CHALMERS

Kinematics and shoulder belt position of child volunteers when exposed to steering manoeuvres in different restraint systems

Master's Thesis in Biomedical Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

In car crash scenarios, the head is the most frequently injured body region among children. The main injury mechanism for rear seated restrained children, aged 3-13, who sustained head injuries rated AIS2+, has been found to be the contact of the head with the seat back or with other parts of car interior. Previous studies showed that pre-crash manoeuvres could influence the injury outcome.

This thesis quantifies the static belt measurement and the kinematics of child volunteers exposed to steering manoeuvres when restrained on different types of booster cushion. A study was conducted on a test track with 18 children divided into two groups based on their stature. Each child was tested for the static belt measurement on three different booster cushions and performed two steering manoeuvres on each of two of these boosters. Cameras were used to monitor the child during the event. Different parameters were extracted from the videos in order to analyse the kinematics of the child.

From the static belt measurement arose that tall children can achieve a better belt fit than short children, especially in terms of shoulder belt position and its "grabbing" effect.

The analysis of the kinematics showed that head and torso moved inboard in different ways. The position of the belt on the shoulder was also considered throughout the steering event. The belt slip off the shoulder in 11 trials out of 18 for short children when restrained on the accessory booster, while the slip off occurred only in 2 trials when restrained on integrated booster. For tall children no belt slip off occurred regardless of the type of booster cushion.

Key words: pre-crash, steering, child, volunteers, booster cushion

Contents

Preface

This study was carried out at the Division of Vehicle Safety, Department of Applied Mechanics, Chalmers University of Technology in Göteborg, Sweden, as part of a larger project at SAFER Vehicle and Traffic Safety Centre.

The work behind this thesis would not have been possible without the people also involved in this project. I would like to thank especially my supervisor Isabelle Stockman for her support and advices.

Göteborg, July 2013

Elisa De Faveri

1 Introduction

Every year, in the world, 1.2 million people are killed in road traffic accidents. Between 20 and 50 million people in the world sustain severe injuries as a result of road traffic accidents, whereas in Europe the number of injured people is 2.4 million each year (WHO, 2009). In Europe, traffic accidents are the most important cause of mortality and non-fatal injuries leading to disability in children and every year 32 000 people younger than 25 years are killed in traffic injuries (WHO, 2007). More precisely, of the road related deaths for children aged 0 – 14 in the WHO European Region, 32% occurred in car occupants (WHO, 2008).

Statistics show that 30% of 10-year-old children were seated in the passenger front seat when traveling in passenger vehicles (CHOP, 2010). The risk of sustaining injury in a frontal car crashes for these children is 40% higher than for those seated in the rear seat (CHOP, 2010). Furthermore, children seated in the centre position in the rear seat are 43% less likely to sustain injuries in a side crash than those seated in outboard position (Kallan et al. 2008).

The head is the most frequently injured body region for children in car accidents regardless of crash direction (Bidez et al. 2007) leading to death or long term disability (Bohman et al. 2011a). The most common head injury mechanism for rear seated restrained children is head contact with the side interior of the car and with the seat back of the front seats (Bohman et al. 2011a). In fact, Bohman et al. (2011a) identified head to front seat back impact as a predominant cause of head injury for rear seated, seat belt restrained children, aged 3 – 13, who sustained AIS2+ head injuries in frontal impacts. In most of the cases a head contact with the car interior or seat back occurs as a consequence of a change in the child's position before the impact, e.g. moving forward or moving towards the middle of the passenger compartment, due to a previous manoeuvre as steering or braking (Bohman et al. 2011a). As a result of the inboard motion, the shoulder portion of the seat belt may move far out on the shoulder leading to a non-optimal restraint of the child (Bohman et al. 2011b). To decrease the severity of head injuries in car crashes the restraint of the torso needs to be improved (Bohman et al. 2011a).

The relative protection for belted occupants provided by the rear seat over the front seat has declined in newer vehicle models indicating that rear seat occupant protection has not kept pace with front seat safety system development and improvements (Bilston et al. 2010). There is a great need to focus on safety in the rear seat to enhance knowledge in order to adapt vehicle restraint systems to provide an optimal protection for children (Bohman 2013). Since the end of 1990s many devices have been developed in order to improve the front seats safety, reducing the injury risk for adult belted occupants in the front seats, but in a study by Bilston et al. (2010) it has been shown that for kids from 9 to 15 years old rear seats are still safer than the front ones.

A study by Isaksson-Hellman et al. (1997) describes the trend and effectiveness of using Child Restraint Systems (CRS) between 1976 and 1996. During these 20 years in Sweden the use of CRS has increased leading to a decreasing risk of injury for child occupants (Isaksson-Hellman, 1997). Nevertheless, injuries among restrained children still occur. This can be explained by the fact that the CRS might be improperly used. This has been shown in a study by Osvalder and Bohman (2008), in which the potential misuse of booster cushions has been investigated. The results of this study showed that for the booster cushion a misuse occurred in 77% of cases, with mainly incorrect positioning of the lap belt, whereas for the integrated booster cushion the misuse occurred only in 4% of the cases (Osvalder and Bohman, 2008).

In a previous study, Bohman et al. (2011) analysed the kinematic response and the shoulder belt position of rear seated children during steering manoeuvres. The results showed that for most of the short children (aged 4 – 6) seated on a booster cushion the shoulder belt slipped off the shoulder during the swerve, whereas for tall children (aged 8 – 10) no shoulder belt slip off occurred (Bohman et al. 2011b). The difference in kinematics between the group of tall and short children indicates a need to further investigate the shoulder belt restraint effect on children of different sizes. It is clear, then, that further studies are needed to improve both design and use of child restraint systems.

1.1 Child anatomy

The child's anatomy, in terms of body dimension and biomechanical properties, is very different from an adult's one. For this reason a child can't be considered as small version of an adult. At birth, the brain represents 25% of its adult size, even if a child's body weight is 5% of the adult's weight, and during the first two years of life the brain reaches 75% of its adult size (Burdi et al. 1969). Furthermore, at birth the head represents 1/4 of the body's total length, as shown in Figure 1. Since the child's head is proportionally larger and heavier than an adult's head, the centre of gravity is higher in a child (Tarrière, 1995).

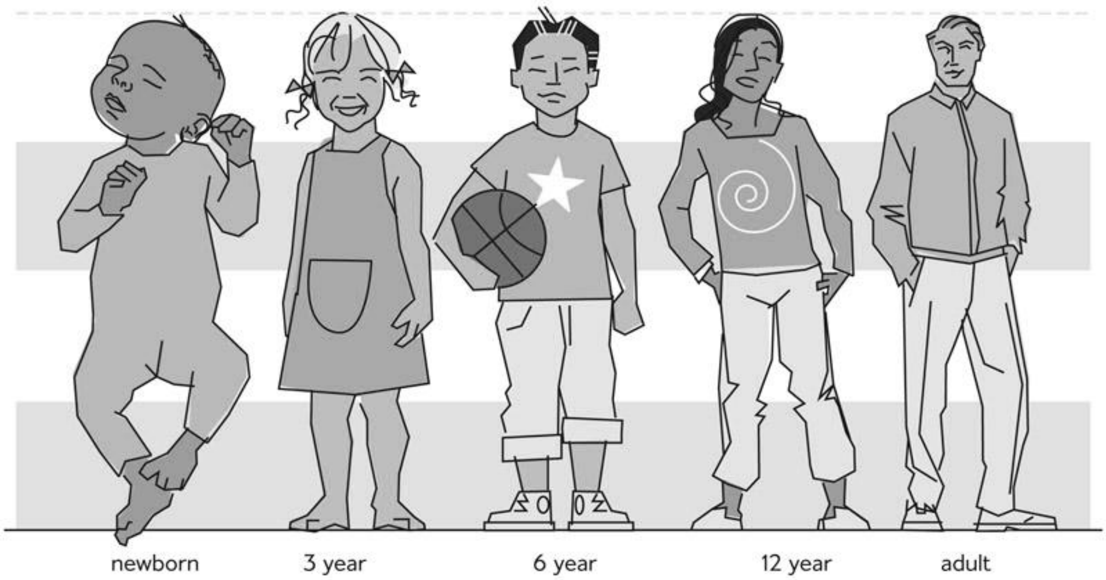

Figure 1 - The proportional changes in body segments with age (courtesy of Volvo Car Corporation).

In a child, the neck muscles are not fully developed yet and their strength increases with age. Hence, the neck is not strong enough to support the violent movements of the head during a car crash. At birth, the neck vertebrae are joined by cartilage and then they fuse during the first years of life: vertebrae C3-C7 fuse during the third year, while C1 and C2 do not fuse until age 4 – 6 (Klinich et al. 1996).

Children subjected to impact to the chest usually sustain injuries to the internal organs of the thorax due to a poor protection given by the rib cage. A child's rib cage is more flexible and the chest wall is thinner than in an adult and, therefore, an impact to the child's thorax can lead to larger chest wall deflections and reduce the probability of rib fracture, however, probability of thoracic organ damage from compression increases (Burdi et al. 1969). A child has a smaller pelvic bone, shorter thigh length and less pronounced iliac wings compared to an adult (Burdi et al. 1969, Tarrière, 1995). With the smaller rib cage and pelvis of the child, the abdominal organs are more exposed than for an adult and can more easily be injured (Burdi et al. 1969).

Since a child's body is weaker than an adult's one, the loading of the body in a restraint system must occur where the body is stronger, e.g. on the skeletal structures (Burdi et al. 1969). Thus, a good belt fit position is achieved when the lap and shoulder parts of the seat belt load skeletal structures. The shoulder belt should load the clavicle and be as close as possible to the child's centreline without touching the neck. If the shoulder belt is too far out on the shoulder it may likely slip off in the moment of the impact leading to a poor restraint of the torso and if it's touching the neck it can causes a discomfort such that the child may put the belt behind the back (Reed et al. 2009). The lap belt should load the pelvis. If it is placed too high up on the abdomen there is a high risk of submarining during the crash resulting in abdominal injuries, whereas if it is too far forward on the thighs the body may not be restrained properly leading to a large excursion and a high acceleration of the occupant (Reed et al. 2009).

1.2 Child Restraint Systems

A Child Restraint System (CRS) is a special child seat whit the aim to protect the child from injuries in a motor vehicle crash. There are different types of CRS (Figure 2) depending on the size of the child, direction of traveling (rearward-facing or forward-facing) and type of internal restraint, for example an internal harness (Weber, 2000). The first rearward-facing child restraint system was introduced in 1964 with the purpose of supporting the spine and head (Aldman, 1964). Since 1960s the rearward-facing seats have experienced a development, which improved their usability. Rearward-facing child restraint systems can be divided into two groups: infant seat and rearward-facing child seat. The second group, mainly present in the Scandinavian regions, is addressed to children aged 1– 4 (Jakobsson et al. 2005). For the smallest children rearward-facing is the safest way of traveling (Jakobsson et al. 2005), because a child's anatomy is different from an adult as mentioned before, especially the weight of the head compared with the total body weight and strength and development of the neck (Burdi et al. 1969). At the age of 3 – 4 years the child can sit forward facing since the head mass is proportionally less than the body's mass, compared to younger children, and the neck is stronger, even if differences with adults' anatomy are still present (Jakobsson et al. 2005).

Forward facing integral harness type is a very common CRS used in many countries, for children from 1 to 4-5 years old, except in the Scandinavian regions.

Forward-facing CRSs are also represented by belt positioning boosters divided into backless Booster Cushions (BC), booster seats with backrests and Integrated Booster Cushions (IBC), and they are used with the normal vehicle seat belts (Jakobsson et al. 2005). The purpose of the belt positioning boosters are to raise the child on the vehicle seat, improve the seat belt positioning and contribute to keep the belt in position during an impact and, last, the booster controls the child's posture reducing the range of possible positions (Reed et al. 2009).

Integrated booster cushions are available in some cars since 1990 (Jakobsson et al. 2005). A study by Osvalder and Bohman (2008) identified the IBC as a better restraint system, both from safety and comfort aspects, compared with an accessory booster, because of its lower misuse rate (Osvalder and Bohman 2008).

When the child reaches the stature of approximately 140 cm, adult seat belt can be used without booster (Jakobsson et al. 2005). In other countries, as in Italy, the use of BCs is recommended until the child reaches 150 cm of stature.

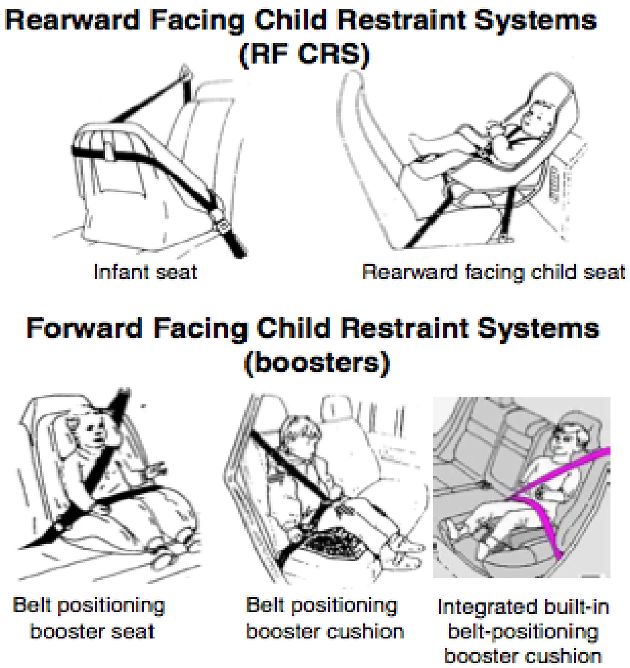

Figure 2 - Different types of restraint systems (Jakobsson et al. 2005).

A proper use of CRS can nearly eliminate seat belt-related injuries to abdomen and spine (Durbin et al. 2003), but it's known from field test that children vary continuously their seating position (Bensten 1971) and they may assume a suboptimal posture on the booster which may lead to a suboptimal restraint during an impact. Andersson et al. (2010) performed a naturalistic study in order to better understand the behaviour of children while seated on boosters during on-road traveling. Six children aged 3 – 6 were positioned in highback boosters in the rear seat while a parent drove the car. The study comprised two different booster designs: one equipped with large head and torso side supports, and one equipped with small head side supports without torso side supports. They found that the design equipped with large side head supports more often resulted in a seated posture without the head and shoulder being in contact with the booster's back, resulting in the head being further away from the seat back. It has been shown that in general children assume a wide range of different positions and some of them may result in a less effective protection in a crash, as putting the belt under the arm or seated with the head further forward in the seat (Andersson et al. 2010).

1.3 Emergency steering manoeuvres

Some of the drivers in a pre-crash situation have a preview that a crash is going to occur. Releasing of the acceleration pedal, steering, braking and head and neck withdrawal are the most common driver's action just before the crash (McGehee and Carsten 2010). In a study by Thomas et al. (1999) it was shown that not all the drivers perceive the risk of the imminent accident in the same way. Generally the drivers responsible for the crash have a higher perception than other drivers involved in the crash. The former group responds by braking and steering with the same percentage whereas the latter only brakes (Thomas et al. 1999). In a study, Hault-Dubrulle et al. (2010) simulated a car-to-truck collision using a driving simulator. The results showed that a typical response was to brace rearward in the seat, hold the steering wheel and swerve to avoid the other vehicle (Hault-Dubrulle 2010).

Steering manoeuvres can be of two types: the first one is represented by a low steering angle (3°-7°) and low speed of the vehicle and it represents the typical action of the responsible drivers in a car-to-car accident, whereas the second type is characterized by wider steering angle and higher car speed and it's mostly observed in curve crashes to adjust a wrong trajectory (Thomas et al. 1999).

During an emergency manoeuvre the occupant's motion from the initial seated position leads to a different posture from the one use for the development of restraint systems (Hault-Dubrulle et al. 2010). Generally, in the development of a restraint system Anthropomorphic Test Devices (ATDs) are used. ATDs are not able to simulate the human behaviour in a pre-crash situation since they are developed for crashes and higher velocity and acceleration changes and they do not do any action to try to keep the posture during a pre-crash manoeuvre. The changes in the human body position caused by inertia in a pre-crash manoeuvre might affect the injury outcome (Antona et al. 2010).

A child seated in the rear seat during an emergency manoeuvre, is likely to go out of position due to the fact that usually rear seats don't have the side support provided in the front seats, therefore during a swerve a child occupant may move inboard resulting in a non-optimal position for the effectiveness of the restraint system (Bohman et al. 2011a).

1.4 Aims

The overall aim of this thesis work is to develop methodologies for analysing children of different sizes in different restraint systems and with different belt geometry during emergency steering manoeuvres and when sitting still. The methods are to be applied on a set of volunteer child data and will provide input into validation of mathematical child models as well as restraint system development.

The specific aims are:

- Method development and analysis of static belt measurement for three types of restraint systems.
- Method development and analysis of kinematic response of child occupants during emergency steering manoeuvres, focusing on child inboard movement and on shoulder belt position.

2 Method

2.1 Physical test

The physical tests were divided into 3 parts: static belt measurements in three different restraint systems, steering manoeuvres in two out of these three restraint systems and an emergency braking. Only the static belt measurements and steering manoeuvres are analysed and presented in this master thesis report.

2.1.1 Test set up

A driving study has been conducted in order to analyse the kinematic response of child volunteers during steering manoeuvres. The repeatability of the test performances were achieved by using the same car and the same professional driving instructor for all the tests and by placing cones on the track, followed by the driver, to identify the beginning of the steering manoeuvres. This was also the same vehicle and driving instructor as in the previously performed study with child volunteers (Bohman et al. 2011b, Stockman et al. 2012).

Eighteen children, recruited by the Division of Design & Human Factors at Chalmers, were divided into two groups based on their stature: a group of short children (110-120 cm) and a group of tall children (135-145 cm). All children were tested in two different CRS (Figure 3): an integrated booster cushion IBC and the cushion part of a Volvo Booster Seat (BC1), similar to the Britax Kid Plus. For the static belt measurement they were also tested on another accessory booster cushion (BC2), shown in Figure 3. The IBC was set on the first level for tall children and on the second level for short children. The measurements for the IBC are shown in Table 1, while the ones relative to the BC1 and BC2 are shown in Table 2.

Figure 3 – From left to right: integrated booster cushion (IBC), booster cushion BC1 and booster cushion BC2.

Table 1 – Measurements for the IBC.

CRS	Height from the floor	Height from the seat		Width	Depth
		Front	Back		
IBC level 1	40cm	7cm	5cm	34cm	32cm
IBC level 2	43cm	10cm	7cm	34cm	32cm

Table 2 – Measurements for the two BCs.

CRS	Height		Width		Depth	Guiding loops	
	Front	Back	Front	Back		Height	Depth
BC 1	16cm	11cm	42cm	22cm	40 cm	16 cm	24 cm
BC 2	11cm	8cm	37cm	25cm	38 cm	12 cm	19 cm

The children were restrained with the 3-point seatbelt on the right rear seat of a Volvo XC70 (year model 2010) equipped with leather upholstery seats incorporating a coarse grain pattern on the central panel. A professional driving instructor drove the vehicle and child's parents travelled on the front passenger seat during the tests.

The car was equipped with two different measurement systems. The FOT-system, comprehensive of a camera and recording system as used in the EuroFOT project for monitoring the driver (FOT Net), was used only in a small part of the kinematic analysis to extract the tilting angle of the torso of the child and is therefore not described in detail in this thesis. The other system included an accelerometer, located approximately 10 cm above the floor between the front seats, with a sensibility of 1.2 V/g and offset of 2.5 V and two video cameras. Motion capturing was made with two UI-5220CP-C Gigabit Ethernet CMOS colour cameras (IDS GmbH, Obersulm, Germany) with wide-angle lenses (LM5NCL, Kowa Co., Tokyo, Japan) with a 4.5 mm (side view) and 3.5 mm (front view) focal length. The cameras were running in triggered mode at 50 Hz and routines for the acquisition were written in Labview 2011 (National Instruments, Austin, Texas). Images were 768x480 pixels and saved in uncompressed .png format. The side view camera was mounted on the left rear door and the front view camera on the head restraint of the front passenger seat. Before each event the driver triggered the system, which recorded for 20 seconds.

The coordinates axes used are show in Figure 4. The x-axis is forward in the traveling direction of the car, y-axis is to the side and z-axis is upward.

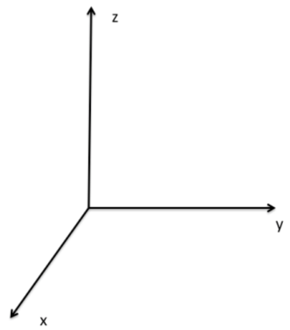

Figure 4 – Coordinates axes.

2.1.2 Test procedure

Every child was exposed to steering manoeuvres and emergency braking events in a random order. The braking events are not described in this thesis.

2.1.2.1 Static belt measurement

Static belt measurements were made for each child seated on the IBC, on booster cushion with backrest removed BC1, and on the booster cushion without backrest BC2. For the last two restraint systems the static belt measurement was made both for the shoulder belt under the inboard guiding loop and above the inboard guiding loop. The measurements were based on pictures of the children seated on the booster inside the car.

2.1.2.2 Kinematic response

Driving at a velocity of 50 km/h, the driver made a sharp turn to the right following the cones on the track. All the children performed a less evasive curve, which had a radius of 16.5 m for the first cone and 26.5 m for the second cone (Figure 5, left). The last 5 children (2 short and 3 tall) performed also two evasive curves, one for each booster, with a radius of 16.5 m for both cones (Figure 5, right).

The average lateral acceleration for the less evasive and evasive steering manoeuvres performed by the driver, which simulates an emergency turn in order to avoid a crash, is shown in Figure 6. All the tests were synchronized at a lateral acceleration of -0.2 g (labelled by S in Figure 5). Then the reference time, T1, of the event was defined as the time point 1,7s before the synchronization point and the event's end was fixed 6s after T1. T1 is indicated at time point zero on the x-axis in the figures.

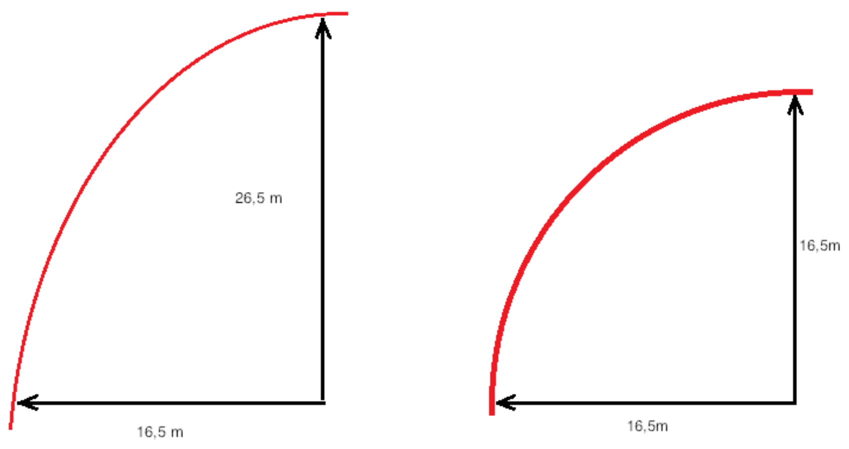

Figure 5 – Schematic of the curves: on the left the schematic of smoother curve, on the right the schematic of sharper curve.

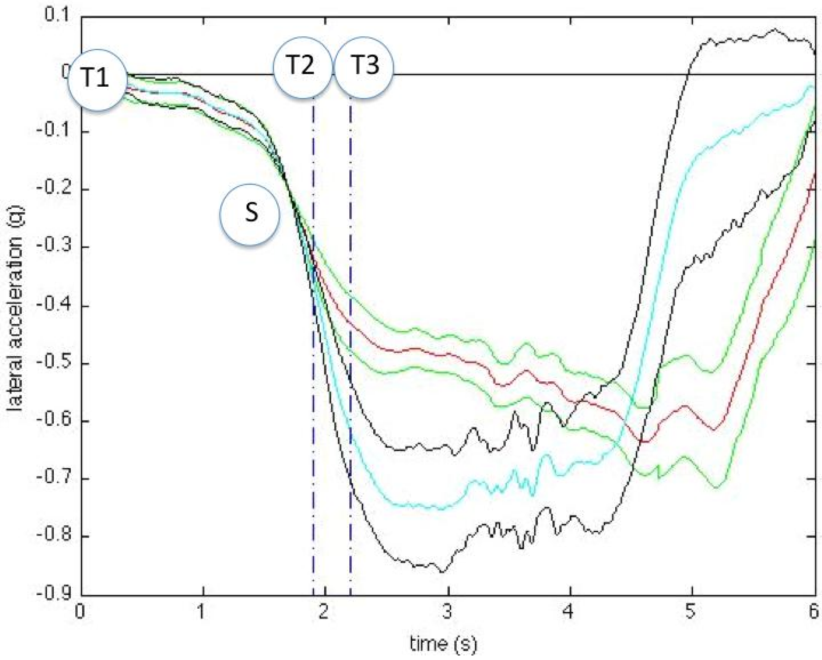

Figure 6 – Average lateral acceleration (red)± standard deviation (green) for the less evasive curve and average lateral acceleration (light blue) ± standard deviation (black) for the evasive curve.

