total	Mean	110	85	156	99	207	221	69	93	201
	N	120	120	120	120	110	110	120	120	120
	SD	24	25	18	65	102	171	43	44	162
	Minimum	46	6	99	4	21	0	22	32	0
	Maximum	165	152	188	359	346	360	354	351	360

When the same measures were calculated for each seating condition, only one measure was statistically different. The femur XZ angle was 148 degrees (SD 19) for the longer seating condition, while it was 162 degrees (SD 13) for the shorter seating condition. These values agree with the trend of more children with their knees pulled toward their torso in the longer seating condition.

Comparison to ATD Postures

The ATDs were placed in the rear-facing test condition in three different postures: legs relaxed, legs elevated, and legs crossed. Figure 45 shows images of a child volunteer with the 18MO ATD and 3YO ATD in the legs relaxed posture. The 18MO ATD can be placed in this posture without any problems. However, when the 3YO ATD is placed in this posture, the feet must push against the rear vehicle seat back, and the upper thigh pushes against the abdomen flesh, causing the flesh to wrinkle from the applied force. Review of the child volunteer relaxed postures indicated that many of them placed their knees out with the feet wider apart. This version of the relaxed posture was more easily achieved with the 3YO ATD, and did not cause the same tension levels between the upper legs and abdomen.

Figure 46 compares relaxed postures of the children selecting this posture to the 3YO ATD. The child postures are shown in dotted green lines. The mean values of their angles were calculated, and then depicted in solid green lines using the same lower-extremity lengths as the 3YO ATD. The 3YO ATD position in relaxed posture is shown in black. When the child postures are scaled to match the dimensions of the ATD, the relaxed orientations are similar. Figure 47 and Figure 48 show all subjects' rear-facing postures, plus the 3YO ATD in the relaxed posture in black, and the wider relaxed posture in gray. Although the 3YO ATD postures have a larger XZ angle at the knee than most subjects, some children do choose postures similar to the 3YO ATD.

Figure 45. Legs relaxed position for a child volunteer (top), the 18MO ATD (left), 3YO ATD relaxed (middle), and 3YO ATD relaxed with feet apart (right)

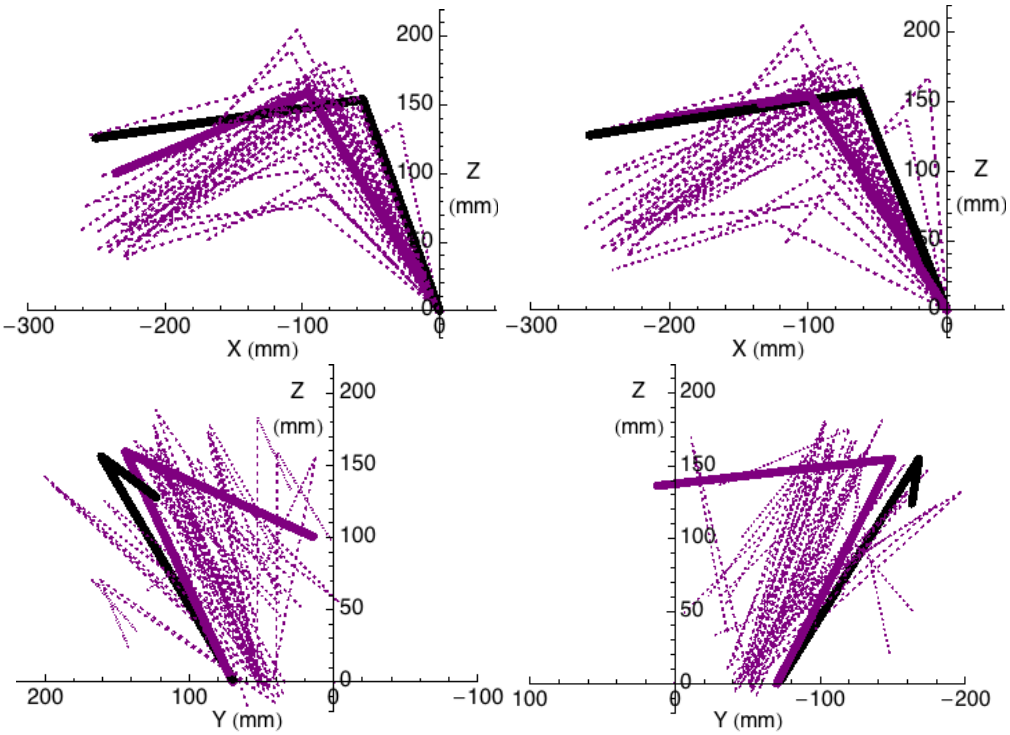


Figure 46. Relaxed child postures (dotted), mean child postures normalized to 3YO ATD lengths (solid purple), and 3YO ATD (black)) in “relaxed posture.”