Black and yellow film targets were placed on the volunteers in specific places, shown in Figure 7, in order to be able to track these points for the kinematic analysis. The targets on the child face were painted: on the forehead, on the nasion and on the chin. One black tape identified the line passing through the outboard armpit and on the top of the shoulder. Regarding the torso, two targets were placed under the clavicles, one target on the upper sternum just under where the clavicles meet followed by several targets positioned vertically on the centreline of the child.

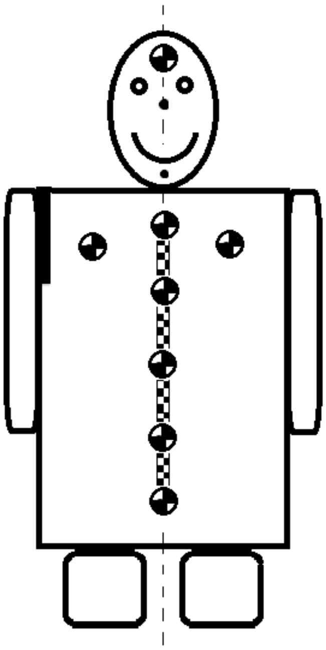

Figure 7 – Position of the targets on child's body.

Before the tests were performed, some anthropometric measurements, such as stature and sitting height, were collected by taking pictures of the child standing in front of a chequered board and by analysing them with TEMA v.3.12 (a motion tracking software). Table 3 shows a summary of the anthropometric measurements while information about the number of trials on each restraint system is shown in Table 4.

Table 3 - Anthropometric data of the volunteers. The shaded rows correspond to short children.

Child	Age	Height (cm)	Sitting Height (cm)	Weight (Kg)
1	7y 2m	115,7	69,2	21
2	5,5 y	109,2	68,8	19
3	5,5 y	113,7	64,5	19
4	10y	142,3	77,1	29
5	8y	137,2	75,1	29
6	7y	135	76,7	32
7	10y	145,6	77,5	35
8	5,5y	119	69,4	23
9	5,5y	113,8	65,9	21
10	8,5y	141,3	78,6	32
11	5,5y	110,9	61,4	16
12	5y	113	61,3	18
13	5,5y	118	65,5	21
14	9y	135	74,3	29
15	5y	112	62,4	18
16	5y	117	67,4	21
17	8,5y	140,3	78,2	31,5
18	9y	133,6	77,5	31
Mean Short	**5,5**	**114,2**	**65,6**	**19,7**
Mean Tall	**8,8**	**138,8**	**76,9**	**31,1**

Table 4 - Information about the trials. Non-performed trials are marked with a dash (-), while N/A means that it was not possible to analyse the kinematics due to loss of frames or impossibility to track the target. The shaded areas indicate which was the first restraint system used, while in bold are the information corresponding to tall children.

# Child	BC1		IBC	
	Less evasive steering	Evasive steering	Less evasive steering	Evasive steering
1	1 - N/A	-	N/A	-
2	1 - N/A	-	1 - N/A	-
3	2	-	2	-
4	**2**	**-**	**1**	**-**
5	**2**	**-**	**1**	**-**
6	**2**	**-**	**2**	**-**
7	**2**	**-**	**2**	**-**
8	2	-	2	-
9	2	-	2	-
10	**2**	**-**	**2**	**-**
11	2	-	2	-
12	2	-	2	-
13	2	-	2	-
14	**2**	**1**	**2**	**1**
15	2	1	2	1
16	2	1	2	1
17	**2**	**1**	**2**	**1**
18	**2**	**1**	**2**	**1**

2.2 Method of analysis

Before each test, static belt measurement was made for all the children in each booster cushion with the aim of categorizing the position of the belt on the shoulder and on the pelvis. Then, an analysis of the kinematic response was made by analysing the videos to quantify the head and torso inboard movement and the belt displacement on the shoulder during the steering manoeuvre.

2.2.1 Static belt measurement

According to Reed et al. (2009), an optimal belt fit is achieve when the shoulder belt is positioned on the mid shoulder loading the clavicle and the lap belt is positioned horizontally on the thighs loading the pelvis.

Using the black tape on the child shoulder as reference, the position of the belt on the shoulder was divided into three different categories shown in Figure 8:

- A: belt close to the neck;
- B: belt positioned in the mid shoulder;
- C: belt far out on the shoulder.

Figure 8 - From the left to the right: position A, position B, and position C for the shoulder belt.

The presence of a contact between the shoulder belt and the top of the shoulder, shown in Figure 9, was taken into account as well as the presence of a gap between the shoulder belt and the lower torso (Figure 10).

Figure 9 – On the left an example of contact between shoulder belt and the top of the shoulder, on the right an example of non-contact.

Figure 10 – Example of gap between the shoulder belt and the lower torso.

Also for the lap belt were identified three different positions (Figure 11):

- A: belt not horizontal on the thighs and only partially on the pelvis;
- B: horizontal on thighs and on the pelvis;
- C: far forward on the thighs.

Figure 11 - From left to right: position A, position B and position C for the lap belt.

2.2.2 Kinematic response

The child's posture and displacement during the steering manoeuvres relative to the initial position and to the centre of the seat were measured in the whole interval of interest based on the recorded images. In particular, two time points were considered: T2, taken 0.2s after the synchronization point, thus 1.9s after the reference time T1, and T3, defined as the time at the end of the ramping in the lateral acceleration, taken 0.3s after T2, thus 2.2s after T1 (Figure 6).

Several targets on the child's body were tracked in TEMA in order to obtain the lateral and vertical displacements of different body regions:

- Forehead target to measure the head displacement;
- Nasion and chin targets to measure the changes in head tilting angle, with respect to the y-axis, throughout the manoeuvre;
- Sternum target to measure the inboard displacement of the upper torso;
- Two targets horizontally aligned on the torso to construct the line passing through these points and moved up to the shoulder level (line 1) (see Figure 12).
- Two targets on the seat belt to construct the line going through the shoulder belt (line 2) (see Figure 12);
- The point on the top of shoulder taken on the external edge of the black tape positioned from the armpit to the shoulder;
- Two targets vertically aligned on the torso to measure the changes in the torso tilting angle.

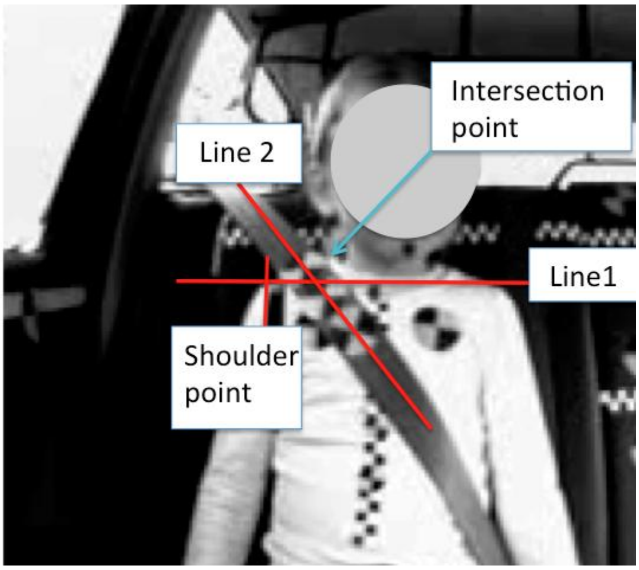

Figure 12 – The lines used to assess the shoulder belt position on the shoulder.

Based on the tracking of these targets, it was possible to obtain the following measurements, during the whole steering manoeuvre and especially at T2 and T3, for each child in every trial:

- Head lateral displacement at T2 and T3 and the maximum displacement as the difference between the actual position and the initial position and with respect to the centre of the seat;

- Head angle, that is the angle between the line passing through the chin and the nasion targets and the y-axis, at T2 and T3 and the maximum inboard tilting angle from the initial position and with respect to the centre seat. An angle of 90° corresponds to a vertical sitting position on the seat with no tilting angle, inboard tilting results in a decreased of the head angle while an outboard tilting results in an increased head angle;
- Upper torso lateral displacement at T2 and T3 and the maximum displacement as difference between actual and initial position and with respect to the centre of the seat;
- Changes in torso tilting angle at T2 and T3 and the maximum inboard angle with respect to the initial position and to the centre of the seat. An angle of 90° corresponds in a upright position on the seat and the torso angle increases if the child tilts outboard or decreases if the child tilt inboard;
- Shoulder belt position on the shoulder, defined as the horizontal distance from the tracked point on the top of the shoulder and the intersection point between line 1 and line 2. A negative horizontal distance means that the shoulder belt was far out on the shoulder (on the outboard side of the shoulder target) or completely off, similar to position C used for the static belt measurement. In the case of shoulder belt slip off, the time and lateral acceleration at which the slip off occurred was determined.

3 Results

3.1 Static belt measurement

All the 18 volunteers were tested for the static belt measurement of these three boosters, except two children (child #2 and child #3) who were tested only on the BC1. Since the analysis was based on pictures, in some cases (child #4 and #6) it was impossible to identify whether a gap between the shoulder belt and the lower torso was present and if there was contact between the outboard shoulder and the shoulder belt.

All the results for the static belt measurement are presented in Appendix A.

For the booster cushion BC2, which was used only for the static belt measurement, the results are summarized in Figure 13 and Figure 14 and in Table A1. For child #4 the presence of a gap between the lower torso and shoulder belt and of a contact between the shoulder and the belt was not identified.

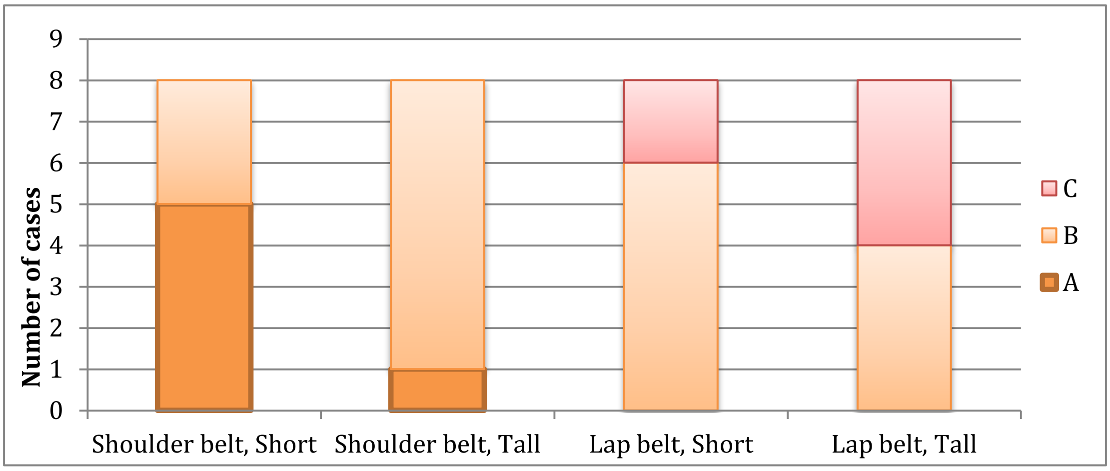

Figure 13 – Static belt measurement for short and tall children on BC2 with shoulder belt above the inboard guiding loop.

When the shoulder belt was above the inboard guiding loop (Figure 13), the majority of the short children (5/8) had the shoulder belt in contact with the neck (position A), whereas for the remaining short children the belt was on the mid shoulder (position B). For 7/8 of these children there was no contact between the belt and the shoulder. The lap belt was far forward on the thighs (position C) for two children in the short group and a gap between belt and lower torso was present only in one case. For the children in the tall group, 7/8 had the shoulder belt placed in the mid shoulder (position B) and 4/8 had the lap belt far forward on the thighs (position C). A gap between the belt and the lower torso was present only in one trial a contact between shoulder and belt was present except in 2 cases.

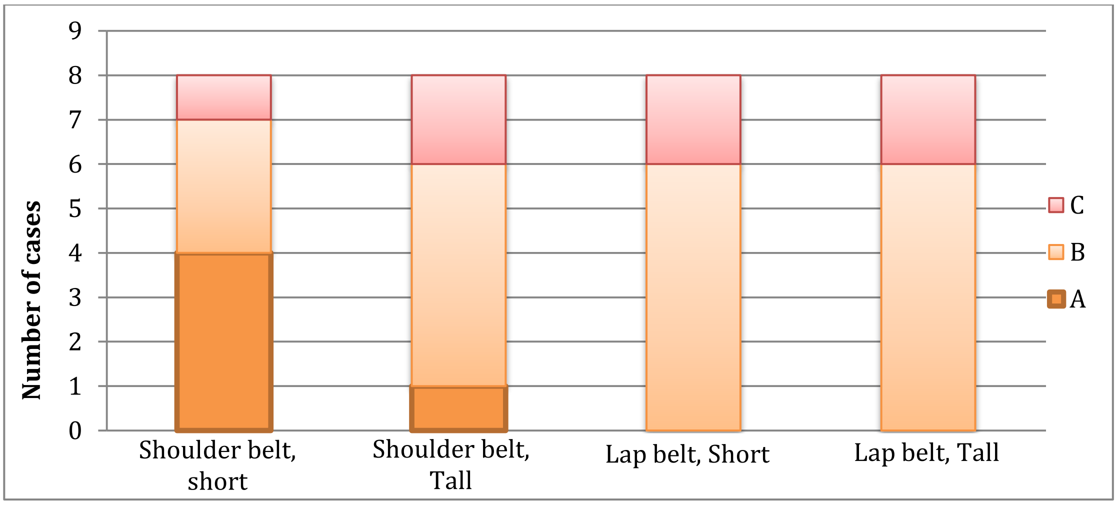

Figure 14 – Static belt measurement for short and tall children on BC2 with shoulder belt under the inboard guiding loop.

When the shoulder belt was under the inboard guiding loop (Figure 14), 4/8 of the short children had the shoulder belt positioned close to the neck (position A) and 3/8 had the belt position on the mid shoulder. The lap belt was horizontal on the thighs (position B) for 6/8 of short children and in the other case it was far forward on the thighs (position C). Belt-shoulder contact was never present, while a gap between the lower torso and the shoulder belt was present in the majority of trials. For 5/8 of the tall children the shoulder belt was on the mid shoulder (position B) and in two trails the belt was far out on the shoulder (position C). The lap belt was horizontal on the thighs (position B) for 6/8 children, whereas for the remaining children was far forward on the thighs. A belt-shoulder contact (as shown in Figure 8) was always present for the tall children. Also for tall children a gap between the lower part of the torso and the shoulder belt was present in the majority of the cases.

The results for the static belt measurement on the Volvo Booster Seat with removed backrest (BC1) are shown in Figure 15 and 16 and in Table A2. All the volunteers participated in this test.

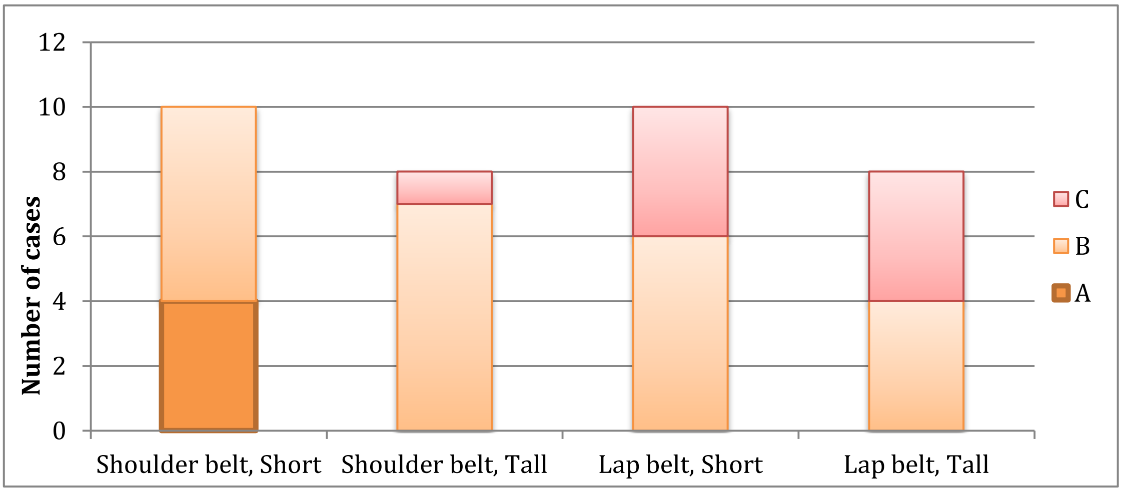

Figure 15 – Static belt measurement for short and tall children on BC1, shoulder belt above the inboard guiding loop.

With the shoulder belt positioned above the inboard guiding loop (Figure 15), 6/10 short children had the belt on the mid shoulder (position B) and the remaining 4 had the belt close to the neck (position A). Regarding the lap belt position, 4/10 of the short children had the lap belt far forward on the thighs (position C). For 6/10 a gap between lower torso and seat belt was present. Shoulder-belt contact was present in the majority of the cases.

For the tall children 7/8 had the shoulder belt on the mid shoulder (position B) and 1/8 had the belt far out on the shoulder (position C). For 4/8 of tall children the lap belt was far forward on the thighs (position C). A gap between lower torso and seat belt was present in 4 trials and the contact between shoulder and belt was present in most of the cases.

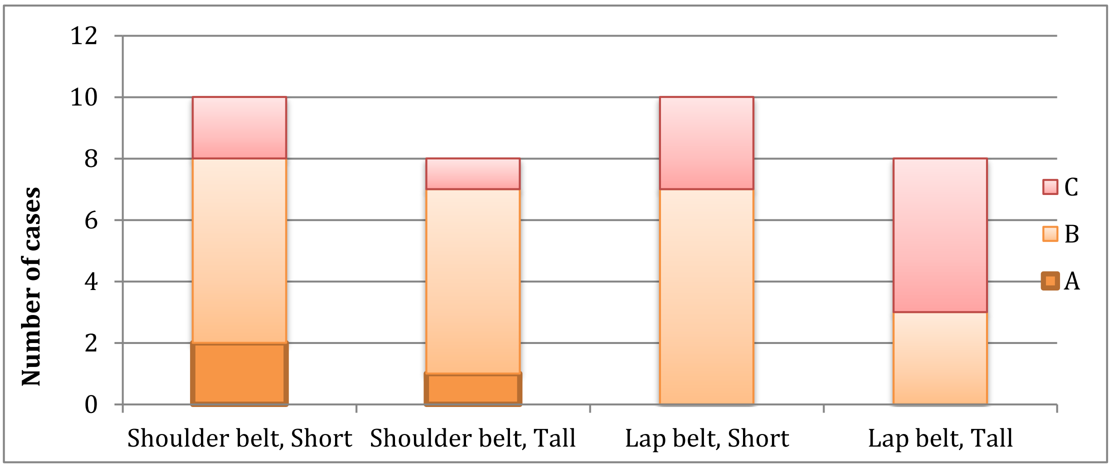

Figure 16 – Static belt measurement for short and tall children on BC1, shoulder belt under the inboard guiding loop.

When the shoulder belt was positioned under the inboard guiding loop (Figure 16), 6/10 of the short children had the shoulder belt on the mid shoulder (position B), 2/10 close to the neck (position A) and the remaining 2/10 far out on the shoulder (position C). The lap belt was horizontal on the thighs (position B) for seven of the short children. Shoulder-belt contact was present only for 2/10 of the children, while the torso-belt gap was present for 9/10 children of the short group.

For the tall children in 6/8 cases the belt was positioned on the mid shoulder (position B), the lap belt was far forward on the thighs in 5/8 cases (position C). A gap between the shoulder belt and the lower torso was always present but the shoulder belt was always in contact with the top of the shoulder.

Static belt measurements on the integrated booster cushion (IBC) were missing for two of the shorter children (child #2 and child #3). The results are shown in Figure 17 and summarized in Table A3. The shoulder belt was on the mid shoulder (position B) for 5/8 of the short children and for the remaining 3/8 children was close to the neck (position A). Regarding the lap belt, for 6/8 of the short children it was not horizontal and only partially loaded the pelvis (position A). Among the short children a gap between lower torso and seat belt was present only in one case, whereas a shoulder-belt contact was present in 4/8 cases.

For all the tall children the belt was on the mid shoulder (position B) for all cases except for one in which the belt was far out on the shoulder. The lap belt was horizontal on the thighs (position C) in 5/8 cases and not horizontal and partially on the pelvis (position A) on the remaining cases. A gap between lower torso and seat belt was present in 7/8 cases and the belt was always in contact with the top of the shoulder.

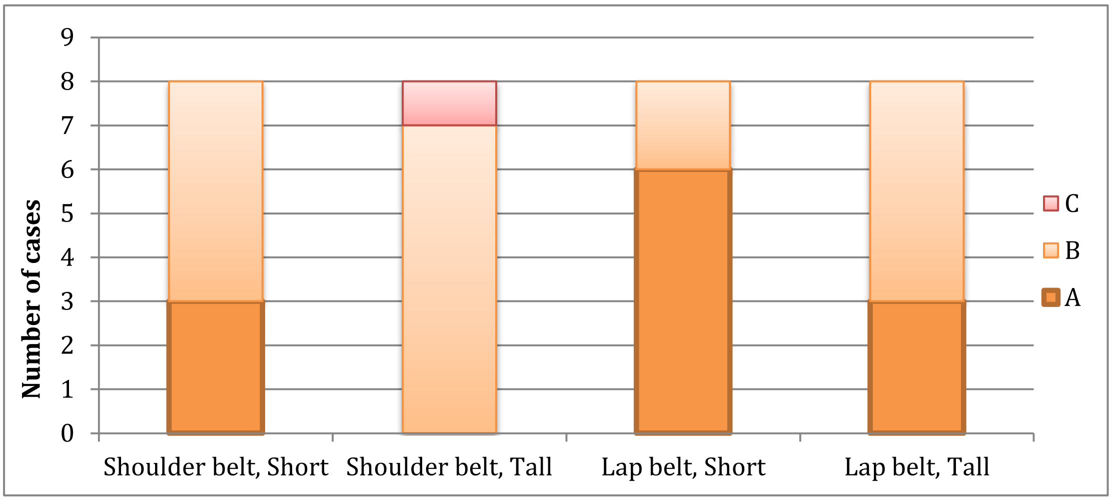

Figure 17 – Static belt measurement for short and tall children on IBC.

3.2 Kinematic response

The analysis of the kinematic response was carried out for all trials except 7 cases in which it was impossible to perform the analysis. For child #1 only the first manoeuvre was analysed and the other three were discarded due to loss of frames. Child #2 performed five steering manoeuvres but only two were analysed since in the other three manoeuvres the child adopted positions that made the analysis impossible due to poor visibility of the targets. For children #4 and #5 only 3 manoeuvres were recorded. For child #5 for the first manoeuvres the tracking of the torso angle was not possible.

The data relative to the head and torso lateral displacement and head and torso tilting angle with respect to the initial position are presented in Appendix B, while the data for each child relative to head and torso lateral displacement with respect to the centre of the seat are presented in Appendix C.

3.2.1 Less evasive steering manoeuvres

3.2.1.1 Head lateral displacement

The head average lateral displacements relative to the initial position for short and tall children are shown in Figure 18, while the head displacements at time T2 and T3 and the maximum head displacements are summarized in Figure 19.

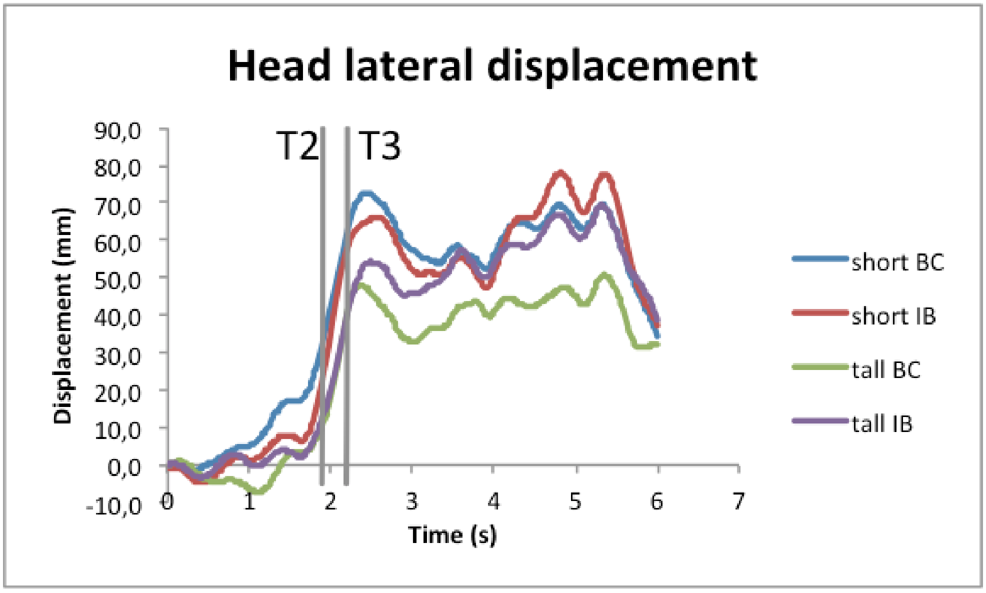

Figure 18 - Head average lateral displacement with respect to the initial position for short and tall children on Booster Cushion BC1 and Integrated Booster IBC.

The average head inboard displacement at T2 from the initial position was 33mm (±28mm) for short children seated on BC1 and 24mm (±25mm) for short children on IBC, while at time point T3 the inboard movement was 60mm (±45mm) and 56mm (±37mm) respectively. The maximum inboard motion for short children on BC1 was on average 97mm (±57mm) reached after 4.1s (±1.5s). On the IBC the maximum value reached was 93mm (±37mm) after 4.1s (±1.4s).

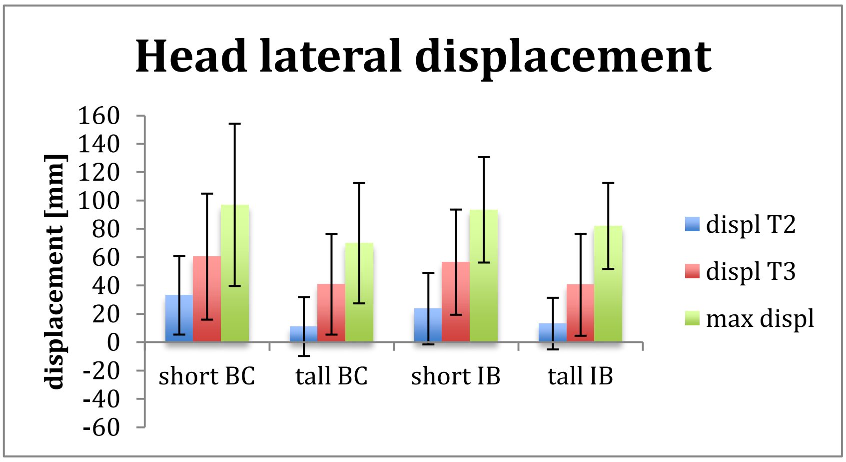

Figure 19 - Head lateral displacement for short and tall children on BC1 and IBC at time T2 and T3 and the maximum lateral displacement with standard deviations.

For the tall children the inboard motion at T2 with respect to the initial position was on average 11mm (±21mm) when seated on BC1 and 13mm (±18mm) when seated on IBC. At T3 the inboard motion was 41mm (±36mm) on BC1 and 40mm (±36mm) on IBC. The maximum displacement from the initial position was on average 70mm (±43mm) reached after 3.8s (±1.6s) on BC1 and 82mm (±30mm) after 4s (±1.5s) on IBC.

3.2.1.2 Head tilting angle

The average head tilting angle is described by the curves in Figure 20 for both short and tall children when seated on BC1 and IBC.

For the group of short children, the initial head angle was 88° on both BC1 and IBC. The change in head angle with respect to the initial position at T2 was on average 0.2° (±5°) inboard when seated on BC and 0.9° (±4°) inboard when seated on IBC. At T3 it became 1.3° (±7°) and 2.6° (±5°) inboard respectively. The maximum change in head angle was on average 9° (±7°) inboard after 2.9s (±1.9s) on BC and 4° (±6°) inboard after 2.2s (±1.1s) on IBC.

For tall children, the initial head angle was 90° on both the booster cushions. The average change in head angle at T2 was 2° (±7°) outboard on BC1 and 2° (±4°) outboard on IBC, while at T3 it was 2° (±8°) and 0.9° (±6°) outboard respectively. The maximum value for the change in head angle was on average 5° (±5°) inboard for children seated on BC1 reached after 2.4s (±2s) and 6° (±8°) for children seated on IBC reached after 2.3s (±1.7s).

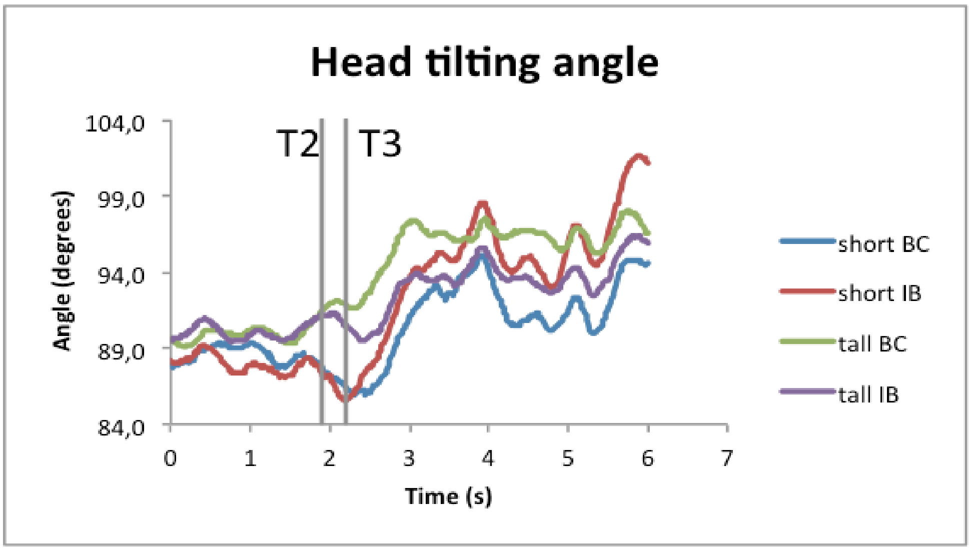

Figure 20 - Average head angle for short and tall children on BC1 and IBC.

3.2.1.3 Upper torso lateral displacement

The trend of the lateral displacement of child upper torso is shown by the curves in Figure 21.

Among the short children the lateral movement from the initial position of the upper torso at T2 was on average 22mm (±15mm) inboard when seated on BC1 and 21mm (±11mm) inboard on the IBC, while at T3 it was 42mm (±21mm) and 46mm (±21mm) inboard respectively. The maximum value measured in each trial for the lateral displacement was on average 75mm (±34mm) reached after 4.8s (±1.1s) when the children were traveling on the BC1 and 80mm (±27mm) reached after 5.1s (±0.7s) when traveling on the IBC (Figure 21).

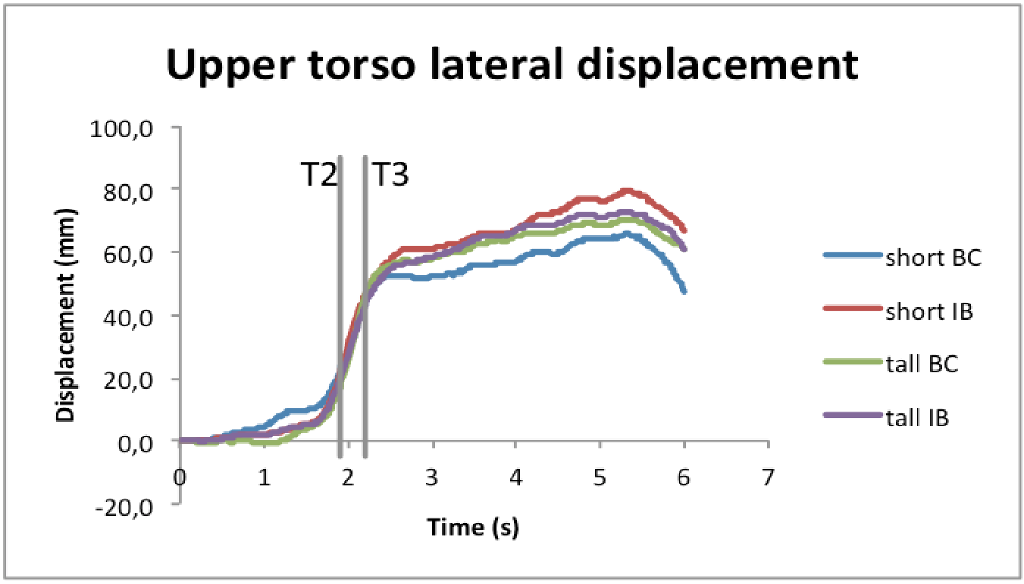

Figure 21 - Upper torso average lateral displacement with respect to the initial position for short and tall children on BC1 and IBC.

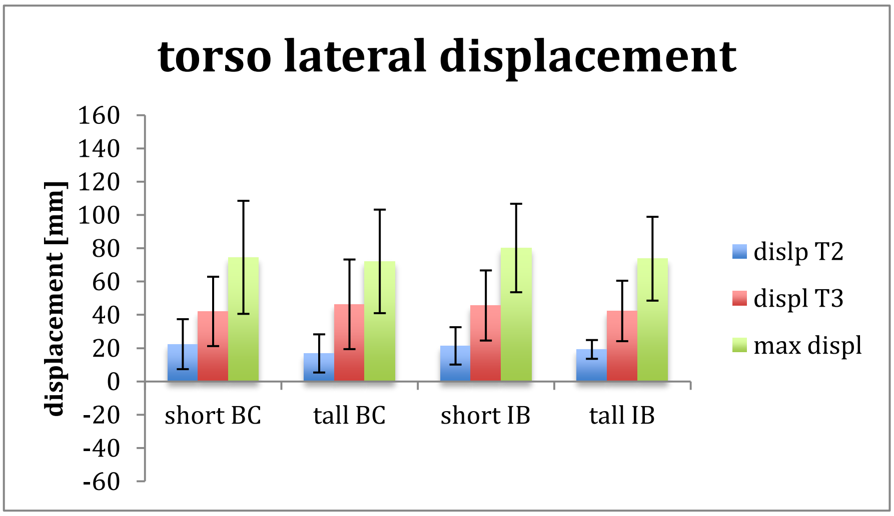

Figure 22 - Upper torso inboard displacement for short and tall children on BC1 and IBC at time T2 and T3 and the maximum inboard displacement with standard deviation.

For the group of the tall children at T2 the average lateral displacement of the upper torso with respect to the initial position was 17mm (±12mm) on BC1 and 29mm (±6mm) on IBC, while at T3 the displacements became 46mm (±27mm) and 42mm (±18mm) respectively. After a mean time of 4.8s (1.4s) the upper torso had reached the maximum inboard displacement on BC1: 72mm (±31mm). On IBC the maximum value was 74mm (±25mm) reached after 5.2s (±0.3s) (Figure 22).

3.2.1.4 Torso tilting angle

The average torso tilting angle is shown in Figure 23 for short and tall children when seated on BC1 and on IBC.

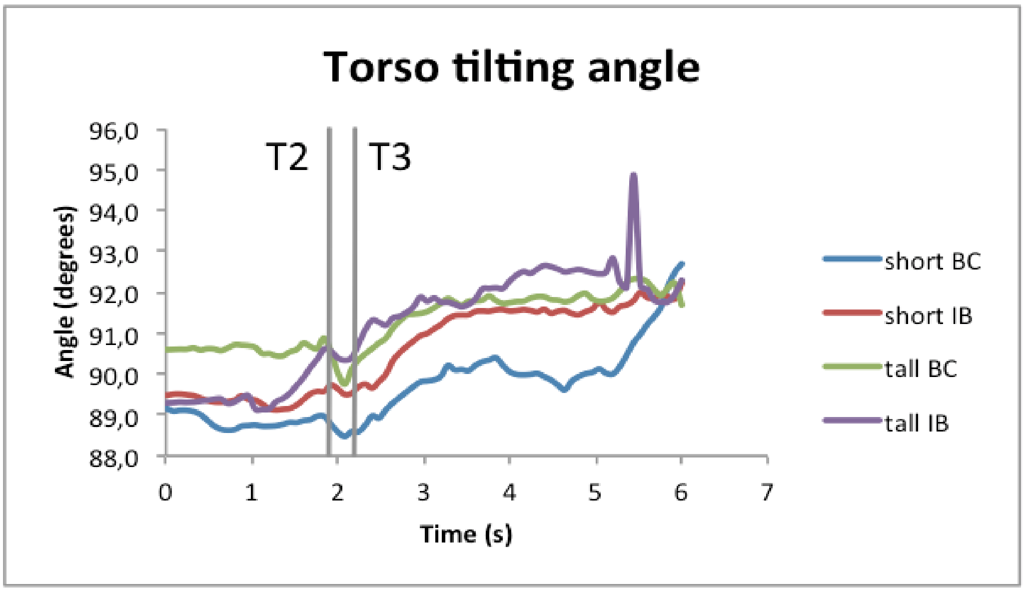

Figure 23 - Average torso tilting angle with respect to the initial position for short and tall children on BC1 and IBC.

For the short children the initial torso angle was 89° for both the boosters. The change of torso tilting angle from the initial torso angle was 0.4° (±2°) inboard at T2 when on the BC1 and 0.3° (±2°) outboard when on the IBC, while at T3 it was 0.6° (±4°) inboard and 0.2° (±3°) outboard respectively. The maximum inboard tilt from initial torso angle was on average 3° (±3°) reached after 2.4s (±1.6s) for short children when seated on BC1 and 2° (±3°) reached after 2.3s (±1.9s) for the short children when seated on the IBC.

For tall children, the initial angle of the torso was 91° when seated on BC1 and 89° when seated on the IBC. The change in torso tilting angle relative to the initial angle was, at T2, 0.3° (±2°) outboard on BC1 and 1.3° (±2°) outboard on IB, while at the time point T3 the change was 0.5° (±4°) inboard on BC1 and 1.5° (±2°) outboard on IBC. The maximum difference inboard from the initial torso angle was 2.5° (±3°) after 1.7s (±1.9s) for the BC1 and 1.4° (±2°) after 1.5s (±1.8s) for the IBC.

3.2.1.5 Shoulder belt position

In 11 of 18 trials for the short children seated on BC1 the shoulder belt slipped off during the manoeuvre. In two trials (child #16 seated on BC1) the shoulder belt was already far out at T1. In 4 trials the belt slip off occurred after the time point T3, in 4 trials the belt slip off occurred before T2 and in one trial occurred between T2 and T3. The time of shoulder belt slip off and relative lateral acceleration for each child when seated on BC1 are shown in Table 5. The relative shoulder belt horizontal displacement from the initial position was on average 16mm (±20mm) at T2 and 27mm (±28mm) at T3.

Table 5 - Information about the shoulder belt position on the shoulder for short children restrained on BC1. "Off" means that a belt slip off occurred (similar to position C), while "on" means that the belt is on the shoulder (similar to position A or B)

# Child	Shoulder belt	Time (s)	Lateral acceleration (g)
1	off	2.8	-0.5
2	off	0.02	0
3	off	0.5	-0.03
	off	2.1	-0.5
8	on	-	-
	on	-	-
9	off	2.3	-0.4
	off	1.3	-0.08
11	off	4.7	-0.6
	off	4.3	-0,56
12	on	-	-
	off	0.2	-0.01
13	on	-	-
	on	-	-
15	on	-	-
	on	-	-
16	off	0	0
	off	0	0

For short children on IBC 2 trials out of 17 resulted in a shoulder belt slip off (Table 6). In the first case the belt slipped off before T2 and in second one after T3. In average the displacement of the shoulder belt was 3mm (±8mm) at T2 and 8mm (±12mm) at T3.

Table 6 – Information about shoulder belt position on the shoulder for short children on IBC. "Off" means that a belt slip off occurred (similar to position C), while "on" means that the belt is on the shoulder (similar to position A or B).

# Child	Shoulder belt	Time (s)	Lateral acceleration (g)
1	N/A	N/A	N/A
2	off	1.6	-0.15
3	on	-	-
	on	-	-
8	on	-	-
	on	-	-
9	on	-	-
	on	-	-
11	on	-	-
	on	-	-
12	on	-	-
	on	-	-
13	on	-	-
	off	3.5	-0.54
15	on	-	-
	on	-	-
16	on	-	-
	on	-	-

No shoulder belt slip off occurred for tall children regardless of the type of booster used. At T2 the relative shoulder belt displacement was in average 0mm (±5mm) and at T3 2mm (±6mm) for tall children restrained on a BC1, while for children restrained on IBC the displacement was 1mm (±3mm) at T2 and 2mm (±6mm) at T3.

3.2.2 Evasive steering manoeuvres

3.2.2.1 Head lateral displacement

Head lateral displacement (Figure 25) from the initial position for short children restrained on BC1 was on average 10mm (±11mm) at T2 and 45mm (±11mm) at T3, whereas for short children on IBC the lateral movement was 36mm (±24mm) at T2 and 87mm (±62mm) at T3. The maximum head lateral movement was on average 124mm (±27mm) reached after 4.47s (±0s) and 115mm (±57mm) reached after 2.58s (±0.3s) for short children on BC1 and IBC respectively.

For tall children the average lateral displacement, shown in Figure 25, was 13mm (±11mm) at T2 and 55mm (±36mm) at T3 when seated on BC1, while it was 18mm (±15mm) at T2 and 63mm (±21mm) at T3 when restrained on IBC. The maximum lateral movement of the head was 134mm (±39mm) on the BC1 and 99mm (±18mm) on IBC, both reached after 2.7s (±0.3s).

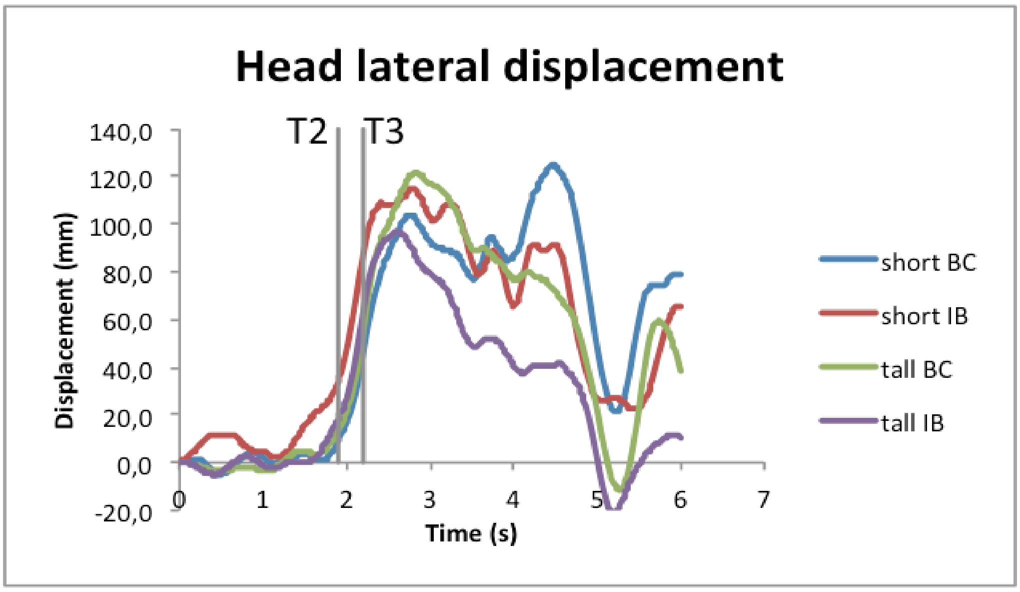

Figure 25 – Head average lateral displacement with respect to the initial position for short and tall children on BC1 and IBC during evasive steering manoeuvres.

3.2.2.2 Head tilting angle

The average head angle in evasive manoeuvres is shown in Figure 26 for short and tall children when seated on BC1 and IBC. For short children the initial head angle was on average 93° when restrained on BC1 and 90° when restrained on IBC. The average change in head angle with respect to the initial position at T2 was 1.5° (±4°) outboard when using BC1 and 5° (±4°) inboard when using IBC. At time point T3 the head angle was 0.8°(±6°) more outboard than the initial one on BC1 and 8° (±7°) more inboard than the initial angle when on IBC. The average maximum change in head tilting angle was 11° (±4°) inboard reached after 5.94s (±0s) for children restrained on BC1 and 10° (±7°) inboard after 2.36s (±0s) when they were seated on IBC.

For the group of tall children the head angle at the beginning of the event was on average 86° when restrained on BC1 and 89° when restrained on IBC. At the time point T2 the change in head angle with respect to the initial angle was 1° (±3°) outboard on BC1 and 1° (±4°) outboard on IBC, while at T3 it became 3° (±7°)

outboard and 0.4° (±4°) inboard respectively. The maximum change for the head tilting angle was 6° (±4°) inboard on BC1 and 6° (±6°) inboard on IBC, values reached after 3.7s (±2s) and 2.6s (±0.1s) respectively.

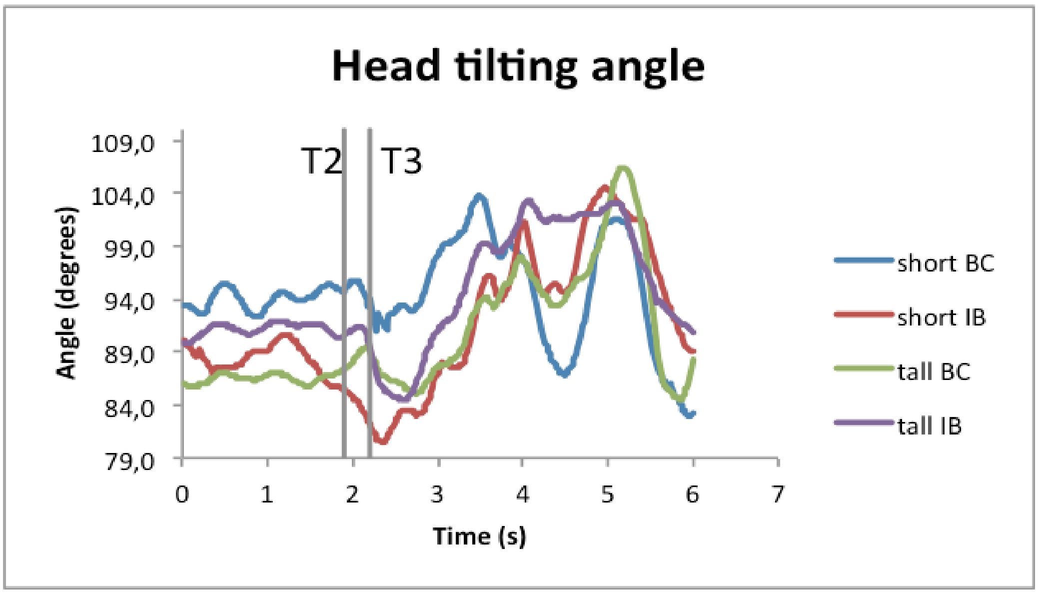

Figure 26 – Average head angle for short and tall children on BC1 and IBC during evasive manoeuvres.

3.2.2.3 Upper torso lateral displacement

Short children's upper torso at T2 moved on average 9mm (±4mm) from the initial position when restrained on BC1 and 16mm (±0.4mm) when restrained on IBC. At T3 the lateral displacement was 35mm (±13mm) and 55mm (±58mm) respectively. The maximum movement from the initial position was 82mm (±11mm) on BC1 and 83mm (±16mm) on IBC reached after 4.5s (±0s) and 4s (±0.3s) (Figure 27).

Among the tall children, at T2 the upper torso lateral displacement relative to the initial position was 15mm (±2mm) on BC1 and 19mm (±4mm) on IBC, while at T3 it was 55mm (±10mm) and 58mm (±16mm) respectively. The maximum lateral movement for children restrained on BC1 was 114mm (±52mm) and was reached after 3.7s (±0.7s). For children restrained on IBC the maximum value was 74mm (±15mm) reached after 3.5s (±0.8s) (Figure 27).

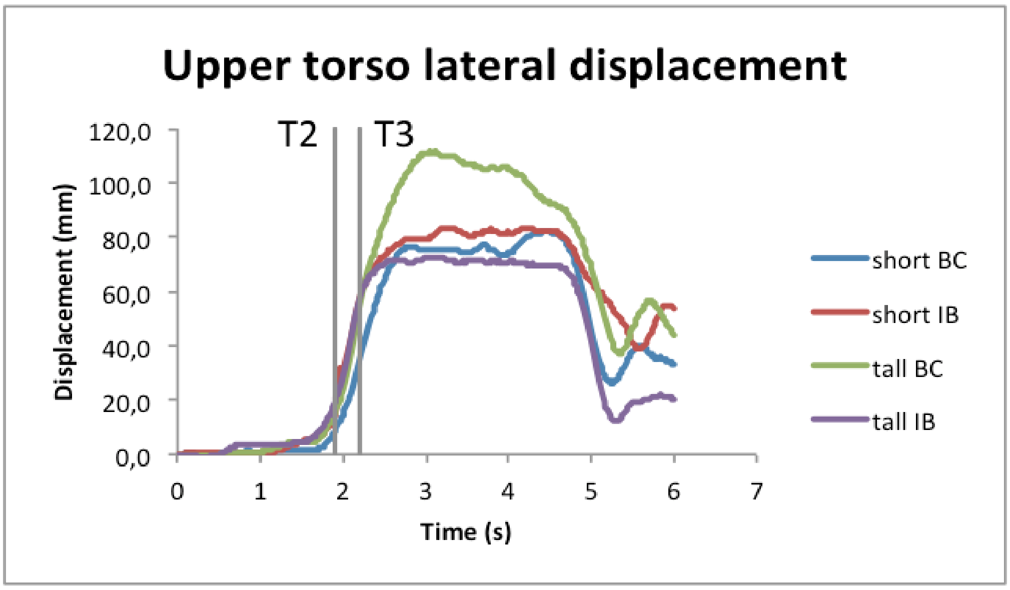

Figure 27 – Average lateral movement of upper torso for short and tall children on BC1 and IBC during evasive steering manoeuvres.