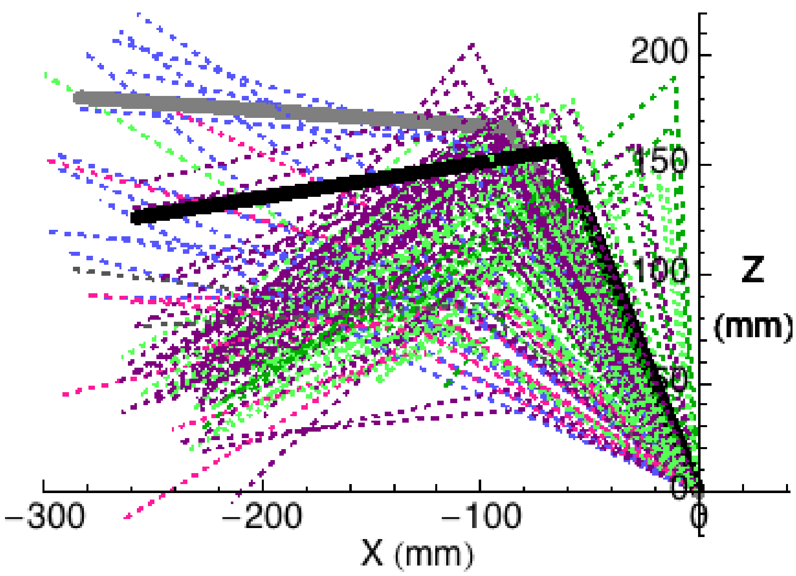


Figure 47. All subjects (both left and right) compared to 3YO ATD in relaxed (gray) or wider relaxed (black) postures.

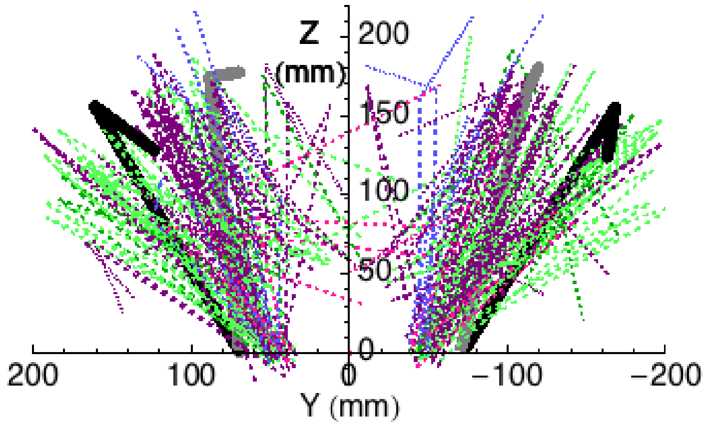


Figure 48. All subjects (both left and right) compared to 3YO ATD in relaxed posture (gray) and wider relaxed (black).

The legs elevated posture is shown in Figure 49. The 18MO ATD can be placed in this posture fairly easily. For the 3YO ATD, the lower extremities cannot be positioned parallel to each other (although not all child volunteers did so either), because the harness buckle interferes with the ATDs inner thighs. Figure 50 shows the orientation of the child volunteers who chose the extended posture (dotted blue), the position of the 3YO ATD (black), and the average orientation of the child volunteers, with lower-extremity dimensions adjusted to match those of the 3YO ATD.

Figure 49. Legs elevated position for volunteer child (top), 18MO ATD (left), and 3YO ATD (right).