3.2.2.4 Torso tilting angle

The average torso angle in evasive manoeuvres is shown in Figure 28 for short and tall children restrained on BC1 and IBC.
For the group of short children the initial torso angle was 91° both when they were restrained on BC1 and IBC. At time T2 the changing in torso angle from the initial angle was 3° (±0.7°) outboard on BC1 and 4° (±5°) inboard on IBC. At T3 it became 2° (±0.7°) outboard on BC1 and it remained 4° (±3°) inboard for IBC. After 3.9s (±2s) the maximum tilting angle of 1.5° (±0.2°) inboard was reached when the children were restrained on BC1. For short children restrained on IBC the maximum value of tilting angle reached was 5° (±3°) inboard after 3.8s (±2.7s).

The tall children had an average torso initial angle of 90° when seated on the BC1 and 89° when seated on IBC. At T2, there was no tilting relative to the initial position regardless of the booster type. At T3 the tall children tilted 0.5° (±3°) inboard on BC1 and 2° (±0.4°) outboard on IBC. From the initial position the maximum tilting angle was 8° (±10°) inboard when children were restrained on BC1 and it was reached after 3.65s (±2s), whereas for children on IBC the maximum tilting angle from the initial position was 1° (±0.3°) inboard after 2.5s (±2.4s).

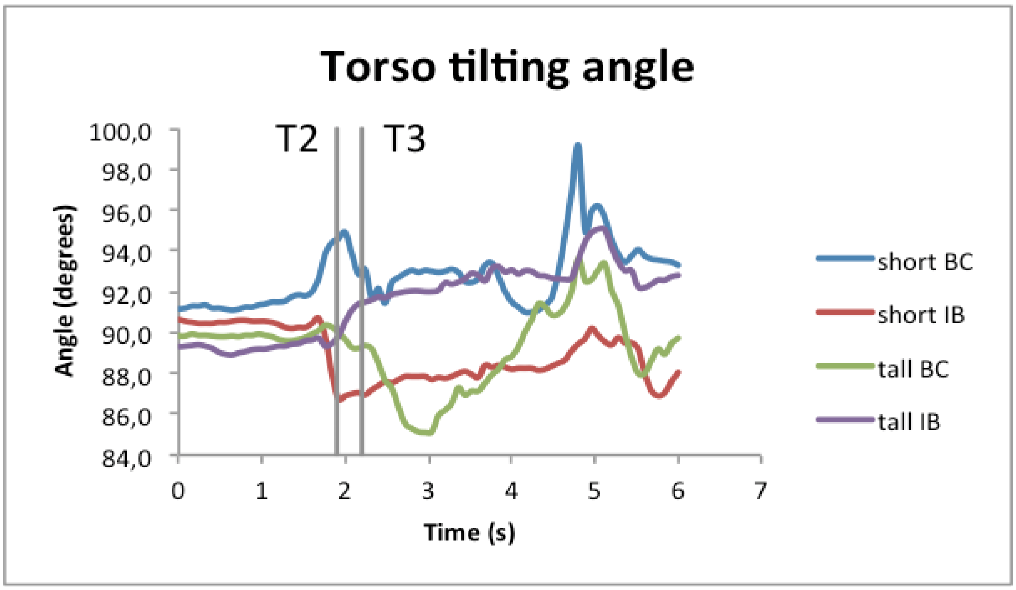

Figure 28 – Average torso angle for short and tall children on BC1 and IBC during evasive manoeuvres.

3.2.2.5 Shoulder belt position

The shoulder belt slipped off the shoulder in 2/2 trials for short children when restrained on BC1. In one of these trials (child #16) the shoulder belt was already off at the event's start. In the other case the shoulder belt slip off occurred after T3. The shoulder belt lateral movement from the initial position was on average 0.4mm (±1.3mm) at T2 and 16mm (±4mm) at T3. No belt slip off occurred when short children were restrained on IBC. The horizontal lateral movement of the belt on the shoulder was in average 3mm (±5mm) at T2 and 15mm (±12mm) at T3.

The time of slip off and relative lateral acceleration for short children on both the boosters are shown in Table 7.

Table 7 - Information about shoulder belt position on the shoulder for evasive steering of short children on BC1 and IBC. "Off" means that a belt slip off occurred (similar to position C), while "on" means that the belt is on the shoulder (similar to position A or B).

CRS	# Child	Shoulder belt	Time (s)	Lateral acceleration (g)
BC1	15	off	2.7	-0.7
	16	off	0	0
IBC	15	on	-	-
	16	on	-	-

In one trial out of 3 for the tall children on BC1 the shoulder belt slipped off. In average the horizontal displacement of the belt relative to its initial position on the shoulder at T2 was low (0.1mm ± 0.6mm). At T3 this movement was 2mm (±5mm). When tall children were restrained on IBC, no shoulder belt slip off occurred. At T2 the horizontal movement of the belt on the shoulder was on average 0.1mm (±1mm) and at T3 it was 1.5mm (±3mm). Time and acceleration values for belt slip off are shown in Table 8.

Table 8 - Information about shoulder belt position on the shoulder for evasive steering of tall children on BC1 and IBC. "Off" means that a belt slip off occurred (similar to position C), while "on" means that the belt is on the shoulder (similar to position A or B).

CRS	# child	Shoulder belt	Time (s)	Lateral acceleration (g)
BC1	14	on	-	-
	17	off	2.3	-0.7
	18	on	-	-
IBC	14	on	-	-
	17	on	-	-
	18	on	-	-

4 Discussion

4.1 Method

In this thesis work, first of all, a method for the analysis of the static belt measurements was developed. The analysis of static belt measurements was based on photos taken while the child was seated on the booster cushions inside the car.

The three different positions for the shoulder belt were chosen based on the optimal belt fit recommended by Reed et al. (2009). According to this optimal belt fit, the shoulder belt should load the clavicle without touching the neck, if possible. Position B defined in this study provides the optimal belt fit. Also position A assured a good belt fit since it is still loading the clavicle, but being close to the neck can cause discomfort for the child. Position C, instead, provides a poor belt fit since the belt is more likely to slip off the shoulder.

Also for the lap belt, the optimal belt fit suggested by Reed et al. (2009) was considered, according to which the lap belt should load the pelvis. This loading can be achieved when the lap belt is positioned horizontally on the thighs. This optimal fit for the lap belt was defined by position B in this thesis. Also position C (lap belt far forward on the thighs) was defined according to the belt fit suggested by Reed et al. (2009). Unlike in Reed et al. (2009), where the other position for the lap belt is vertically on the abdomen, in this thesis position A was chosen as the position in which the lap belt is not horizontal on the thighs and it is loading only partially the pelvis.

From the photos it was sometimes difficult to identify the different positions of the belt, especially to identify the presence of a gap between belt and lower torso, and the position of the lap belt for those children who were wearing dark trousers. In most of the cases, if the gap was small, its presence was not so clear. However, in these cases the gap was considered present. Only in 2 cases it was impossible to say anything about its presence (child #4 and #6). In future works it would be better to combine the photos with notes taken during the trials by the test leader. This could help to make the assessment of the belt fit easier.

In this study a method was developed in order to study also the kinematic response of children subjected to pre-crash steering manoeuvres. The repeatability of the trials was achieved by using the same professional driver throughout the tests performing a turn indicated by cones on the track.

The children were aware that two types of manoeuvres (steering and braking) would be performed during the test but they were not aware about the order. This better simulates a real life situation in which the occupant is not prepared for an unexpected manoeuvre.

All children in the study completed the test. For some of them the analysis of collected data was impossible due to loss of frames (3/4 trials for child #1) or because they adopted a wide range of different positions during the manoeuvre that made impossible to track the targets on their body (3 trials for child #2 and data on the torso angle for one trial of child #5). However their kinematic response could still be analysed through observing the videos and it was shown that they moved inboard during the steering as the other children in the test.

Black and yellow targets were attached on child's body and then tracked using the software TEMA.

For some of the shorter children the tracking of the targets on the torso were difficult since they were too low in the camera view. The front colour camera had a more narrow view than the FOT camera and the frames included only the upper part of the torso. The FOT camera provided a wider view but it had a worse resolution and so it was used to track only the torso tilting angle. The camera should have been positioned lower down to allow seeing the whole child's upper body and, in this way, tracking all the parameters from one set of frames instead of using two cameras with different frame rate.

The analysis of child's kinematics was done from the event's start at time T1 to the end of the event fixed 6s after T1. The two time points T2 and T3 were taken into consideration for the analysis in order to easily compare the data from the less evasive turns to the ones from the evasive turns and the data from the evasive turns to the data from Bohman et al.'s study (2011b). Furthermore, the maximum value for the different analysed parameters achieved during the event was investigated to check if there is still movement toward the middle of the car after T3.

The precision of the values, such as head and upper torso displacement and head and torso angle, can be affected by imprecision. Some of the targets, for instance the ones on the torso and the shoulder, were in most of the cases hidden by the shoulder belt during the tracking and, thus, for those points the tracking had to be done manually and this can be considered the main reason for a potential lower precision in the obtained results. However, the overall movement of the child was followed throughout the manoeuvres.

In this study more parameters, such as the lateral displacement and the tilting angle for head and torso separately, were considered than in Bohman et al.'s study in order to analyse the movements of different parts of child's body when subjected to steering manoeuvres. Like in the study by Bohman et al. (2011b) the position of the shoulder belt on the shoulder was investigated, but in this study the exact time of belt slip off was known and this allowed knowing the lateral acceleration related to it.

The method developed for the analysis of the kinematics took into account different parameters. Unlike in the previous study by Bohman et al. (2011b), to evaluate the inboard displacement and tilting angle of the child, the head and torso were considered separately. Head and torso move in different ways and this cannot be neglected when analysing the kinematic response.

The lateral displacement during the steering manoeuvres was measured both with respect to the initial position and to the centre of the seat. In this way the two displacements can be compared to verify whether a great displacement from the initial position truly corresponds to a great inboard displacement with regards to the seat.

The assessment of the belt position on the shoulder during the manoeuvres was based on the position of the belt relative to the black tape on the child's shoulder. The belt was considered off the shoulder as soon as the intersection point between line 1 and line 2 (see Figure 12) passed the outboard edge of the black tape. Imprecision in the time of belt slipping off can be present since when the black tape was hidden by the belt the tracking had to be done manually. However, also in this case, the overall motion was followed during the tracking.

A limitation of this study was the use of only one vehicle model since the belt geometry might be different in other models. This study was limited to two different types of booster cushions and to well-restrained children, thus no cases of misuse were tested. Two different types of turns were performed: a less evasive turn and an evasive turn. The evasive turn was performed only for the last 5 children. This can lead to a limitation in the kinematic analysis since only two short and three tall children were tested on the evasive turn providing few data for achieving reliable mean value of the measured parameters. However, as it is shown in Figure 6, the initial phase before the plateau was reached, was similar for the two types of turn. In this work the attention was focused on the initial phase until the time point T3, which was at an acceleration of -0.4g and -0.6g for the less evasive and the evasive turns respectively, where the two types of curve differ only in the value of the peak. Hence, for the purpose of this study, the low number of trials for the evasive steering is not so relevant for the evaluation of the inboard displacement of the children.

4.2 Results

From the static belt fit analysis some differences between short and tall children arose. Concerning BC1 and BC2, tall children benefited from positioning the shoulder belt above the inboard guiding loop, since in this situation the belt was in position B in most of the cases. Short children, instead, had more benefits when the shoulder belt was positioned under the inboard guiding loop. If, for short children, the belt was positioned above the inboard guiding loop the belt was touching the neck, which may cause discomfort. Hence, for tall children it should be recommended to position the shoulder belt above the guiding loop, while for short children it should be positioned under the guiding loop.

Regarding the lap belt, for tall children both BC1 and BC2 resulted in a less good lap belt position, since it was far forward on the thighs in many cases. For short children there were no significant differences between the two booster cushions even though the geometry of the two boosters was slightly different. Hence, the differences between BC1 and BC2 are not relevant when assessing the belt fit.

The IBC resulted in a more optimal restraint system for tall children than BC1, since it provided a shoulder belt positioned on the mid shoulder (position B) and the lap belt positioned horizontal on the thighs (position B).

For the short children the IBC resulted in less optimal belt fit compared to the tall children. In fact, when seated on integrated booster the short children were more likely to have the lap belt only partly on the pelvis (position A) compared to the tall children. This can be due to the differences in sitting height between short and tall children, as shown in Table 3. However, the integrated booster improved the belt fit in terms of contact and gap for short children compared to the one provided by BC1 and BC2, but for tall children the presence of a gap between lower torso and shoulder belt was present in more cases than when they were restrained on the booster cushions.

In particular, concerning the contact between the belt and shoulder, for the tall children it was present in the majority of cases, regardless from the type of booster contributing to the “grabbing” effect of the shoulder belt on the shoulder. This effect was missing for the short children, probably due to a lower height on the seat.

Comparing tall and short children in the less evasive turns, the inboard movement from the initial position of child's head was always higher for short children. Looking at Figure 18 it is possible to see that for short children there were no significant differences in head movement if they were restrained on the BC1 or on the IBC, whereas tall children on IBC moved more laterally than when they were seated on BC1. In evasive turns the movement for all children was higher than in the less evasive turns, but the movement of short children was still greater than the movement of tall ones. Though, during the evasive turns, tall children on BC1 moved more than when they were on IBC.

From the plots in Figure 18 and 25 it is possible to see that for both short and tall children there was a rapid movement of the head from the initial position in the beginning and then for tall children there was a clear movement back trying to move the head in the opposite direction, whereas for short children this head movement toward the initial position was not so evident. This may be due to the fact that tall children have stronger muscles in the neck than short children and, thus, they are able to control head's movement after the first lateral movement.

Concerning the lateral movement of the upper torso in the less evasive manoeuvres, short and tall children on BC1 had very similar inboard displacement. On the other hand, when they were restrained on the IBC they moved more laterally and this was evident in particular for short children. In the evasive turns, instead, for short children there were no substantial differences on the lateral displacement regarding the type of booster, whereas tall children moved much less laterally when restrained on IBC, keeping the amount of the displacement close to the one measured for the less evasive manoeuvres.

Regarding the head's tilting angle during the less evasive turns, the major difference between short and tall children was that initially the short ones tilted inboard and then, trying to bring the head back to the initial position, their head tilted in the opposite direction, whereas taller children had an initial phase where the head's angle was almost constant around the initial value, and then as for short children their head tilted outboard in an attempt to withstand the lateral acceleration. Furthermore, short children had a higher head tilting angle than the tall children and, during the evasive turns, the difference in inboard head tilting angle became more significant. In this case, as in the head's lateral movement, this may be due to the more developed neck of taller children.

Short and tall children on IBC had a slightly higher head's tilting angle than when they were restrained on BC1. At the time points T2 and T3, the tilting angles from the initial position were rather small (on average 0.5° outboard at T2 and 0.4° inboard at T3). The maximum value for the tilting angle was reached after T3 and in general it was reached earlier when the child was restrained on the IBC than when he/she was on BC1. This is clearly observable in the data from the evasive turns.

Children's torsos tilted inboard less than the heads for both short and tall children regardless of the type of booster, but the attempt to move the body against the lateral acceleration was still present and the children were tilting outboard. Nevertheless, when restrained on BC1 during evasive manoeuvres, tall children had a higher inboard tilting than when they were restrained on IBC. On the other hand, short children moved less when they were restrained on BC1. This can be due to the fact that short children, when restrained on BC1, may have the tendency to hold the guiding loop and, thus, limit the tilting of the torso. Some of the short children, in fact, after the trials said that the felt safer when restrained on BC1 than on IBC and the reason could be that on the BC1 they could hold onto the guiding loops.

From the results of the head's and torso's lateral displacement and tilting angle, it seems that for the less evasive steering manoeuvres there was not a great difference between the performances of the two boosters considered in this study. A clear difference was present in the evasive steering manoeuvres, where the IBC seemed to provide better restraint performances for tall children since they moved less and the belt remained fixed on the shoulder. It may be due to the fact that tall and older children have a better control of their body not only because of stronger and more developed muscles but also because children improve their physical performances over time with experience and practice (Bohman et al. 2011b).

A similar study was conducted previously by Bohman et al. (2011b). Short and tall children were tested on the BC1 while performing a turn similar to the evasive turn performed in this study. Considering the values for the upper torso lateral displacement obtained in Bohman et al.'s study, they were higher than those measured in this study. In the previous study, short children restrained on BC1 moved, on average, 65mm (T2) and 75mm (T3) more inboard than the short children in this study. Also tall children had a greater lateral displacement of the upper torso in Bohman et al.'s study. In fact tall children on BC1 moved on average 51mm at T2 and 27mm at T3 more inboard than the tall children in this study. However the values become similar if the maximum lateral displacement measured in this study is considered, but they were, almost always, reached after the time point T3. Hence, the upper torso lateral displacement was faster in the Bohman et al.'s study than in this study.

Since in both studies the same car and the same professional driver were used, this variation in the lateral displacement may be due to differences in the curve dimensions. In Bohman et al.'s study, the radius of the curve was 14m, while in this study for the evasive manoeuvres the radius was 16.5m. Another reason may be the difference in the trend of the lateral acceleration. Figure 29 shows the mean lateral acceleration for the Bohman et al.'s study and the mean lateral acceleration for the less evasive and evasive manoeuvres performed in this study. It can be seen that in the first phase, where the less evasive and the evasive lateral acceleration decrease gently, the lateral acceleration from Bohman et al.'s study is flat and then suddenly decreases very quickly. This sudden decrease can be the cause of the greater and faster lateral displacement of the upper torso measured by Bohman et al. (2011b).

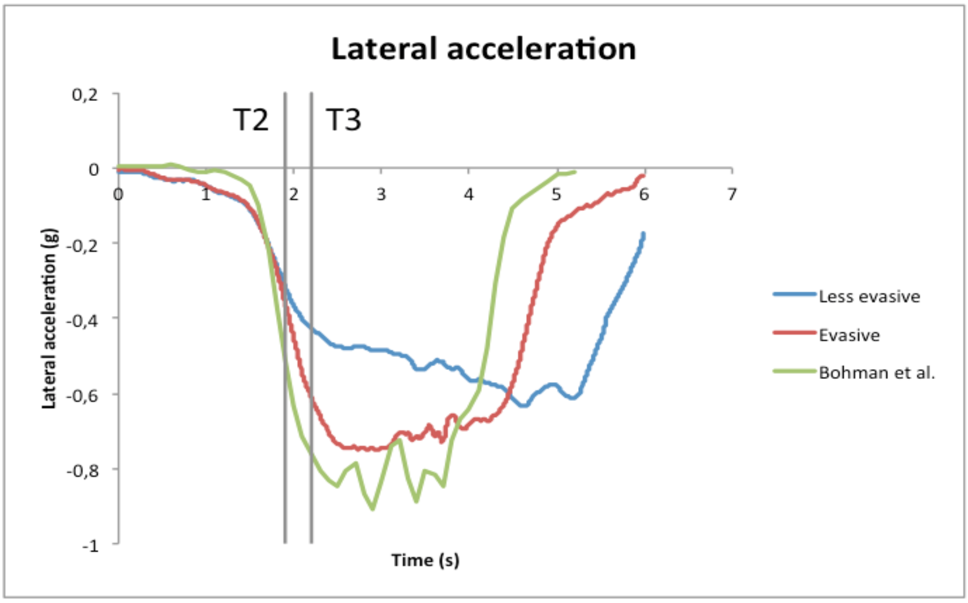

Figure 29 – Mean lateral acceleration in Bohman et al.*'s study and for the less evasive and evasive manoeuvres performed in this study.*

Considering the lateral movement relative to the centre of the seat, which results are presented in Appendix C, it is easy to see from the plots that most of the children were seated more outboard with respect to the centreline of the seat at the beginning of the manoeuvre. In most of the trials, therefore, the effect of the lateral acceleration did not lead to a great lateral displacement from the centre of the seat. Some of the children did not even move beyond the centreline of the seat, staying for the whole manoeuvre on the outboard side of this line. In particular, the children from the tall group, who moved less from the initial position compared to the short children, had a small inboard displacement from the centre of the seat.

Differences in the shoulder belt position on the shoulder between short and tall children and between BC1 and IBC among the group of short children were found. In fact, unlike for the tall children, for short children the shoulder belt slipped off in most of the cases when they were restrained on BC1, whereas only two times the belt slipped off when using the IBC. The reason for this difference may be found in the belt fit assessed with the static belt measurement. In fact, when short children were seated on the IBC in some cases the shoulder belt was close to the neck and the child needed to move more inboard in order to make the belt slip off the shoulder, in other cases there were contact between the top of the shoulder and the belt, therefore the belt had a more grabbing effect on the shoulder, like for the tall children.

The reason why no belt slip-off occurred for tall children can be found in the analysis of the static belt measurement. The presence of the contact between shoulder and belt as well as a good belt fit contributed to keep the shoulder belt in position. The absence of gap between the shoulder belt and the lower torso, on the other hand, provided a tighter restraint of the torso limiting its inboard tilting. Furthermore, tall children tried to move forward the outboard shoulder and to slightly rotate the upper torso in order to keep the shoulder belt on the shoulder.

In some cases among short children, the initial shoulder belt position was position C at T1, while in the static belt measurements it was in position B. This can be explained by the fact that from the time when the photos for the static belt measurements were taken to the event's start the children often moved to look around, since no instruction on how to behave during the trials was given to the children, in order to have the children behaving as naturally as possible. Thus, due to these movements the position of the belt changed.

4.3 Future work

The data presented in this study show that there are differences between short and tall children not only in the kinematic response but also in the belt fit. For this reason further studies are needed to evaluate the initial belt fit and its relation with the kinematics during pre-crash manoeuvres. In particular, the role played by the shoulder belt and how tight the shoulder belt is on the torso should be further investigated also on different type of restraint system and in different test conditions, such as using a different car and test a different curve.

5 Conclusions

The main conclusions regarding the methodology are the following:

- For the static belt measurement, the positions defined for the shoulder belt are related to the optimal belt fit suggested by Reed et al. (2009). Also for the lap belt three different positions were defined considering the optimal belt fit as when the lap belt was horizontal on the thighs loading the pelvis.
- The presence of a gap between lower torso and shoulder belt and the presence of a contact between belt and shoulder were considered in order to understand if they can affect the outcome of the kinematic response as well the initial position of the belt.
- Regarding the method used for the analysis of the kinematic response, the tracking of the parameters of interest was performed throughout the whole steering event. In this way the child's movement could be studied at every time point of the 6s' event and not only in the two time points T2 and T3.
- The inboard movement and tilting angle of the head and torso were studied separately since they move in different way.
- The shoulder belt position on the shoulder was investigated throughout the steering event, checking also the time and the lateral acceleration relative to the eventual belt slip off.

The main conclusions concerning the static belt measurement are the following:

- No differences were found in terms of belt fit between the two booster cushions BC1 and BC2 used in the static belt measurement.
- Differences were found if the shoulder belt was above or under the inboard guiding loop of the booster cushions BC1 and BC2: if the shoulder belt was under the guiding loop the presence of a gap between the lower torso and the shoulder belt was more likely than when the shoulder belt was above the guiding loop.
- The IBC was found more optimal, especially for tall children, in terms of belt fit according to Reed et al. (2009) as compared to the BC1. For short children, instead, it did not improve the belt fit obtained on the BC1, since the lap belt was not horizontal and positioned only partly on the pelvis in some of the cases. The improvement was in terms of gap between shoulder belt and lower torso, since the number of cases with the presence of gap decreased, and in terms of shoulder-belt contact, since on IBC the number of cases with this kind of contact increased, providing a tighter restraint of the torso.

The main conclusions concerning the kinematic response are the following:

- For the less evasive manoeuvres, there was no significant difference in the lateral inboard movement for short children on BC1 and on IBC. Tall children moved laterally to a greater extent when they were restrained on IBC than when restrained on BC1.
- In the evasive manoeuvres, the lateral movement was higher than in the less evasive curves for all the children, but the displacement of short children was still greater than the displacement of the tall children.