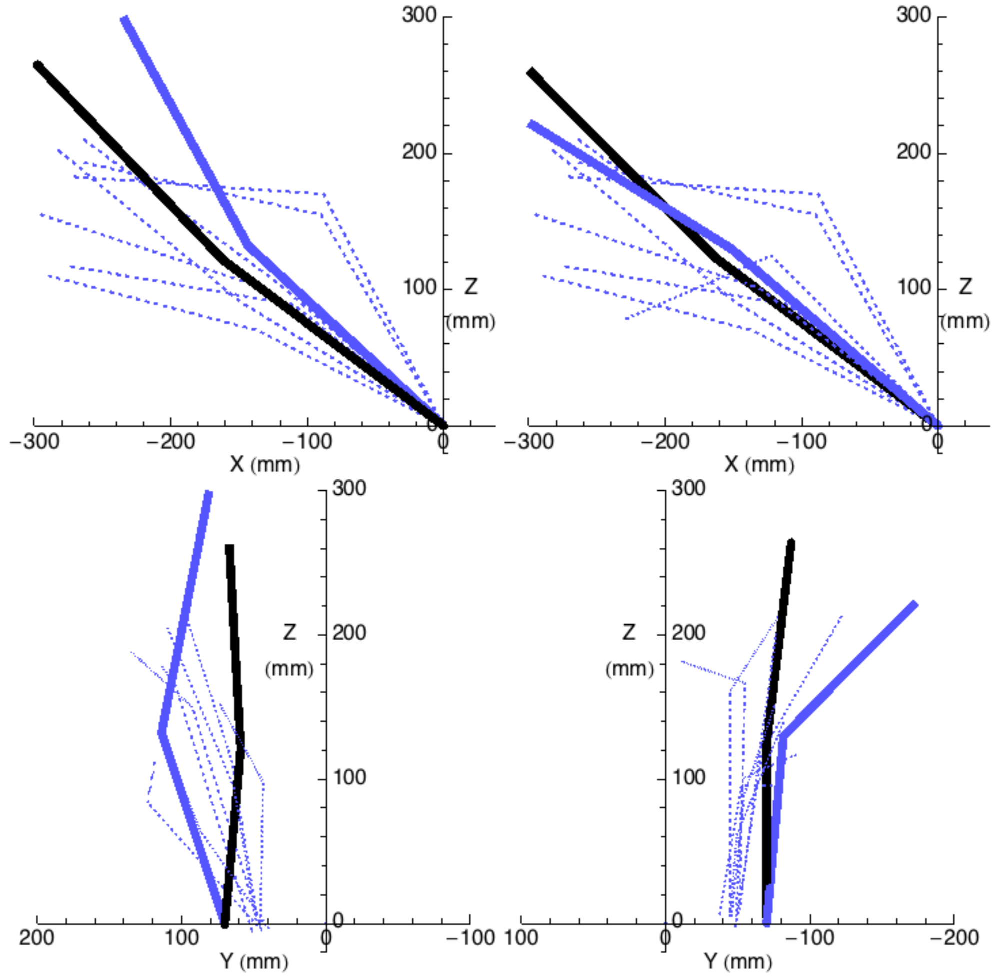


Figure 50. Extended child postures (dotted), mean child postures normalized to 3YO ATD lengths (solid blue), and 3YO ATD in extended posture.

The legs crossed posture is shown in Figure 51. Although the child volunteers often crossed their legs (as shown), they also often put their feet together with their knees out in a similar way. The 18MO ATD could be placed in this position fairly easily. The 3YO ATD could also be placed in this position, with the maximum angle limited by interference between the thigh and pelvis flesh. The 3YO ATD feet were pushing on the seat back, but not as severely as in the "legs relaxed" posture shown in Figure 45. For the 3YO ATD, the ability to achieve this posture may be affected by the width of the child restraint. To examine this possibility, the 3YO ATD was also placed in the legs crossed posture using the inserts to simulate a narrower seat width as shown in Figure 52. It was possible to place the 3YO ATD lower extremities in a posture resembling the child's, either with ankles crossed or feet touching. But there was more severe interference between the upper thigh and pelvis flesh as seen by wrinkling in the torso. In addition, when the legs were bent further back to accommodate the narrower seat width, the buckle could not be fastened as shown in Figure 53.

Figure 51. Legs crossed posture of child volunteer (top), 18MO (left), and 3YO (right).

Figure 52. Alternate attempts to place 3YO in crossed leg posture using narrower seat width. Note wrinkling of flesh in the torso due to posterior rotation of the pelvis resulting from force applied at the feet.

Figure 53. In legs-crossed posture, thigh interference prevents buckle from closing.

Figure 54 and Figure 55 compare the children choosing cross-leg and frog-leg postures, their average values scaled to match 3YO ATD lengths, and the configuration of the 3YO ATD in the closest posture.

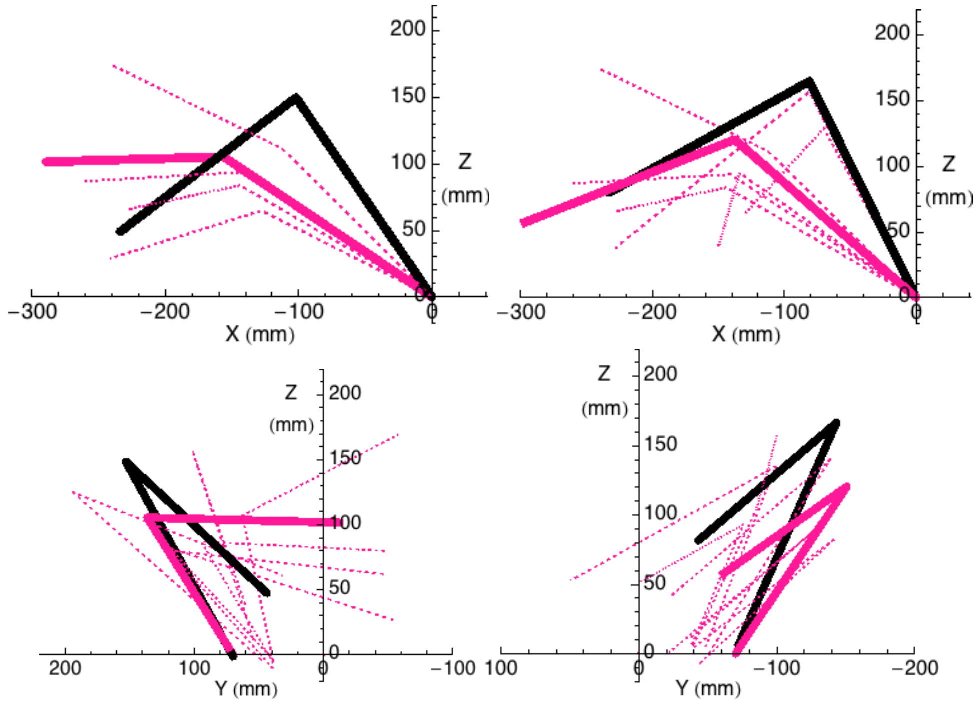


Figure 54. Crossed-leg child postures (dotted), mean child postures normalized to 3YO ATD lengths (solid pink), and 3YO ATD in attempt at crossed legs.

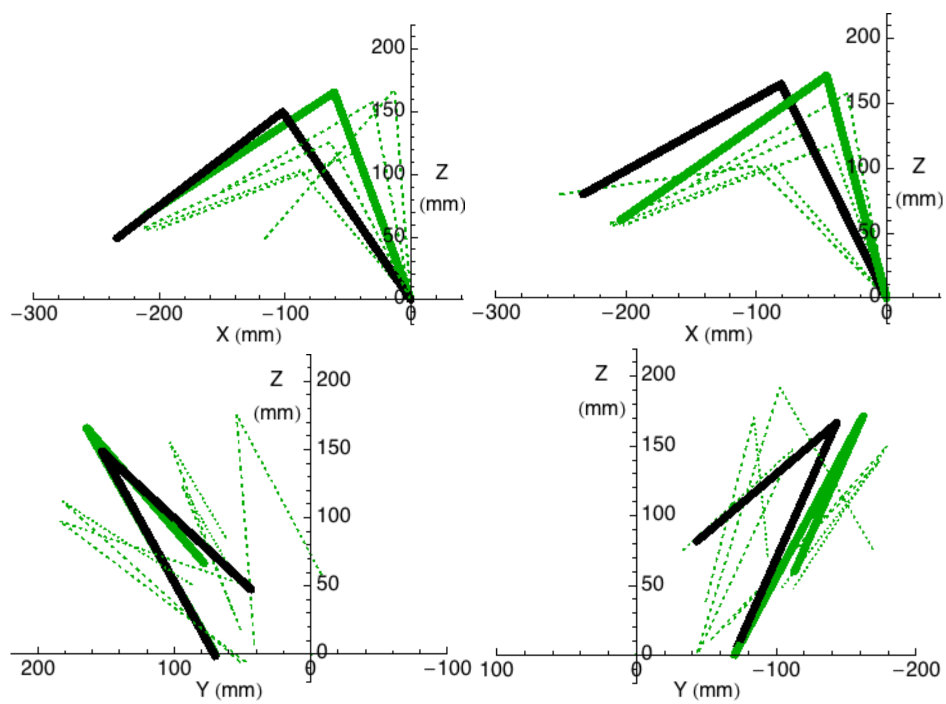


Figure 55. Frog leg child postures (dotted), mean child postures normalized to 3YO ATD lengths (solid green), and 3YO ATD (black) in attempt at frog legs.