- For short children the shoulder belt slipped off in the majority of cases when they were restrained on BC1 and only two times when restrained on IBC during the less evasive manoeuvres. During more evasive manoeuvres the shoulder belt slip-off occurred in all the trials when the short children were restrained on BC1.
- No belt slip-off occurred for tall children during the less evasive manoeuvre and only in one trial during the more evasive steering when restrained on BC1. This may be related to the presence of a contact between the shoulder and the belt assessed during the static belt measurement, but further studies are needed to investigate this relation.

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APPENDIX A – Static belt measurement

Table A1 - Static belt measurement on the BC2 for the shoulder belt above the guiding loops and under the guiding loops. Shaded rows correspond to short children.

# child	BC2 - belt above the guides				BC2 - belt under the guides			
	shoulder belt	lap belt	gap	contact	shoulder belt	lap belt	gap	contact
1	B	C	no	yes	B	C	yes	no
2	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
4	B	C	no	yes	B	B	-	-
5	A	B	no	no	B	B	yes	yes
6	B	C	no	yes	B	C	yes	yes
7	B	B	no	yes	C	B	yes	yes
8	A	B	no	no	A	B	no	no
9	B	C	no	yes	A	B	yes	yes
10	A	B	no	no	A	B	no	no
11	B	B	no	no	C	B	yes	no
12	A	C	no	no	A	B	yes	no
13	B	B	yes	no	B	C	yes	no
14	B	B	no	yes	B	B	yes	yes
15	A	B	no	no	A	B	yes	no
16	A	B	no	no	B	B	yes	no
17	B	C	yes	yes	B	C	no	yes
18	B	B	no	yes	C	B	yes	yes

Table A2 - Static belt measurement on the Volvo Booster Seat with backrest removed. Shaded rows correspond to short children.

# child	BC with backrest removed - belt above the guides				BC with backrest removed - belt under the guides			
	Shoulder belt	Lap belt	Gap	Contact	Shoulder belt	Lap belt	Gap	Contact
1	B	C	Yes	Yes	C	C	Yes	No
2	B	C	No	Yes	C	B	No	No
3	A	B	Yes	No	A	B	Yes	No
4	B	B	No	Yes	B	B	Yes	Yes
5	B	C	No	Yes	B	C	Yes	Yes
6	C	C	No	Yes	B	C	-	Yes
7	B	B	Yes	Yes	C	B	Yes	Yes
8	B	B	No	No	B	B	Yes	No
9	B	B	No	Yes	A	C	Yes	Yes
10	A	B	Yes	No	A	B	Yes	No
11	B	B	Yes	Yes	B	B	Yes	Yes
12	A	B	Yes	No	B	B	Yes	No
13	B	C	Yes	No	B	C	Yes	No
14	B	C	Yes	Yes	B	C	Yes	Yes
15	A	C	No	Yes	B	C	Yes	No
16	B	B	No	Yes	B	B	Yes	Yes
17	B	C	Yes	Yes	B	C	Yes	Yes
18	B	B	Yes	Yes	B	B	Yes	Yes

Table A3 - Static belt measurements on integrated booster. The shaded rows correspond to short children.

	Integrated Booster			
# child	Shoulder belt	Lap belt	Gap	Contact
1	B	B	no	no
2	-	-	-	-
3	-	-	-	-
4	B	B	no	yes
5	B	B	no	yes
6	C	B	-	yes
7	B	A	no	yes
8	B	A	no	yes
9	B	A	no	yes
10	A	A	no	no
11	B	A	no	yes
12	A	A	yes	no
13	B	B	no	yes
14	B	A	yes	yes
15	A	A	no	no
16	B	A	no	yes
17	B	B	no	yes
18	B	B	no	yes

APPENDIX B – Results of the kinematic response with respect to the initial position

Table B1 – Head lateral displacement with respect to the initial position at time point T2, T3 and the maximum value for short children restraint on BC1.

Child	Head lateral displacement [mm]			
	displ T2	displ T3	max displ	time max
1	26,18	19,48	49,70	5,34
2	50,47	111,47	263,27	5,48
3	104,39	185,45	201,70	3,36
	58,87	104,10	124,47	2,36
8	14,72	33,29	75,10	4,82
	16,92	37,78	46,80	5,34
9	24,52	81,26	126,00	2,44
	73,10	68,68	99,02	1,42
11	35,86	72,27	111,31	5,36
	52,55	57,77	67,76	5,44
12	22,10	25,96	38,39	2,60
	42,07	101,22	111,42	2,30
13	28,47	51,05	73,41	4,80
	34,43	50,43	78,90	4,78
15	-1,43	15,29	100,52	5,44
	12,16	42,07	46,16	2,26
16	7,43	7,55	63,76	5,32
	-9,50	19,25	64,63	5,30
Average	32,96	60,24	96,80	4,12
St dev	27,74	44,47	57,28	1,47

Table B2 – Changes in head angle with respect to the initial position at time points T2 and T3 and maximum value for short children on BC1.

child	Changes in head angle [degrees]			
	change T2	change T3	max change	time max
1	7,60	11,82	-23,40	5,38
2	-6,70	-10,60	-22,40	5,54
3	-5,30	-17,00	-22,00	2,68
	-5,20	-8,70	-9,40	2,34
8	1,20	0,30	-5,30	4,84
	-0,80	-3,70	-4,00	2,24
9	-2,20	-7,40	-13,60	2,42
	6,40	7,70	-6,30	0,30
11	-3,90	-6,50	-6,50	2,12
	-6,00	-4,60	-6,30	1,84
12	1,60	1,80	-0,20	0,02
	0,40	-2,40	-5,90	5,44
13	-2,70	-4,20	-4,30	2,22
	-1,20	3,40	-2,90	1,38
15	2,00	0,80	-14,30	5,40
	5,30	5,40	-5,30	0,94
16	-2,00	7,40	-2,30	1,88
	8,20	2,50	-8,60	5,30
Average	-0,18	-1,33	-9,06	2,90
St dev	4,67	7,30	7,15	1,89

Table B3 – Upper torso lateral displacement with respect to the initial position at time points T2, T3 and the maximum value for short children on BC1.

child	Upper torso lateral displacement [mm]			
	displ T2	displ T3	max displ	time max
1	28,53	30,31	48,62	3,46
2	24,73	66,68	186,00	5,46
3	29,63	80,54	107,20	5,06
	21,26	49,22	88,70	5,12
8	16,96	34,89	71,21	5,26
	18,38	35,29	59,55	5,32
9	13,71	49,37	69,61	4,66
	70,12	70,58	80,91	3,70
11	13,38	35,83	71,81	5,32
	26,78	33,15	72,33	5,44
12	24,71	21,76	24,81	1,94
	37,55	78,46	87,09	2,32
13	15,42	29,34	66,00	5,36
	22,90	41,57	75,22	5,24
15	-3,50	2,30	44,73	5,74
	19,42	45,21	86,51	5,96
16	15,29	22,72	56,52	5,32
	7,59	29,88	45,10	5,28
Average	22,38	42,06	74,55	4,78
St dev	15,01	20,82	33,96	1,15

Table B4 – Changes in torso tilting angle with respect to the initial position at time points T2, T3 and the maximum value for short children on BC1.

child	Changes in torso tilting angle [degrees]			
	change T2	change T3	max change	time max
1	-1,00	-1,10	-1,10	2,24
2	-	-	-	-
3	-3,60	-10,00	-13,30	4,64
	-2,20	-4,90	-7,90	4,96
8	1,10	2,80	-0,40	1,12
	-1,10	-0,80	-1,20	2,00
9	4,70	6,40	0,00	0,00
	0,30	-0,30	-0,30	2,16
11	0,10	0,10	-2,30	3,04
	-0,30	-1,50	-4,50	2,48
12	-3,10	-3,00	-3,20	2,00
	-4,70	-5,70	-5,70	2,24
13	-0,80	-0,20	-0,80	1,44
	1,30	-0,60	-0,90	1,52
15	-1,40	-0,80	-1,90	0,56
	4,00	8,80	-0,50	0,64
16	-0,10	0,50	-3,10	5,20
	-0,30	0,20	-1,70	5,12
Average	-0,42	-0,59	-2,87	2,43
St dev	2,41	4,27	3,43	1,64

Table B5 – Head lateral displacement with respect to the initial position at T2, T3 and the maximum value for short children on IBC.

child	Head lateral displacement [mm]			
	displ T2	displ T3	max displ	time max
1	-	-	-	-
2	-5,96	51,98	188,33	5,02
3	39,52	58,45	73,60	4,82
	104,10	125,94	130,60	2,12
8	13,64	16,83	62,50	5,36
	4,10	29,16	82,23	4,80
9	22,54	48,11	105,57	2,50
	22,87	80,18	124,26	4,74
11	5,82	-5,07	58,04	5,46
	27,18	58,96	81,14	4,72
12	39,64	88,43	91,32	2,26
	27,38	112,30	126,51	2,36
13	30,98	97,82	112,88	2,34
	23,41	62,30	93,41	4,92
15	34,36	75,10	103,43	2,48
	11,90	14,37	66,70	5,44
16	-6,56	18,21	30,00	5,22
	5,75	24,82	55,15	5,34
Average	23,57	56,35	93,27	4,11
St dev	25,28	37,13	37,20	1,37

Table B6 – Changes in head angle with respect to the initial position at T2, T3 and the maximum value for short children on IBC.

child	Changes in head angle [degrees]			
	change T2	change T3	max change	time max
1	-	-	-	-
2	-0,90	-3,10	-6,80	3,28
3	-3,00	-2,10	-3,30	2,00
	-11,90	-10,20	14,40	1,94
8	2,70	7,60	-8,40	1,40
	3,50	-0,30	-2,40	1,44
9	2,30	2,70	-4,40	2,38
	0,00	-1,40	-4,70	4,74
11	-6,20	-3,20	-6,90	2,00
	-3,60	-8,50	-10,50	2,34
12	-2,70	-5,70	-6,20	2,28
	-2,90	-10,00	-10,90	2,26
13	-1,20	-7,70	-8,70	2,30
	0,10	-0,60	-2,30	0,90
15	-1,40	-3,00	-3,30	2,46
	-0,70	-0,70	-2,70	0,80
16	4,40	-1,70	-3,50	0,92
	5,90	3,60	-4,50	4,80
Average	-0,92	-2,61	-4,42	2,25
St dev	4,24	4,81	5,57	1,15

Table B7 – Upper torso lateral displacement with respect to the initial position at T2, T3 and the maximum value for short children on IBC.

child	Upper torso lateral displacement [mm]			
	displ T2	displ T3	max displ	time max
1	-	-	-	-
2	41,45	80,97	152,30	5,48
3	20,43	37,20	87,90	4,82
	50,37	63,81	102,20	5,24
8	18,55	29,38	90,70	5,34
	11,33	26,57	71,67	5,34
9	13,85	42,98	69,27	2,46
	16,53	66,86	107,46	4,70
11	6,37	10,04	50,29	5,46
	20,73	32,62	53,29	4,72
12	20,43	53,46	66,73	5,34
	30,86	76,46	90,07	5,34
13	24,57	68,80	91,72	5,26
	21,18	57,81	92,78	5,36
15	27,51	50,65	76,29	5,18
	11,05	20,80	62,45	5,48
16	14,64	30,04	46,35	5,24
	13,17	27,06	51,05	5,32
Average	21,35	45,62	80,15	5,06
St dev	11,23	21,06	26,58	0,71

Table B8 – Changes in torso tilting angle with respect to the initial position at T2, T3 and the maximum value for short children on IBC.

child	Changes in torso angle [degrees]			
	change T2	change T3	max change	time max
1	-	-	-	-
2	-3,50	-6,20	-12,60	4,48
3	0,20	-0,40	-1,60	2,08
	-1,30	0,90	-2,60	1,52
8	0,70	1,20	-2,00	5,36
	6,50	6,20	0,00	0,00
9	1,00	0,30	-0,50	6,00
	0,30	0,00	-0,20	0,40
11	2,80	3,10	-0,20	1,12
	-0,90	-0,30	-2,10	1,20
12	-0,40	-2,40	-2,60	2,08
	-4,10	-4,30	-4,70	2,00
13	0,40	-1,40	-1,40	2,16
	0,80	2,70	-0,40	5,60
15	0,00	0,30	-0,30	1,68
	1,90	3,00	-0,30	0,80
16	-0,70	-0,20	-0,70	1,90
	0,80	1,30	-0,30	0,72
Average	0,26	0,22	-1,91	2,30
St dev	2,34	2,88	3,03	1,88

Table B9 – Head lateral displacement with respect to the initial position at T2, T3 and the maximum value for tall children on BC1.

child	Head lateral displacement [mm]			
	displ T2	displ T3	max displ	time max
4	-4,07	-6,83	0,40	2,36
	30,79	33,45	130,89	4,98
5	51,98	123,18	132,04	2,26
	14,15	65,72	90,56	2,38
6	47,51	101,53	148,42	2,64
	-16,56	37,14	72,56	5,34
7	0,49	49,82	81,17	5,32
	-5,56	19,08	66,60	5,30
10	13,48	34,67	37,18	2,34
	-25,86	-19,83	12,65	0,84
14	11,98	33,19	54,56	5,32
	9,81	28,13	79,24	4,88
17	17,59	30,80	41,83	4,84
	-3,41	20,95	37,45	4,72
18	19,04	63,10	90,68	5,20
	12,87	37,56	39,02	2,24
Average	10,89	40,73	69,70	3,81
St dev	20,77	35,51	42,46	1,57

Table B10 – Changes in head angle with respect to the initial position at T2, T3 and the maximum value for tall children on BC1.

child	Changes in head angle [degrees]			
	change T2	change T3	max change	time max
4	-9,30	-8,80	-13,00	2,94
	0,60	3,50	-11,60	4,96
5	-4,70	-5,10	-7,20	1,52
	2,90	0,50	-2,70	2,38
6	-1,50	-5,70	-11,50	2,62
	11,00	8,20	-2,60	5,98
7	5,70	3,70	-4,20	5,34
	-4,40	-6,70	-9,80	4,12
10	-0,10	-0,40	-2,50	1,48
	22,10	25,60	-1,00	0,80
14	1,20	2,60	-0,80	0,14
	6,50	10,00	-0,10	0,24
17	-4,10	0,30	-8,30	1,42
	3,90	3,90	-0,30	0,04
18	-1,10	-1,10	-3,00	4,04
	0,70	5,70	-0,30	0,68
Average	1,84	2,26	-4,93	2,42
St dev	7,32	8,18	4,56	1,96

Table B11 – Upper torso lateral displacement with respect to the initial position at T2, T3 and the maximum value for tall children on BC1.

child	Upper torso lateral displacement [mm]			
	displ T2	displ T3	max displ	time max
4	-15,48	-14,99	0,00	0,00
	21,65	33,58	101,96	5,54
5	38,27	111,29	128,57	4,80
	21,56	65,93	90,31	5,32
6	31,53	69,72	105,68	3,84
	17,49	62,87	99,16	5,28
7	18,61	56,88	66,95	5,32
	15,49	37,55	65,78	5,24
10	15,93	32,97	55,55	5,24
	20,77	31,61	56,85	4,76
14	11,17	30,64	50,62	5,28
	22,39	42,82	74,14	5,32
17	7,75	30,74	46,05	5,26
	10,72	34,80	48,58	5,20
18	16,31	62,66	98,75	5,82
	15,08	52,16	64,79	4,14
Average	16,83	46,33	72,11	4,77
St dev	11,47	26,91	31,10	1,37

Table B12 – Changes in torso tilting angle with respect to the initial position at T2, T3 and the maximum value for tall children on BC1.

child	Changes in torso angle [degrees]			
	change T2	change T3	max change	time max
4	-1,20	-1,30	-4,80	5,84
	0,10	0,40	-0,90	1,04
5	-	-	-	-
	3,20	4,60	-0,20	0,08
6	-5,30	-6,30	-6,90	2,00
	-0,50	-3,30	-3,60	2,24
7	1,60	4,50	-0,10	0,08
	2,00	1,70	-0,90	6,00
10	-1,60	-5,60	-7,30	2,08
	-3,40	-8,70	-8,90	2,08
14	3,60	4,10	0,00	0,00
	2,50	1,60	-0,20	0,08
17	0,80	0,30	-0,50	0,64
	1,50	2,10	-0,20	0,56
18	-0,10	-2,80	-2,90	2,24
	1,20	1,70	-0,20	1,12
Average	0,29	-0,47	-2,51	1,74
St dev	2,43	4,10	3,07	1,90

Table B13 – Head lateral displacement with respect to the initial position at T2, T3 and the maximum value for tall children on IBC.

child	Head lateral displacement [mm]			
	displ T2	displ T3	max displ	time max displ
4	44,17	106,63	111,26	2,26
5	29,93	68,83	122,16	5,30
6	-7,31	21,53	55,76	5,92
	-15,48	-35,42	42,32	3,68
7	29,18	45,40	127,83	5,34
	6,29	-7,76	105,88	5,32
10	11,19	26,16	45,72	2,58
	1,57	36,34	53,37	5,34
14	20,78	70,38	89,72	2,40
	36,37	77,99	89,05	2,36
17	6,05	33,66	69,32	5,38
	-10,56	22,10	114,75	5,20
18	5,18	57,47	67,18	2,32
	24,40	42,37	52,36	2,38
Average	12,98	40,41	81,91	3,98
St dev	18,24	36,00	30,36	1,52

Table B14 – Changes in head tilting angle with respect to the initial position at T2, T3 and the maximum value for tall children on IBC.

child	Changes in head angle [degrees]			
	change T2	change T3	max change	time max
4	-4,40	-5,80	-6,50	1,58
5	0,50	0,10	-2,80	2,46
6	4,10	4,40	-0,40	0,38
	8,30	10,10	-0,90	0,28
7	-5,40	-10,30	-27,00	5,34
	2,50	9,00	-1,40	1,42
10	3,30	3,80	-1,90	1,00
	2,80	1,30	-1,90	1,40
14	1,40	-0,10	-2,90	2,38
	-3,00	-4,00	-4,60	1,54
17	-0,20	-4,80	-10,80	2,62
	7,60	3,90	-19,30	5,24
18	3,00	1,70	-2,10	5,12
	1,40	3,30	0,50	1,18
Average	1,56	0,90	-5,86	2,28
St dev	3,97	5,65	8,00	1,74

Table B15 – Upper torso lateral displacement with respect to the initial position at T2, T3 and the maximum value for tall children on IBC.

child	Upper torso lateral displacement [mm]			
	displ T2	displ T3	max displ	time max
4	28,18	77,32	106,40	5,20
5	23,32	61,64	112,66	5,86
6	9,57	29,58	54,16	5,14
	16,23	15,21	58,20	5,36
7	25,36	52,03	112,14	5,28
	20,69	25,86	107,02	5,30
10	18,56	35,91	62,50	5,28
	20,58	44,07	59,05	4,82
14	19,99	58,25	82,52	4,74
	25,71	60,13	71,24	5,32
17	19,39	20,10	50,18	5,34
	9,84	26,93	45,69	5,12
18	12,77	49,14	54,74	5,08
	18,89	36,48	55,65	5,08
Average	19,22	42,33	73,73	5,21
St dev	5,64	18,16	25,18	0,26

Table B16 – Changes in torso tilting angle with respect to the initial position at T2, T3 and the maximum value for tall children on IBC.

child	Changes in torso angle [degrees]			
	change T2	change T3	max change	time max
4	-0,30	-2,70	-7,60	5,92
5	2,50	3,20	0,00	0,00
6	1,30	1,70	-0,60	0,24
	2,40	3,10	-0,30	0,24
7	-0,40	-1,10	-2,90	5,12
	2,30	5,80	-0,50	0,96
10	2,80	3,20	-3,40	1,04
	2,50	-2,10	-2,70	2,08
14	1,60	0,60	-0,10	0,40
	1,30	1,00	-0,50	1,28
17	0,60	-0,20	-0,30	0,48
	1,40	2,40	-0,20	0,08
18	0,50	-0,70	-0,80	2,08
	-0,20	1,20	-0,20	1,20
Average	1,31	1,10	-1,44	1,51
St dev	1,12	2,35	2,11	1,83

APPENDIX C – Results of the kinematic response with respect to the centre of the seat

- CHILD 1

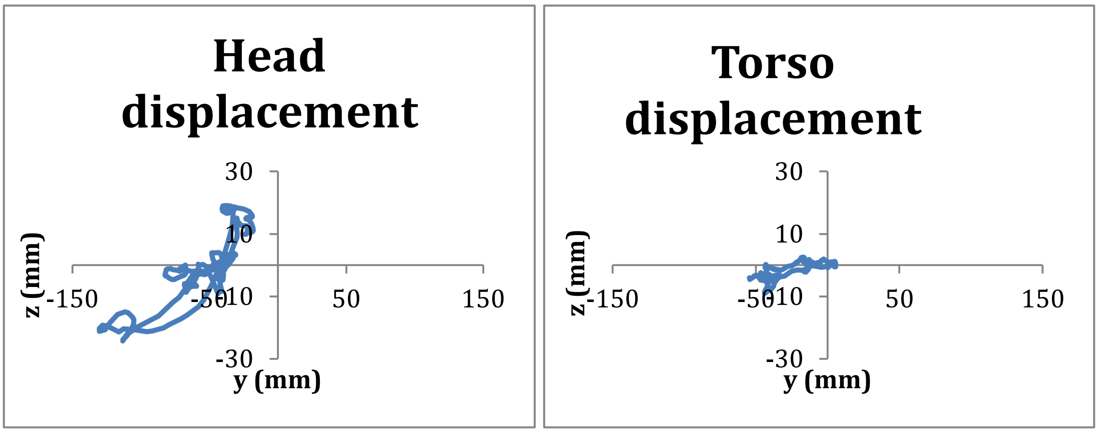


Figure C1 – Head and torso lateral displacements with respect to the centre of the seat for steering 1.

- CHILD 2

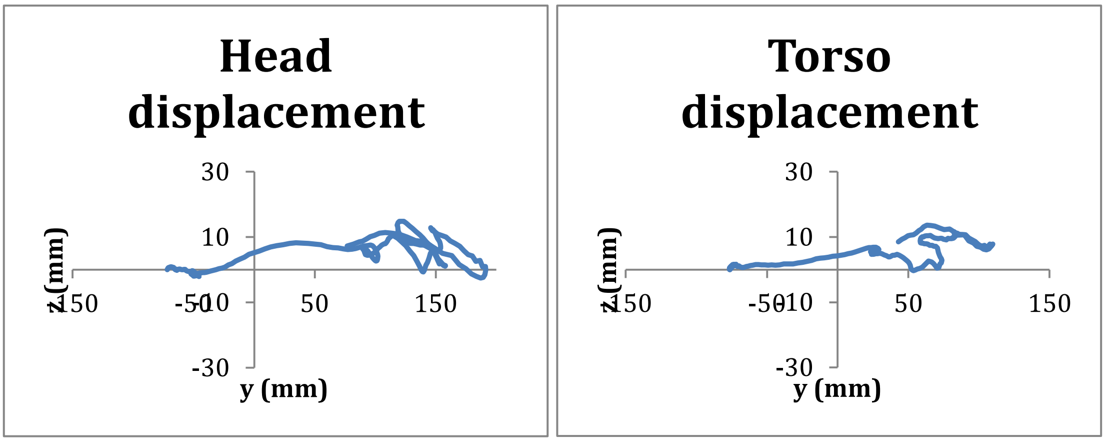


Figure C2 – Head and torso lateral displacement with respect to the centre of the seat for steering 1.

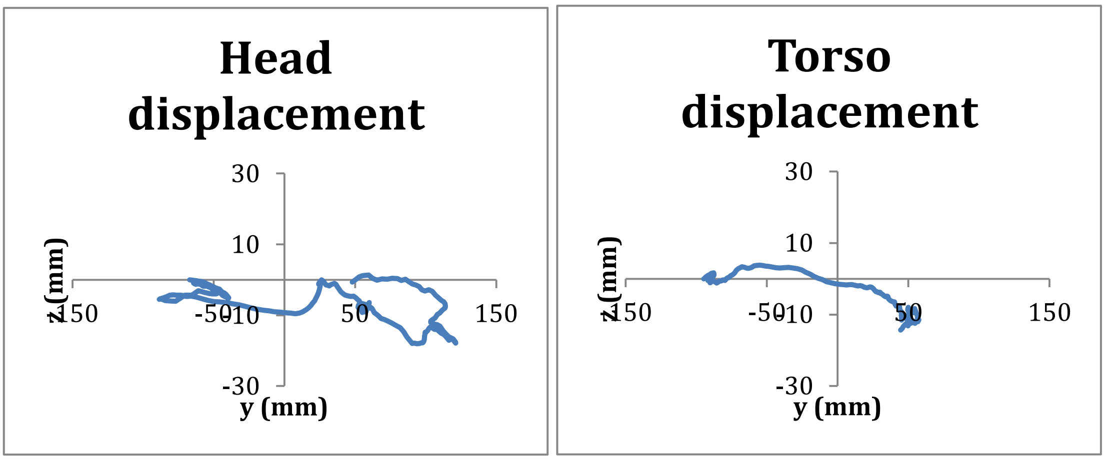


Figure C3 – Head and torso lateral displacement with respect to the centre of the seat for steering 4.

- CHILD 3

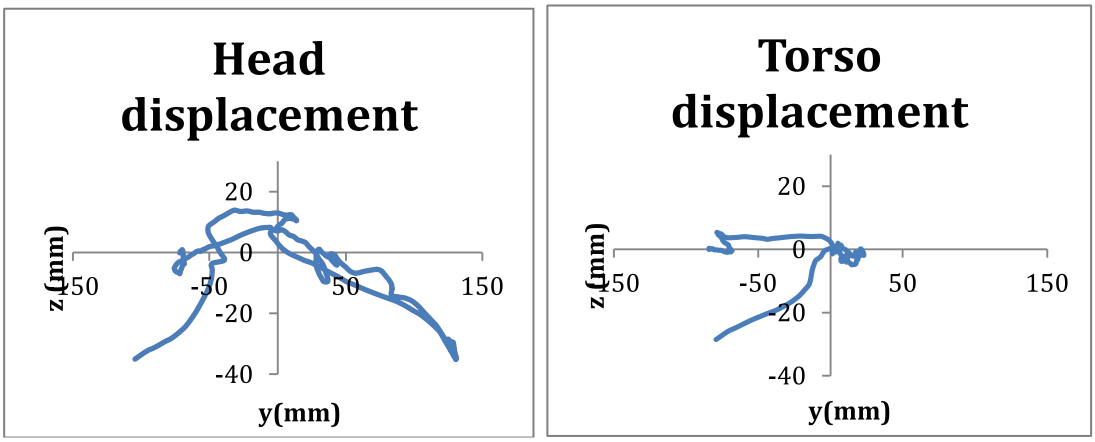


Figure C4 – Head and torso lateral displacement with respect to the centre of the seat for steering 1.

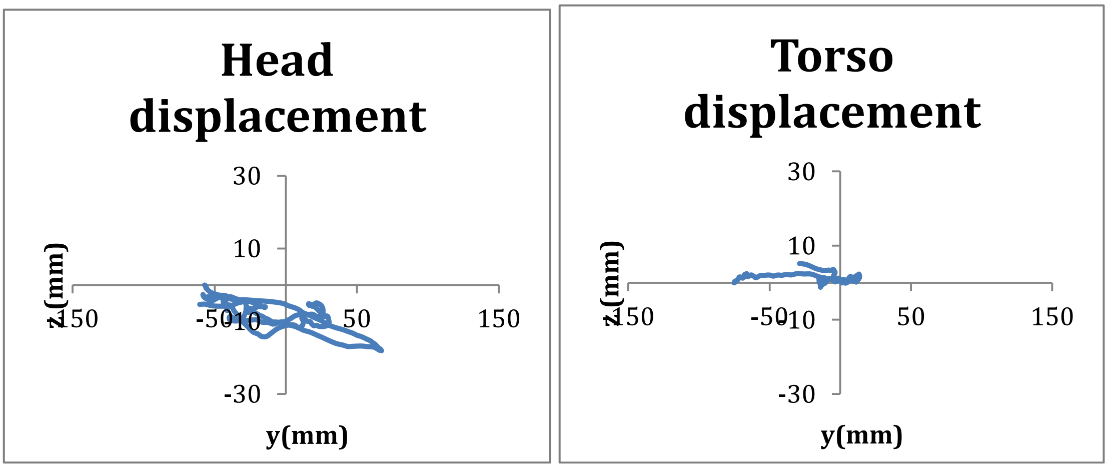


Figure C5 – Head and torso lateral displacement with respect to the centre of the seat for steering 2.

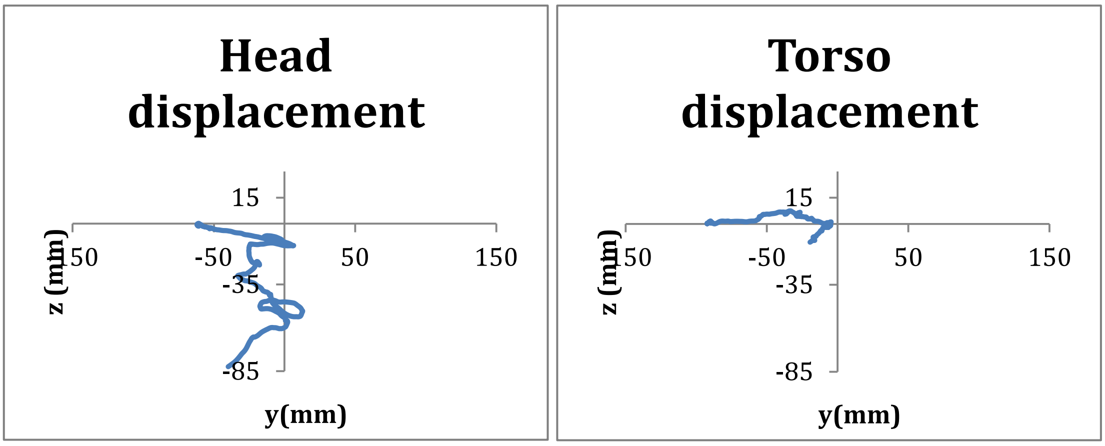


Figure C6 – Head and torso lateral displacement with respect to the centre of the seat for steering 3.

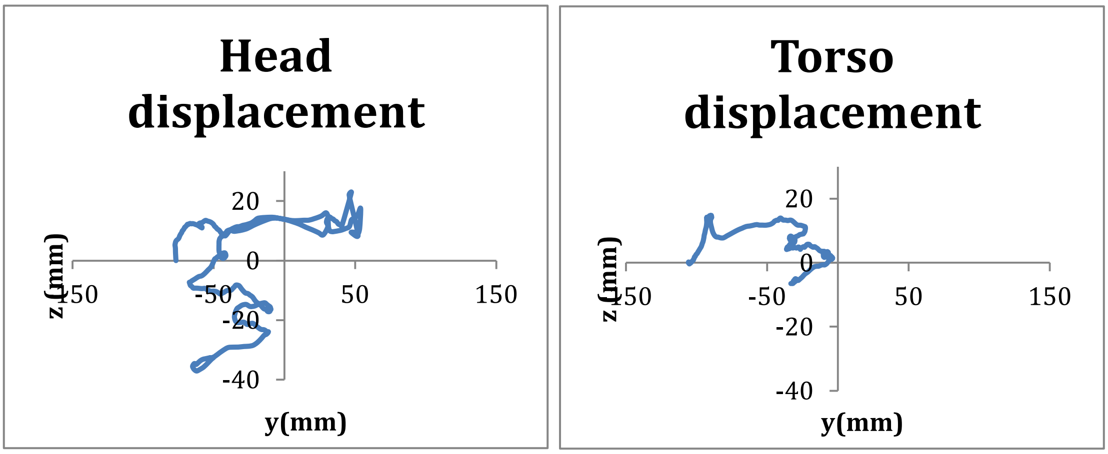


Figure C7 – Head and torso lateral displacement with respect to the centre of the seat for steering 4.

- CHILD 4

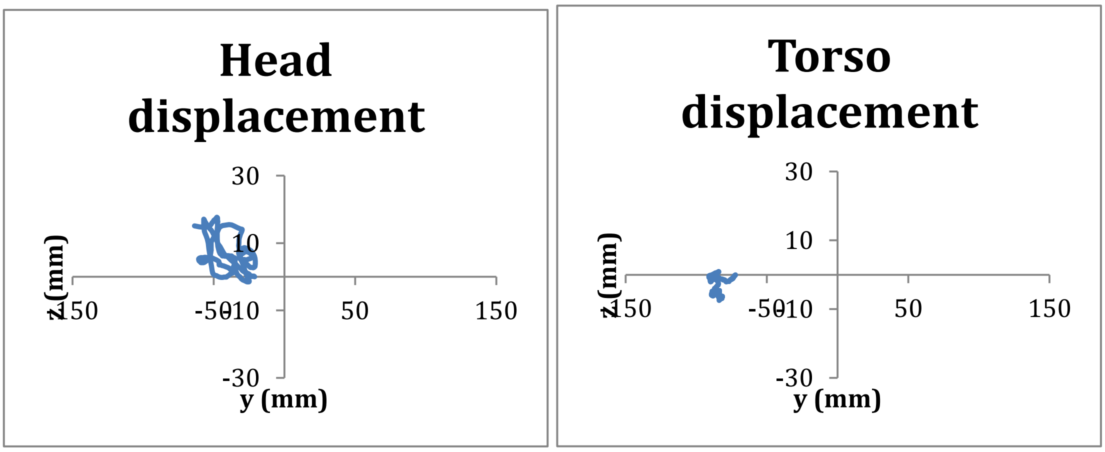


Figure C8 – Head and torso lateral displacement with respect to the centre of the seat for steering 1.

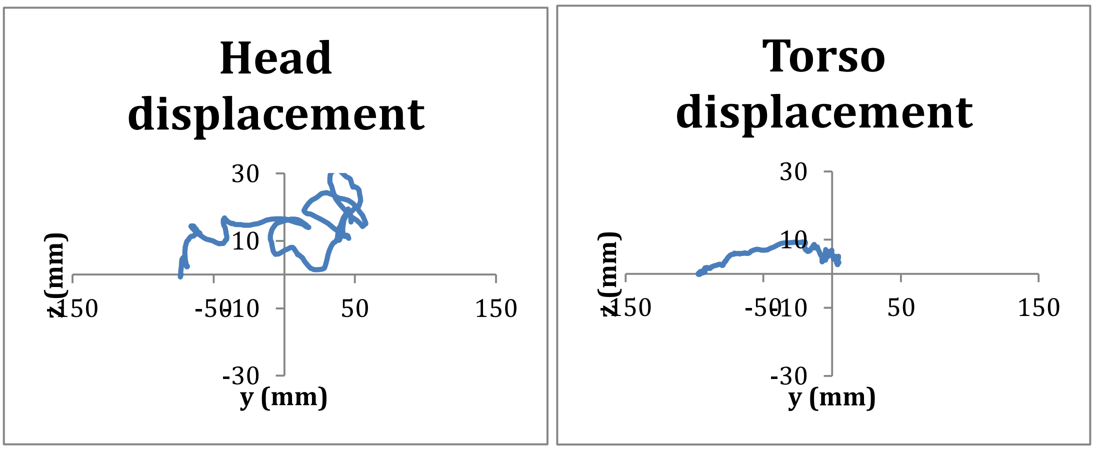


Figure C9 – Head and torso lateral displacement with respect to the centre of the seat for steering 2.

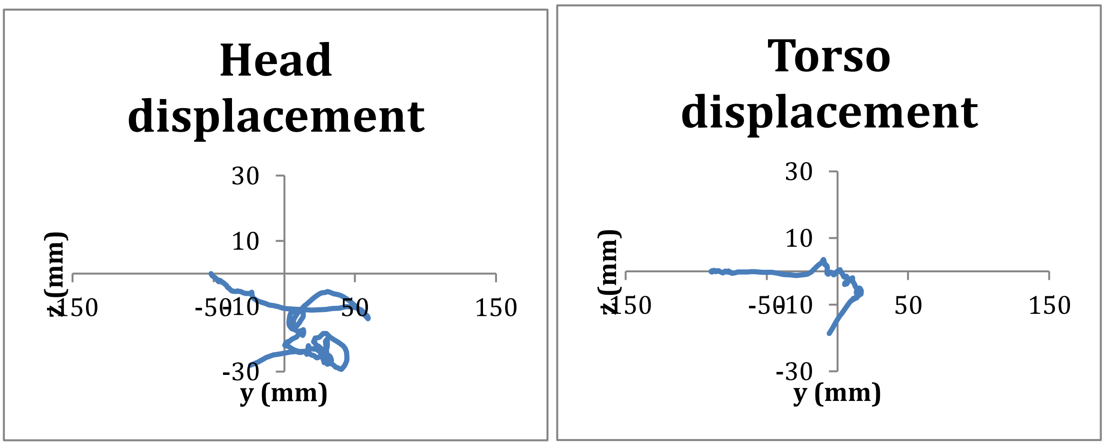


Figure C10 – Head and torso lateral displacement with respect to the centre of the seat for steering 3.

- CHILD 5

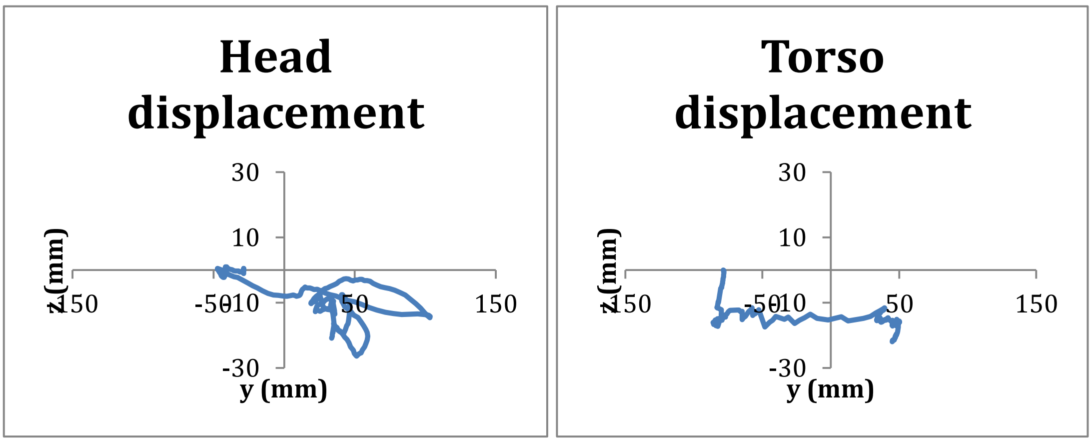


Figure C11 – Head and torso lateral displacement with respect to the centre of the seat for steering 1.

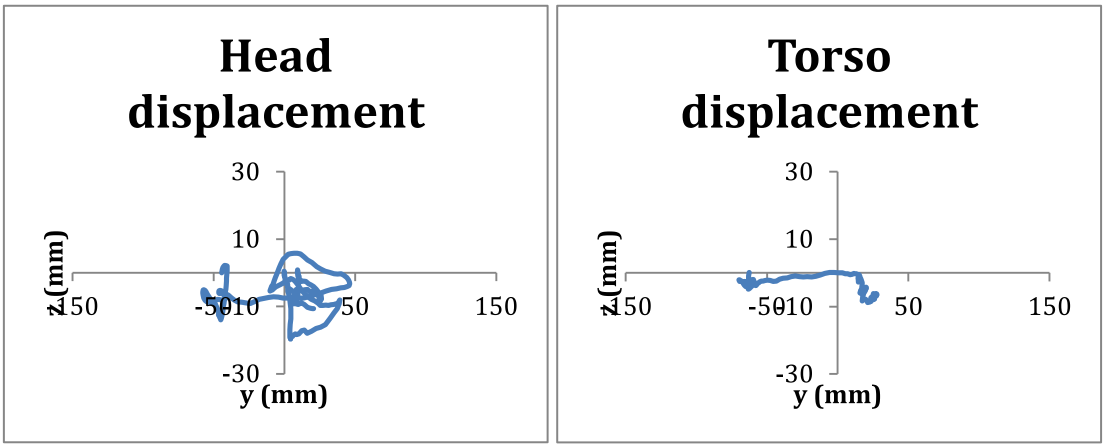


Figure C12 – Head and torso lateral displacement with respect to the centre of the seat for steering 2.

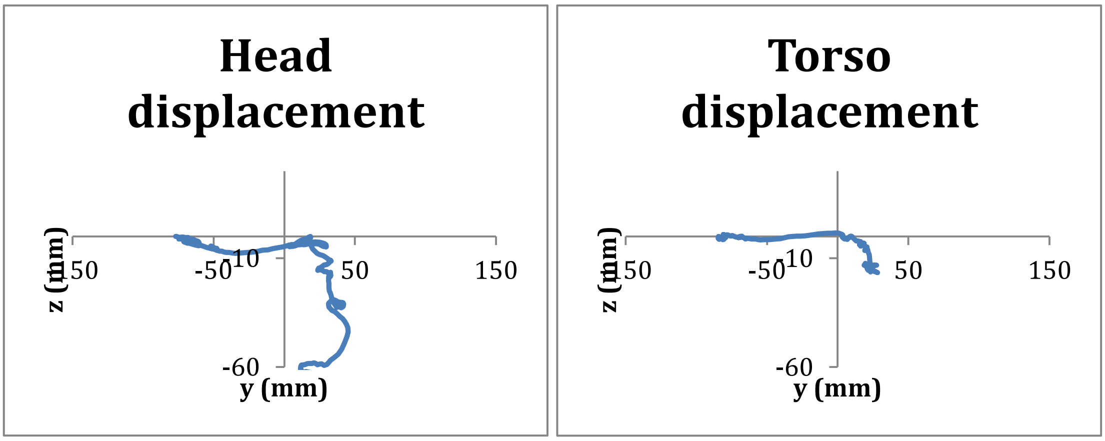


Figure C13 – Head and torso lateral displacement with respect to the centre of the seat for steering 3.

- CHILD 6

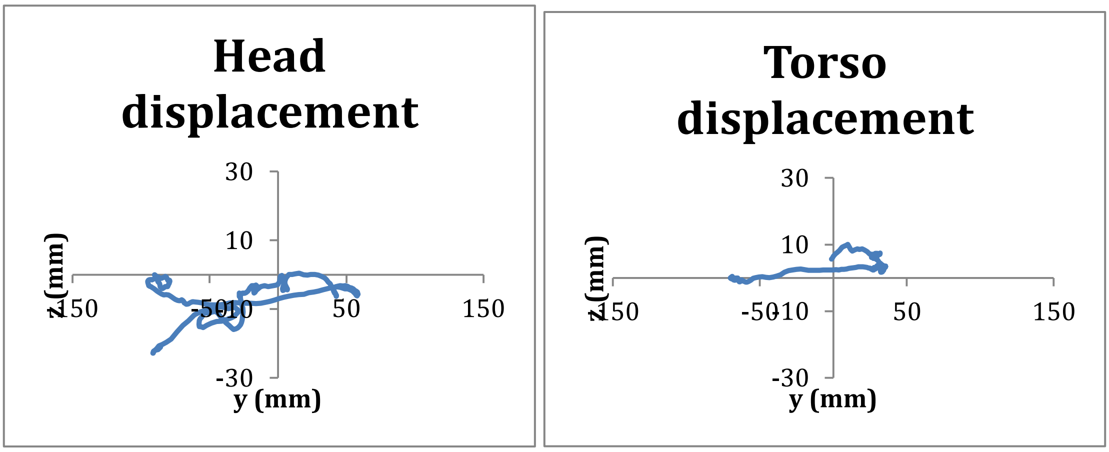


Figure C14 – Head and torso lateral displacement with respect to the centre of the seat for steering 1.

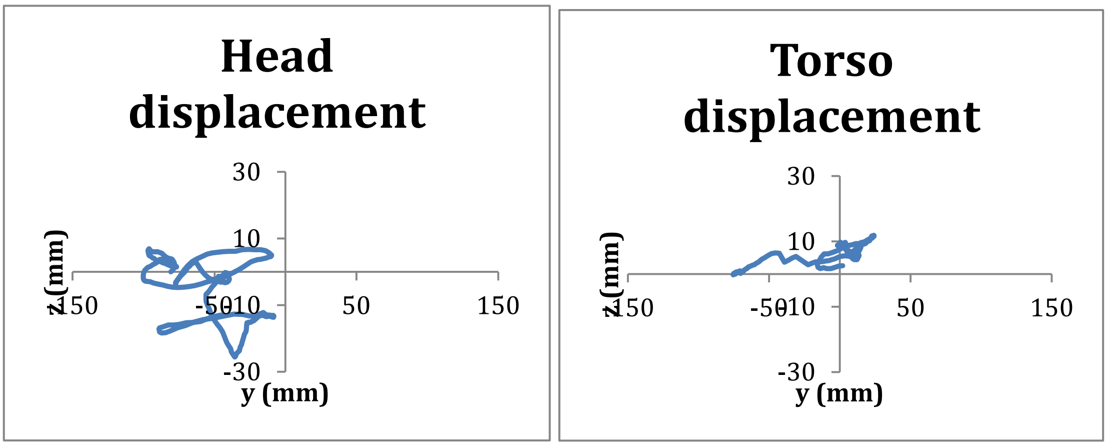


Figure C15 – Head and torso lateral displacement with respect to the centre of the seat for steering 2.

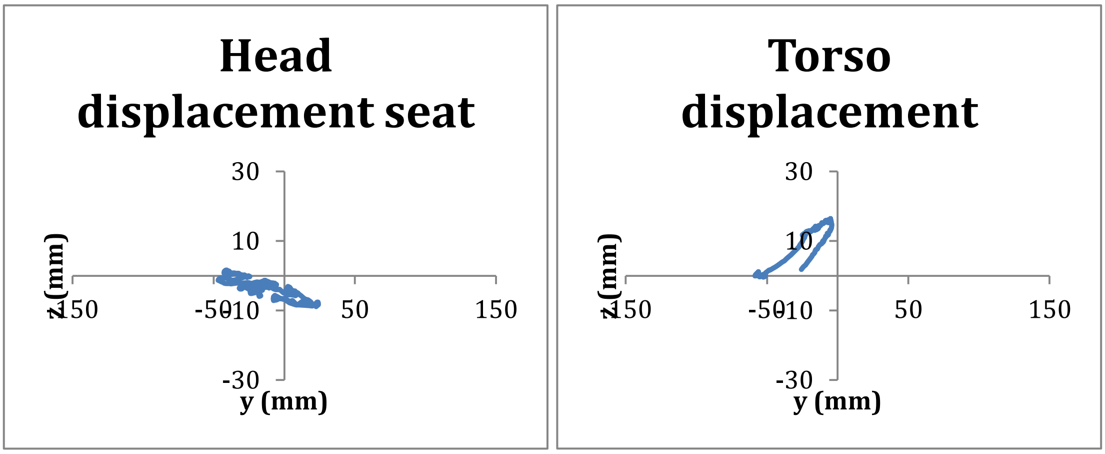


Figure C16 – Head and torso lateral displacement with respect to the centre of the seat for steering 3.

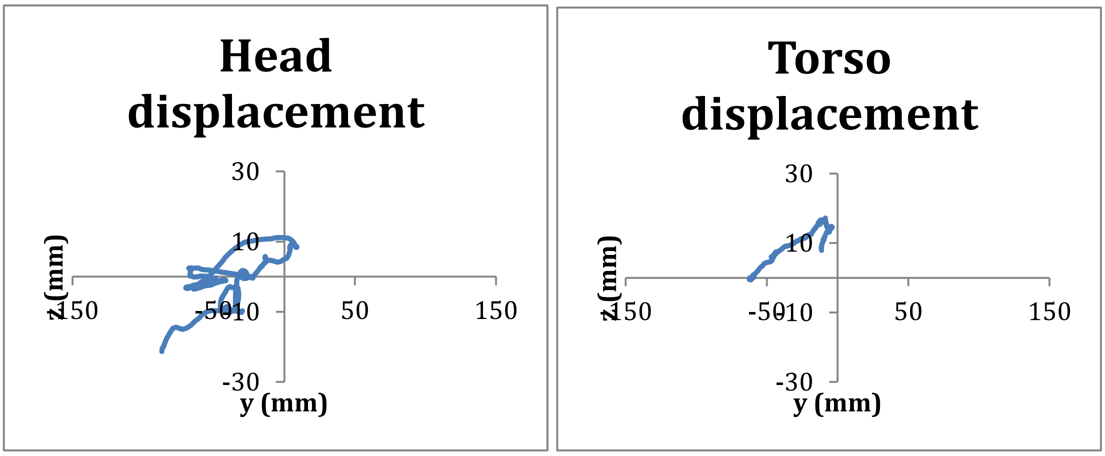


Figure C17 – Head and torso lateral displacement with respect to the centre of the seat for steering 4.

- CHILD 7

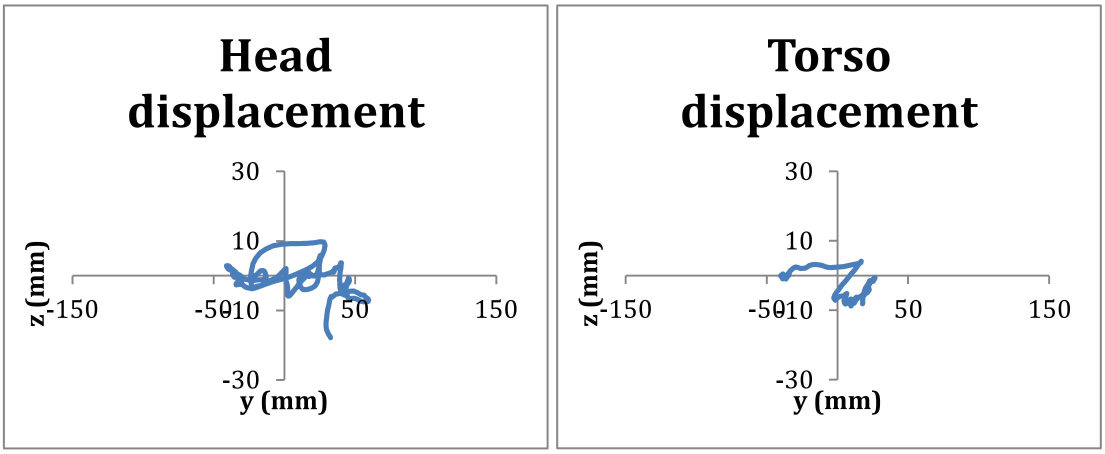


Figure C18 – Head and torso lateral displacement with respect to the centre of the seat for steering 1.