DISCUSSION

This study of child posture in harnessed child restraints is the first to quantify child lower-extremity postures across a range of CRS conditions. Five lower-extremity posture categories of relaxed, feet flat, crossed, frog, or elevated account for 80 percent of the postures selected by forward-facing children and 88 percent of rearward-facing children. Significant differences in the frequencies of posture categories were associated with child restraint geometry. In the narrow rear-facing condition, children were most likely to sit in a relaxed posture. With the wide condition, the most common measured posture was feet flat together, with legs splayed more outward (as visible in Figure 29). Children also were more likely to choose a “frog legs” posture with the wider seat. From the general trends with child restraint width, toddlers seem to splay their legs until they are limited by the inner structure of the child restraint.

Cushion length affected the posture distributions. Less variation in posture was observed with the short cushion length, with more than 80 percent of subjects choosing the relaxed posture. With the longer cushion length, the younger children in particular were more likely to choose a frog leg, feet flat, or crossed leg posture. The cushion length was likely longer than their thigh length, which may have made bent-knee postures more comfortable.

Some of the rear-facing postures observed with children could not be achieved with the ATDs because of interference between the pelvis and thigh flesh. In other conditions, the posture could be achieved but the harness buckle could not be fastened. For several cases, the legs could be positioned in a realistic child posture but excessive pressure between the ATD feet and vehicle seat back was needed to maintain the position.

To allow frequency comparison of the measured postures to those observed throughout the test session, the same investigator qualitatively classified the measured and observed postures for all subjects. When classifying posture qualitatively, the investigator first considered foot position as elevated, extended, crossed, or feet flat. He then visually identified those in frog posture who pulled their femurs towards the chest, or in relaxed posture, with femurs resting on the child restraint surfaces. The classification strategy was somewhat influenced by the knowledge that the study results would be used to guide placement of the ATDs lower extremities during impact testing. Quantitative analysis showed some overlap in measured angle values for some posture categories, particularly in rear-facing trials. While it may have been reasonable to reclassify some measured postures based on the measured data, it would then provide a less consistent comparison of the distribution of measured postures versus observed postures.

When performing a quantitative comparison of the ATD and child postures, we selected the children who chose a particular posture, calculated their average angles, and plotted an average child posture using the lengths of the ATD hip-to-knee joint and knee-to-ankle joint. When these scaled, averaged postures are compared to those achieved with the 3YO ATD, the frog leg, extended, and relaxed positions of the ATD are similar to those of the children.

This study did not identify any factors indicating that children restrained rear-facing might be at higher risk of lower-extremity injury during crashes. We have not been able to identify any case reports in the literature indicating a serious lower-extremity injury to a larger rear-facing child. In contrast, Bennett, Kaufman, Schiff, Mock and Quan (2006) and Jermakian, Locey, Haughey, and Arbogast (2007) have analyzed crash data for children in forward-facing harnessed restraints and identified contact between the lower extremities and back of the front seat as a mechanism for lower-extremity injury to forward-facing harnessed occupants.

This study had several limitations. The study was performed in a laboratory setting using a surrogate vehicle seat cushion and a single seat back angle. Results may not apply to the variations in rear seat geometry and stiffness seen across vehicles. Child restraint configurations included only two rear-facing and two forward-facing conditions, which may not represent the variety of conditions available in the child restraint market. The attempt to measure the voluntary range of motion of the lower extremities was not successful because of likely shifting of the pelvis during the movement and the inability of the subjects to maintain steady during posture measurement.

CONCLUSIONS

This study documented the posture of children 18 to 36 months old in rear-facing and forward-facing harnessed child restraint configurations. Results confirm that children usually change their lower-extremity posture frequently when seated in child restraints. Their posture selections are affected by their age, the width, and length of the child restraint cushion. Although the lower extremities of the 3YO ATD could not be placed to match the extreme conditions selected by children, they could be positioned to represent several typical lower-extremity postures chosen by the subjects.

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