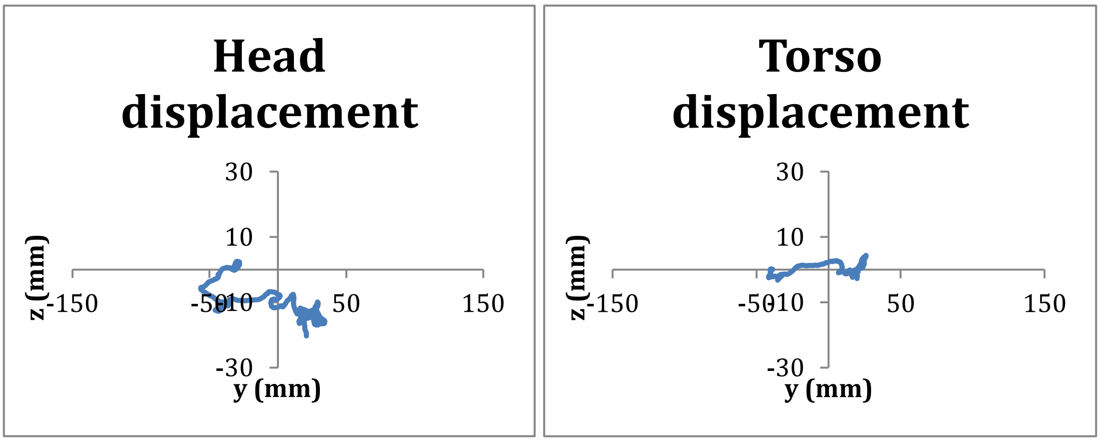


Figure C19 – Head and torso lateral displacement with respect to the centre of the seat for steering 2.

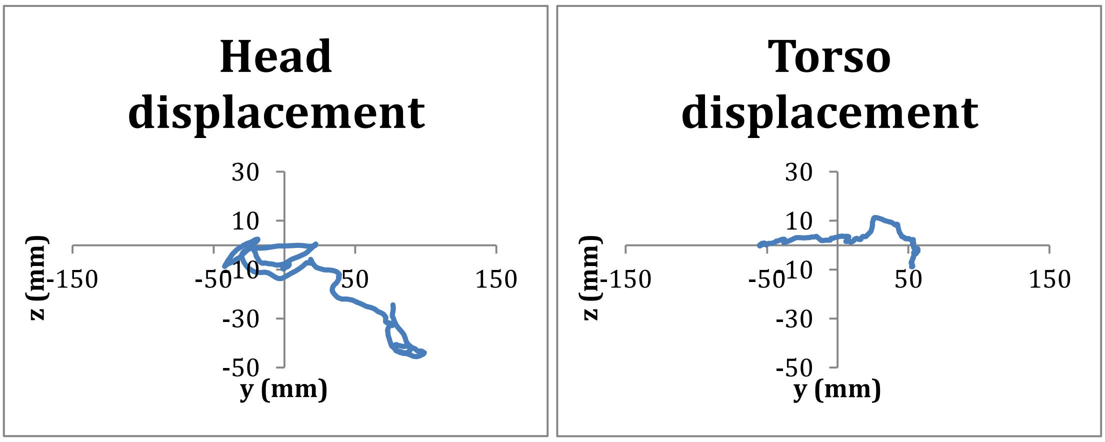


Figure C20 – Head and torso lateral displacement with respect to the centre of the seat for steering 3.

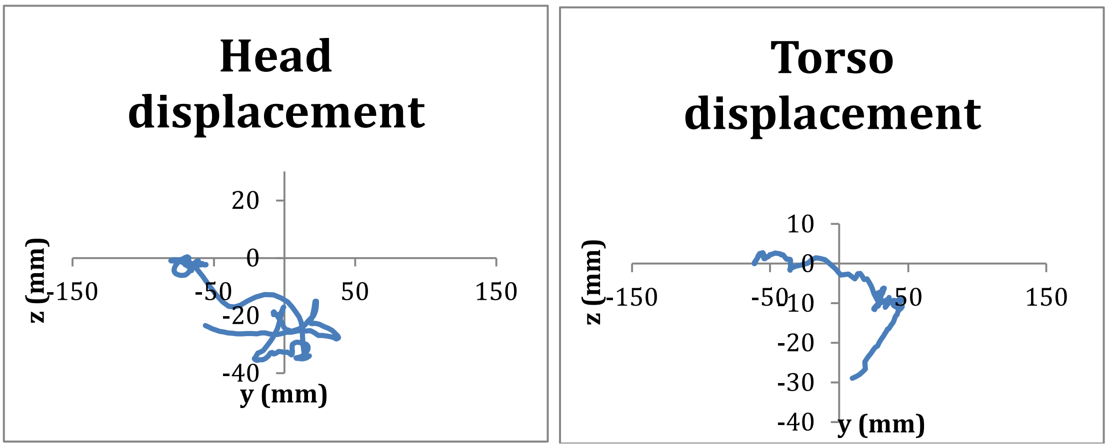


Figure C21 – Head and torso lateral displacement with respect to the centre of the seat for steering 4.

- CHILD 8

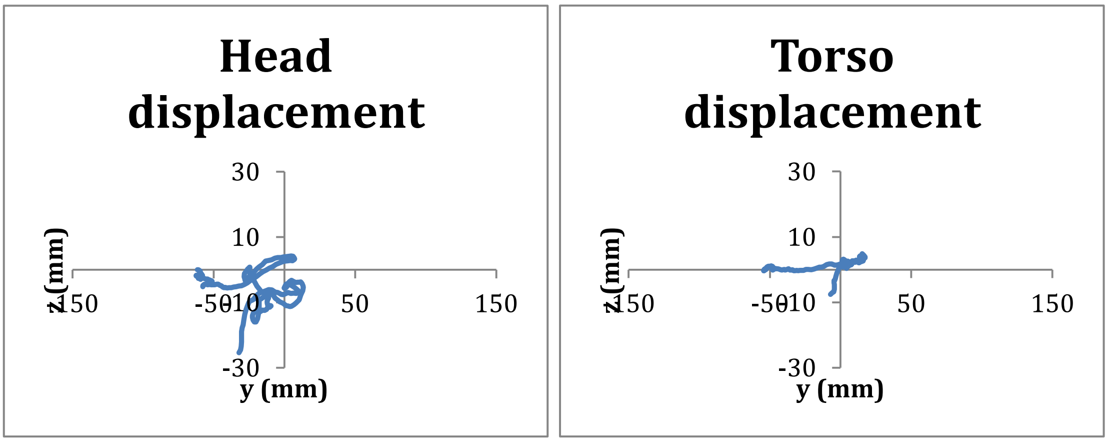


Figure C22 – Head and torso lateral displacement with respect to the centre of the seat for steering 1.

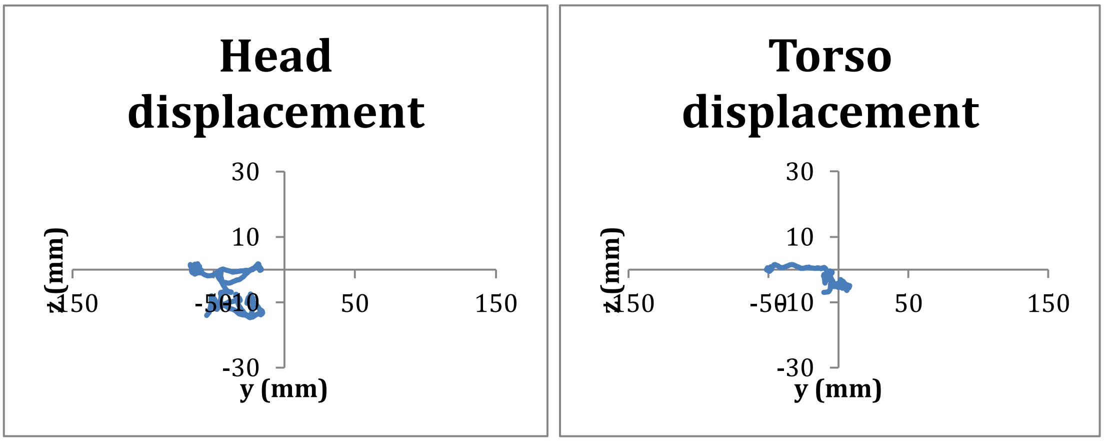
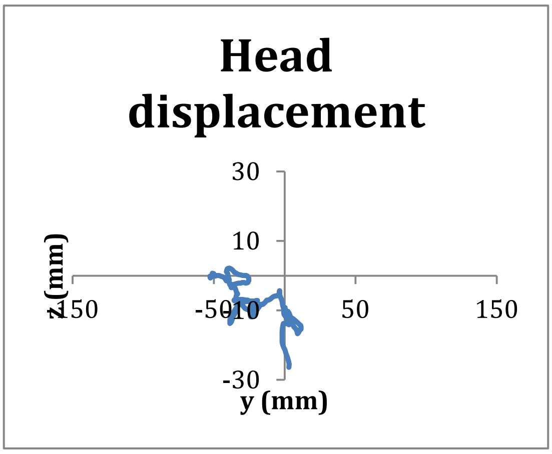


Figure C23 – Head and torso lateral displacement with respect to the centre of the seat for steering 2.



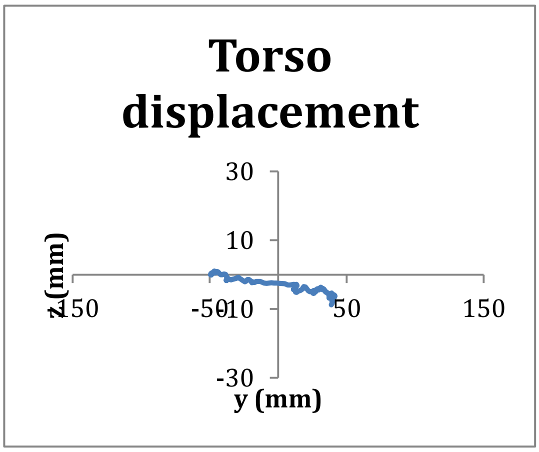
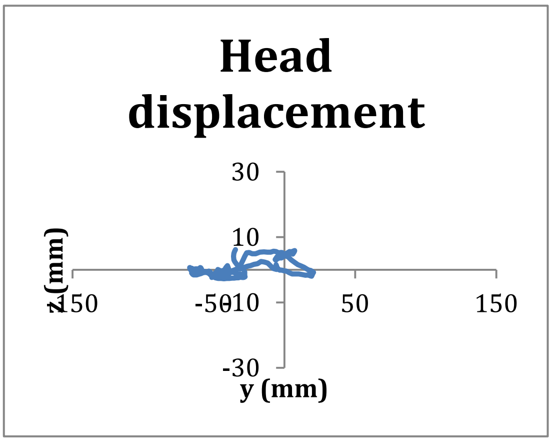


Figure C24 – Head and torso lateral displacement with respect to the centre of the seat for steering 3.



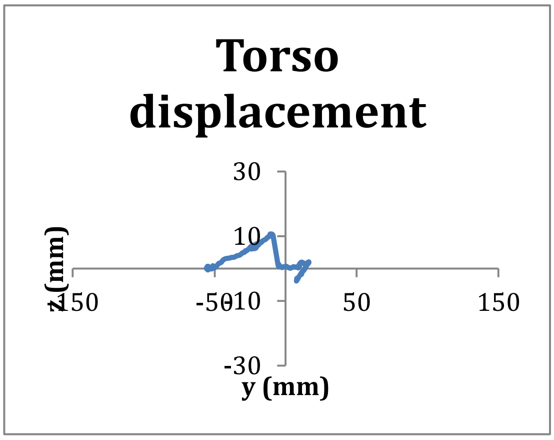


Figure C25 – Head and torso lateral displacement with respect to the centre of the seat for steering 4.

- CHILD 9

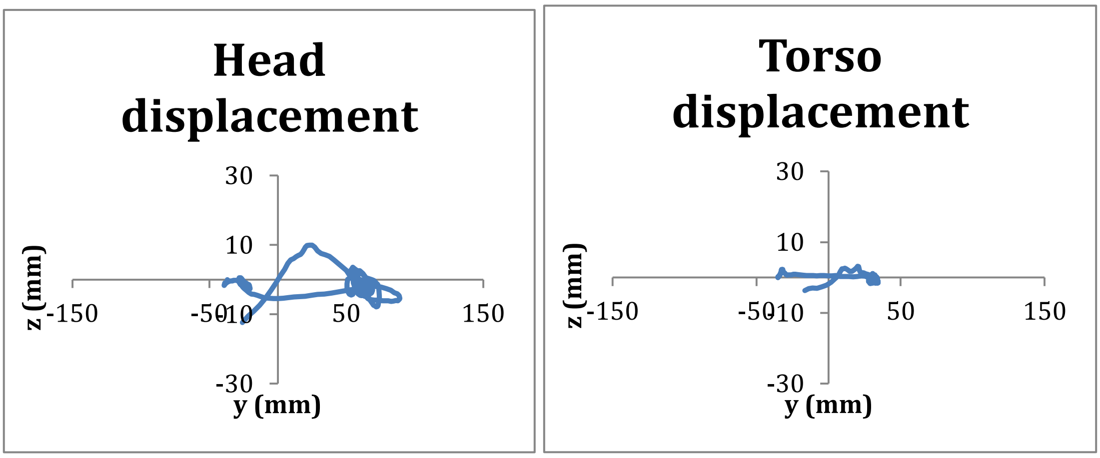


Figure C26 – Head and torso lateral displacement with respect to the centre of the seat for steering 1.

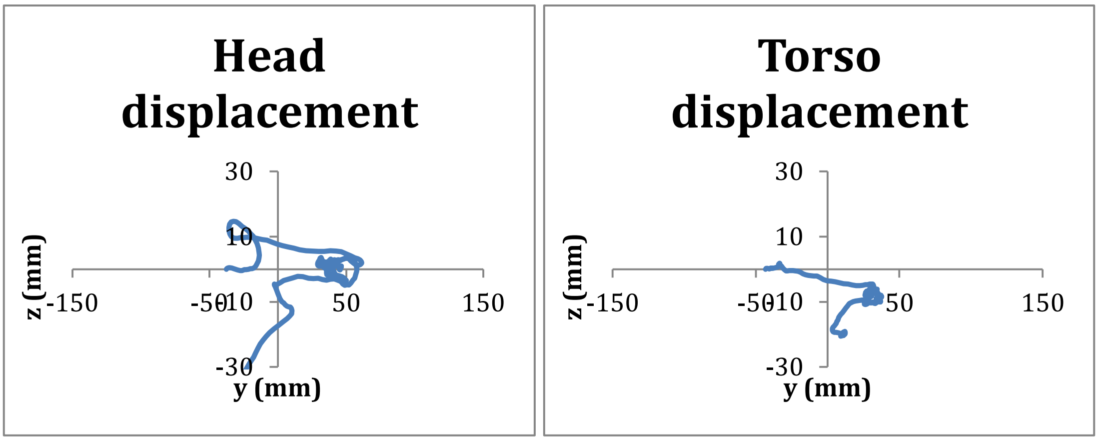


Figure C27 – Head and torso lateral displacement with respect to the centre of the seat for steering 2.

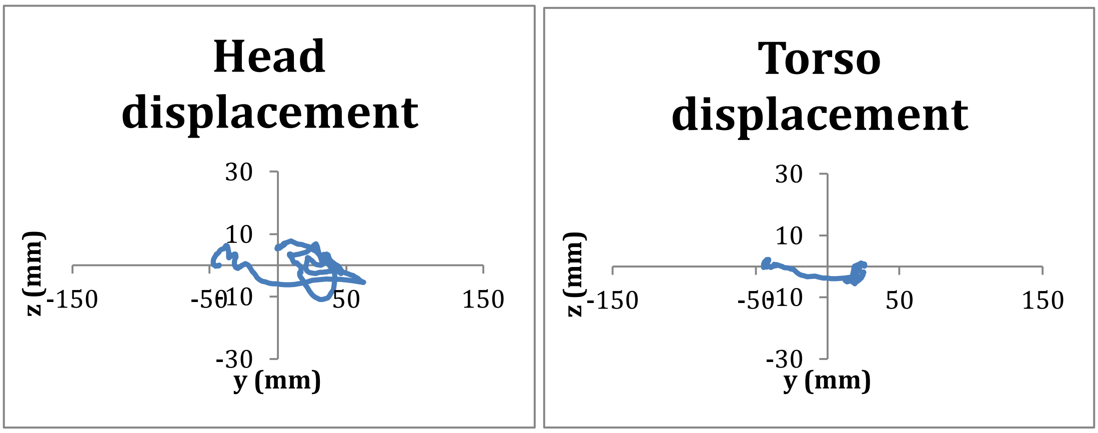


Figure C28 – Head and torso lateral displacement with respect to the centre of the seat for steering 3.

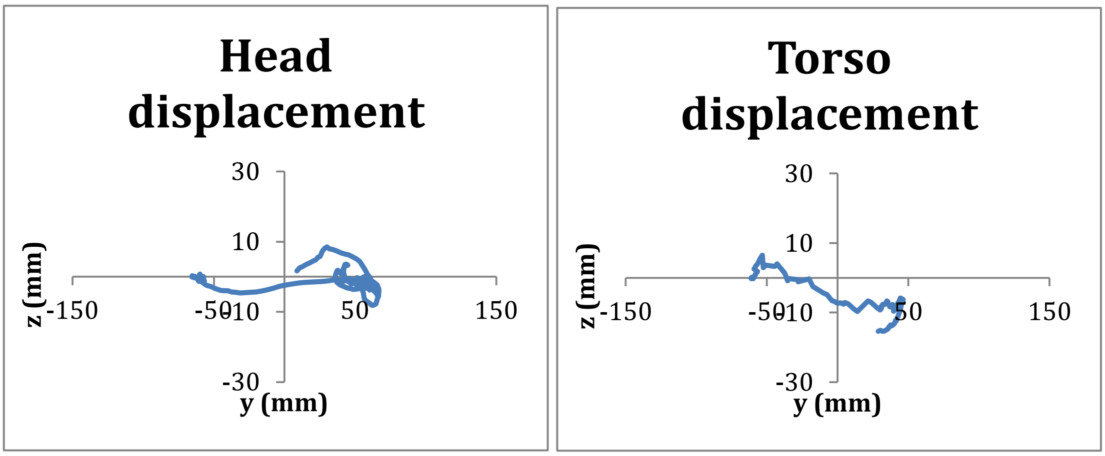


Figure C29 – Head and torso lateral displacement with respect to the centre of the seat for steering 4.

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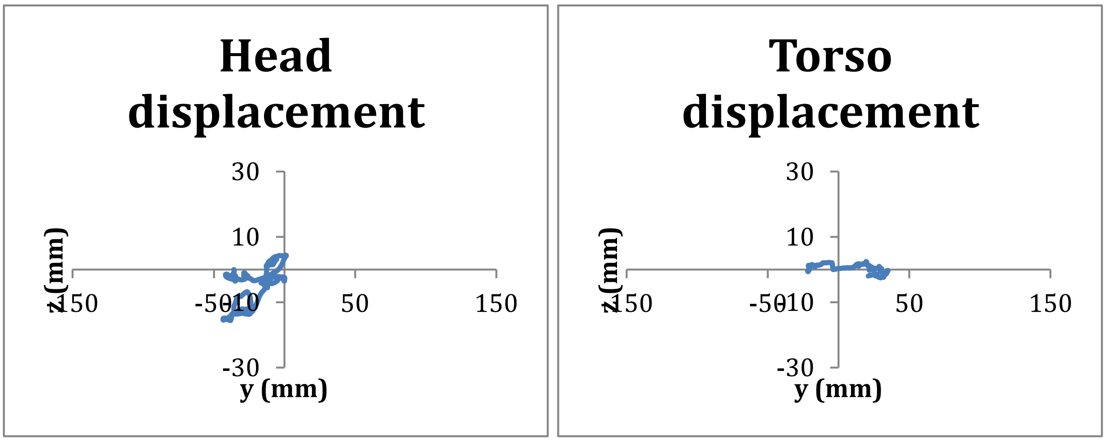

Figure C30 – Head and torso lateral displacement with respect to the centre of the seat for steering 1.

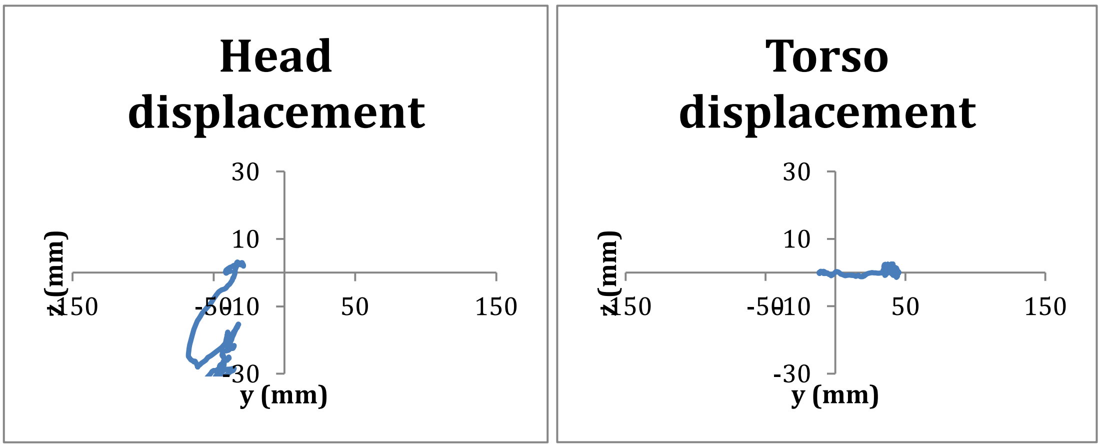

Figure C31 – Head and torso lateral displacement with respect to the centre of the seat for steering 2.

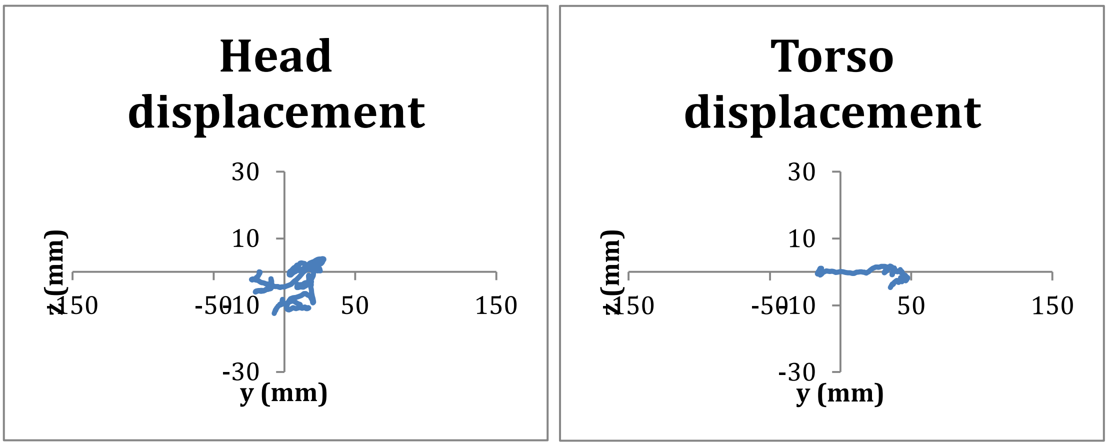

Figure C32 – Head and torso lateral displacement with respect to the centre of the seat for steering 3.

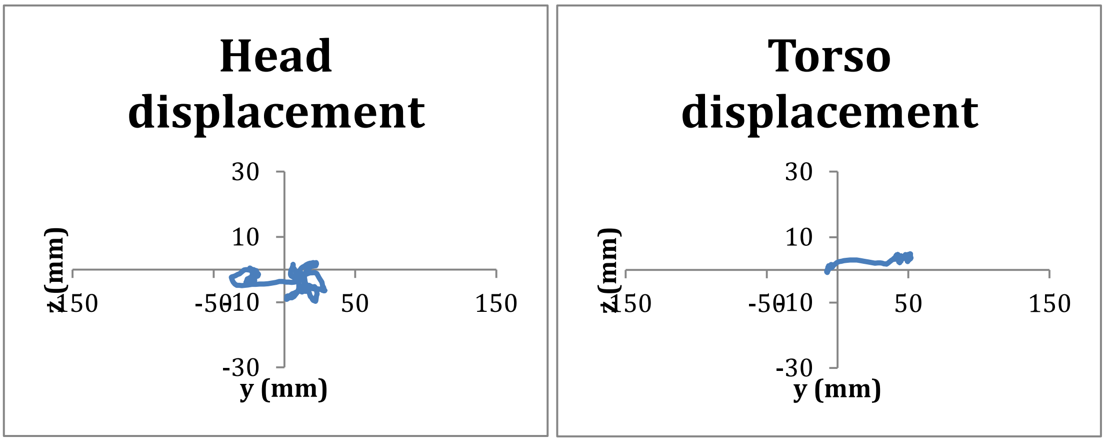

Figure C33 – Head and torso lateral displacement with respect to the centre of the seat for steering 4.

- CHILD 11

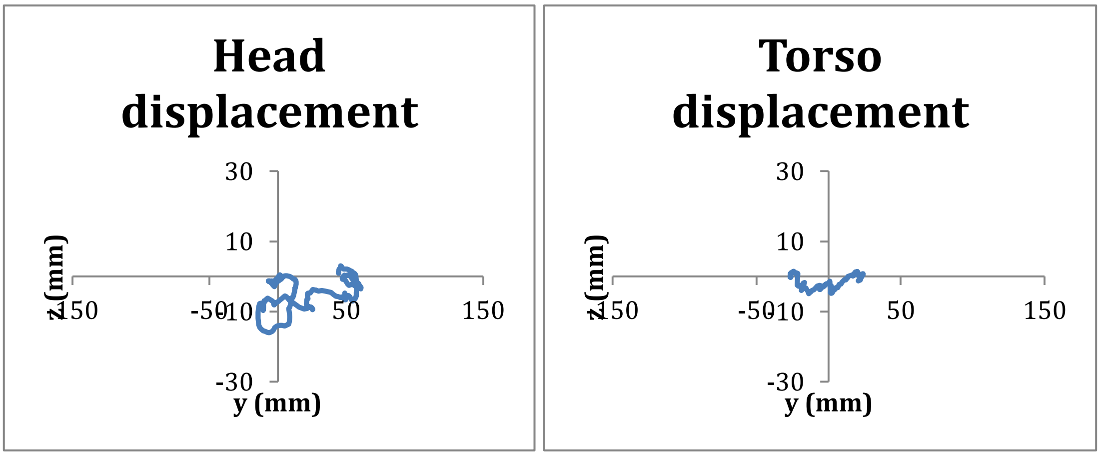

Figure C34 – Head and torso lateral displacement with respect to the centre of the seat for steering 1.

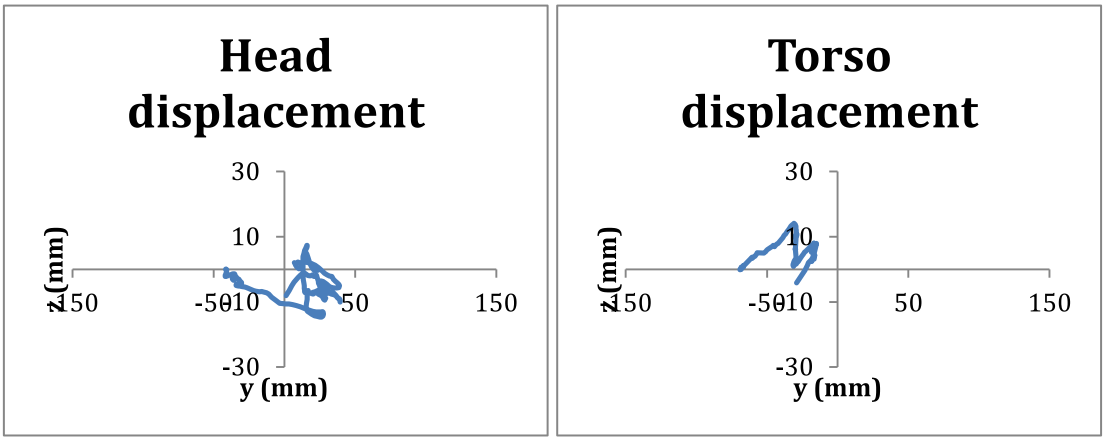

Figure C35 – Head and torso lateral displacement with respect to the centre of the seat for steering 2.

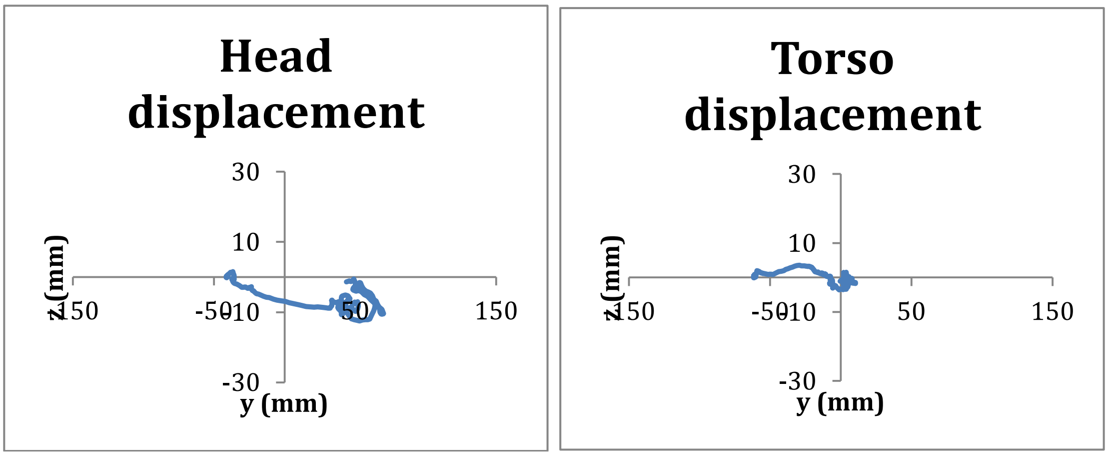

Figure C36 – Head and torso lateral displacement with respect to the centre of the seat for steering 3.

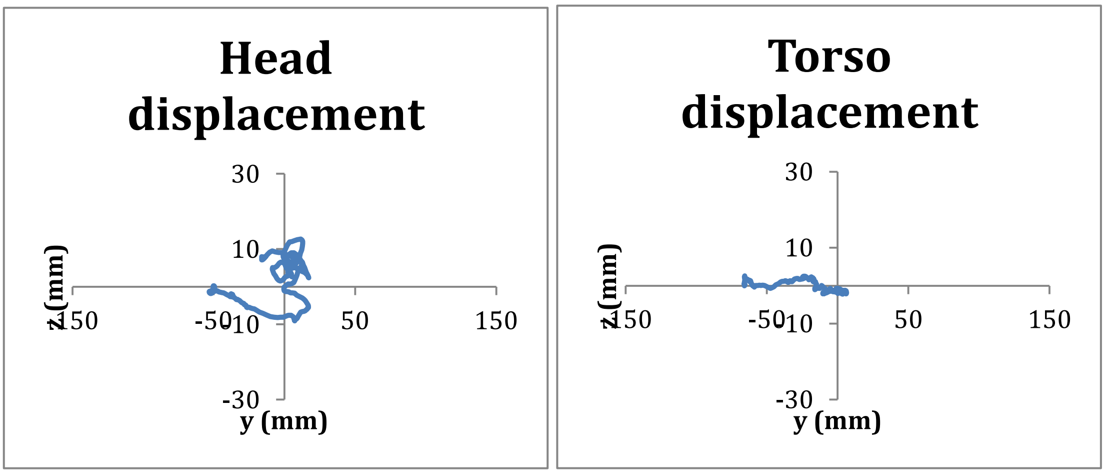

Figure C37 – Head and torso lateral displacement with respect to the centre of the seat for steering 4.

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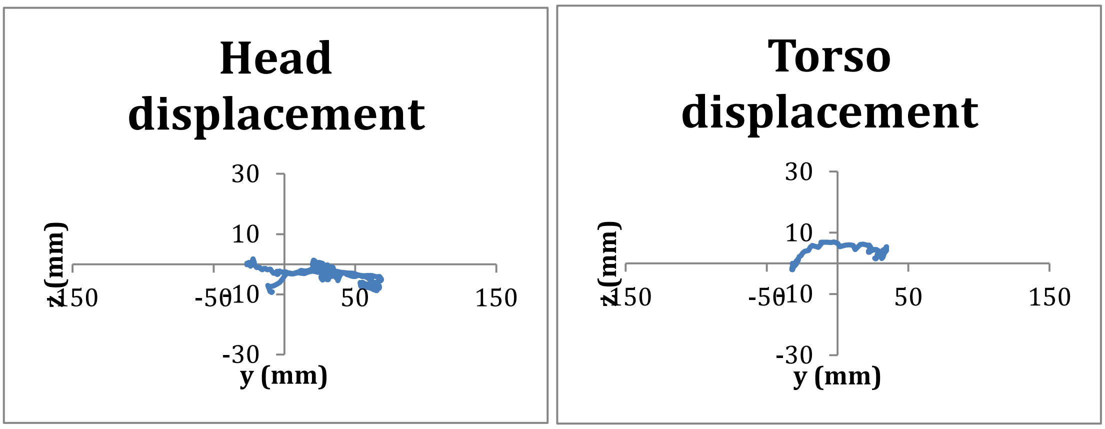

Figure C38 – Head and torso lateral displacement with respect to the centre of the seat for steering 1.

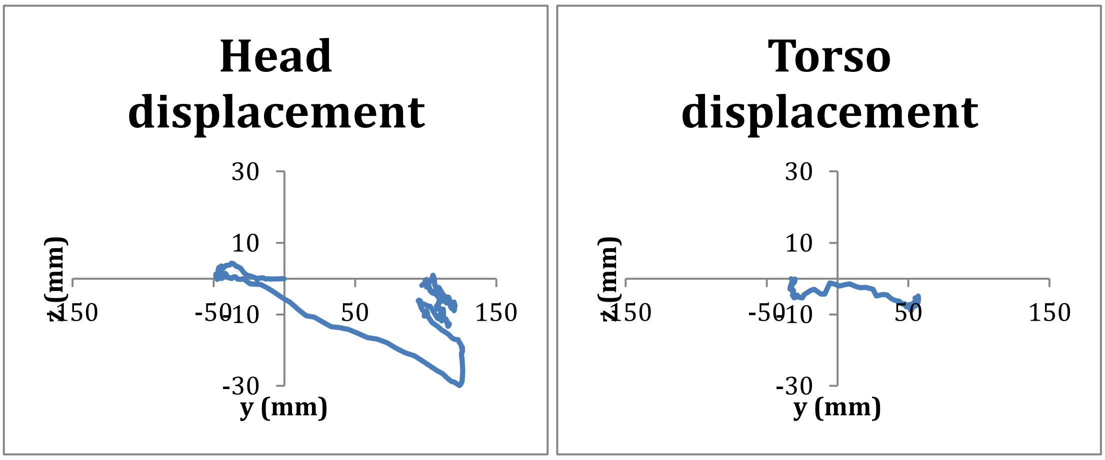

Figure C39 – Head and torso lateral displacement with respect to the centre of the seat for steering 2.

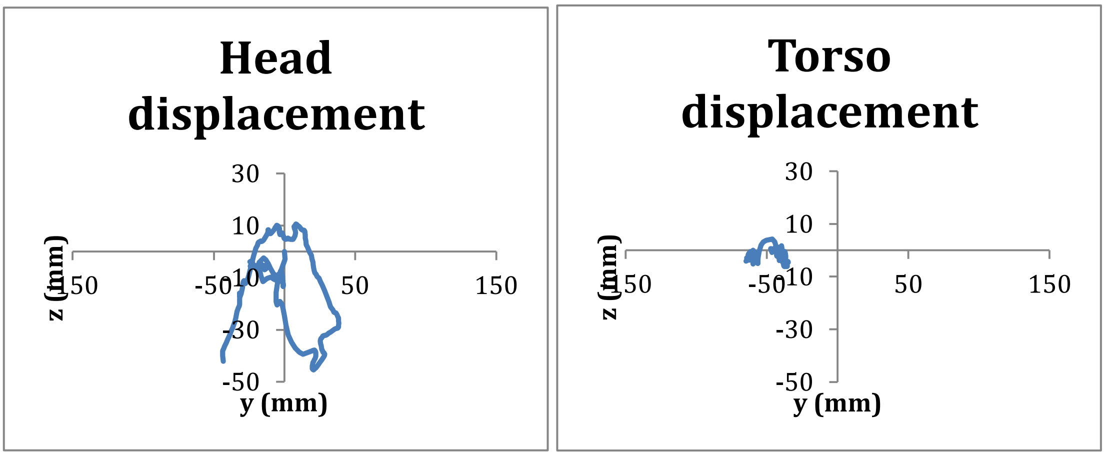

Figure C40 – Head and torso lateral displacement with respect to the centre of the seat for steering 3.

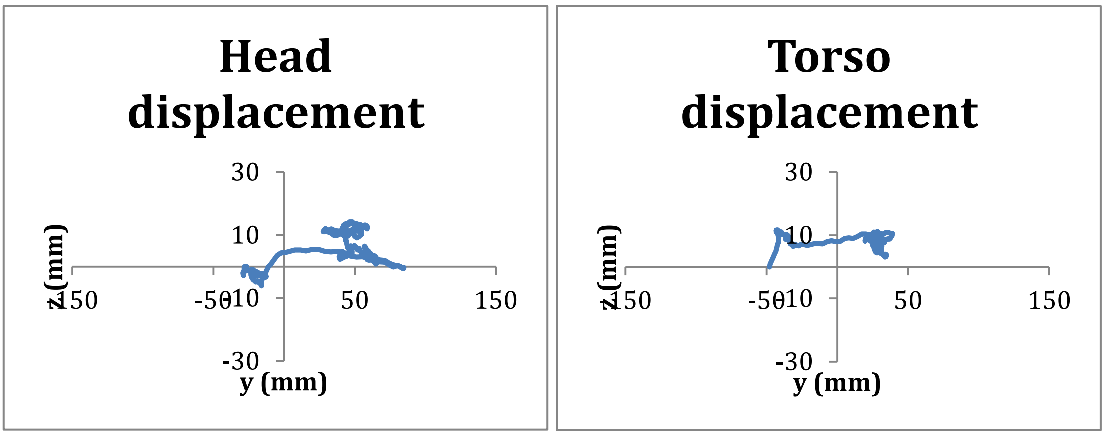

Figure C41 – Head and torso lateral displacement with respect to the centre of the seat for steering 4.

- CHILD 13

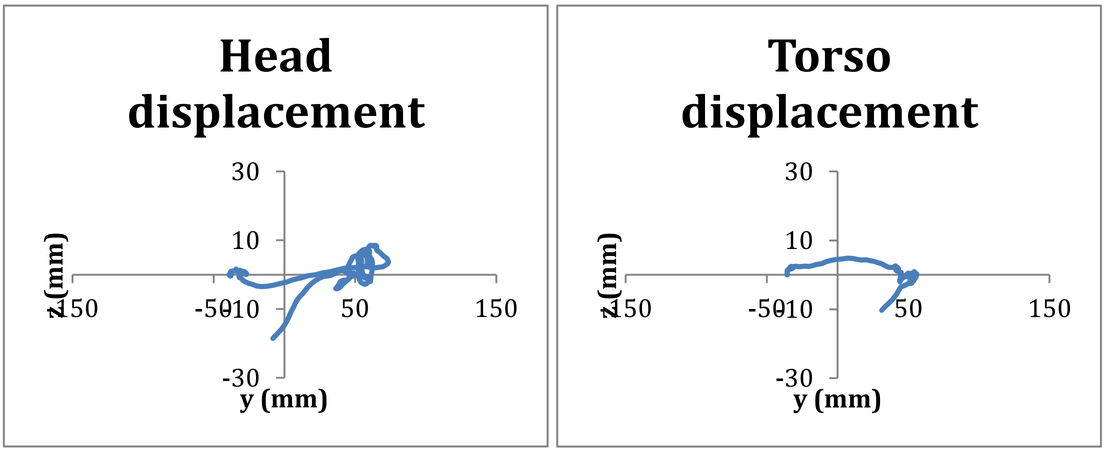

Figure C42 – Head and torso lateral displacement with respect to the centre of the seat for steering 1.

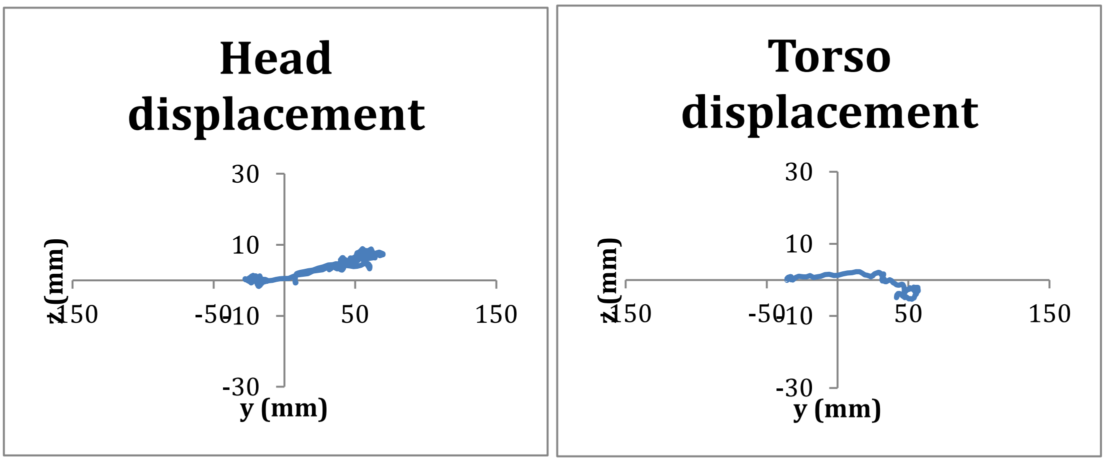

Figure C43 – Head and torso lateral displacement with respect to the centre of the seat for steering 2.

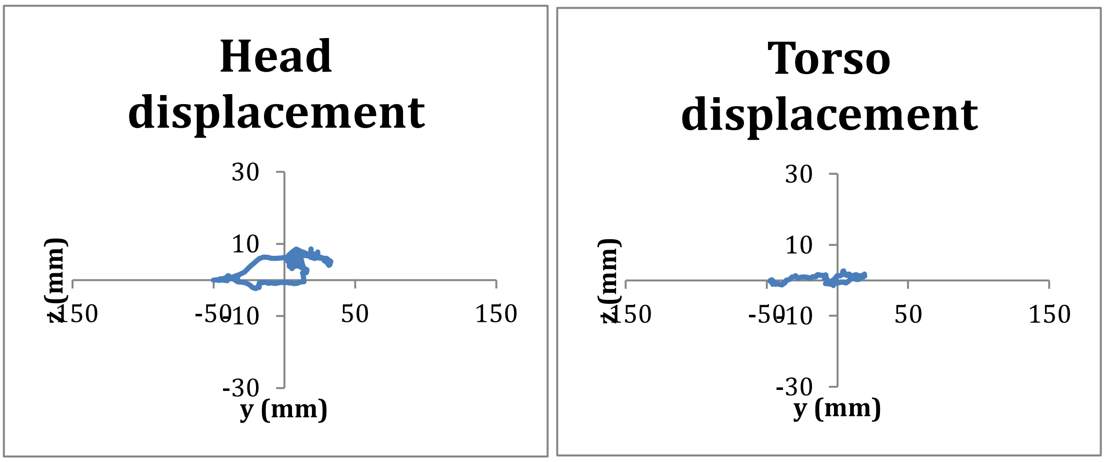

Figure C44 – Head and torso lateral displacement with respect to the centre of the seat for steering 3.

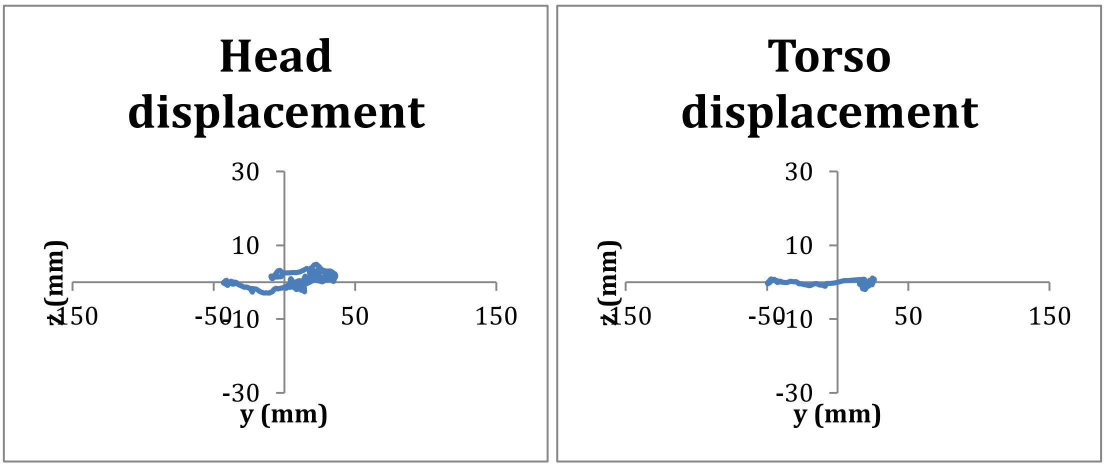

Figure C45 – Head and torso lateral displacement with respect to the centre of the seat for steering 4.

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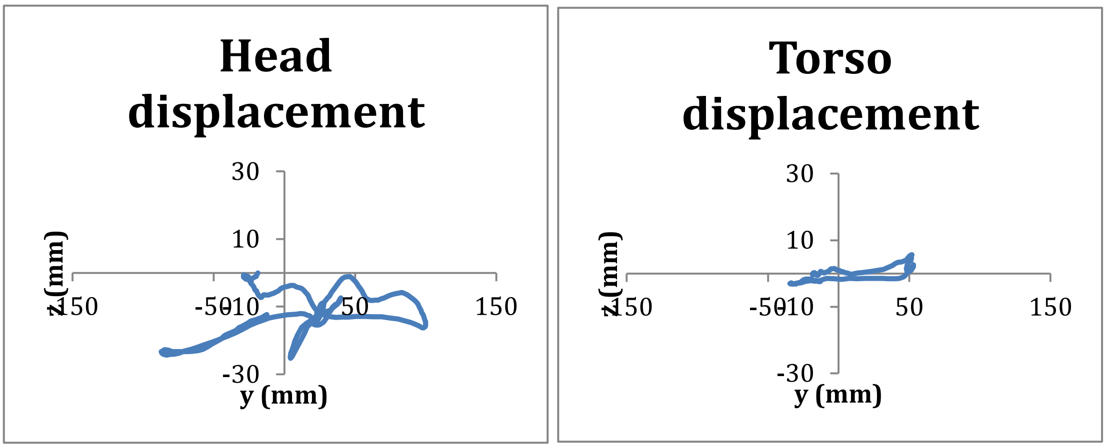

Figure C46 – Head and torso lateral displacement with respect to the centre of the seat for steering 1 (evasive).

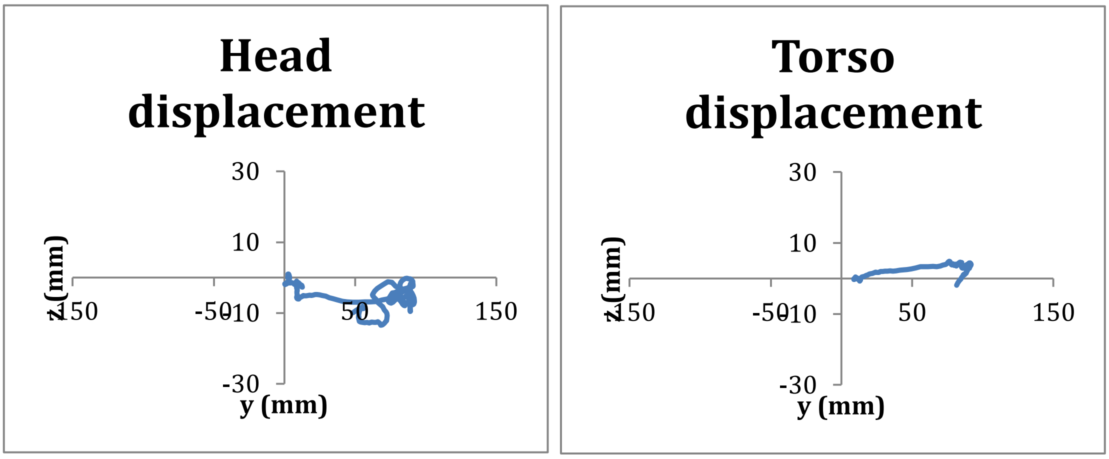

Figure C47 – Head and torso lateral displacement with respect to the centre of the seat for steering 2.

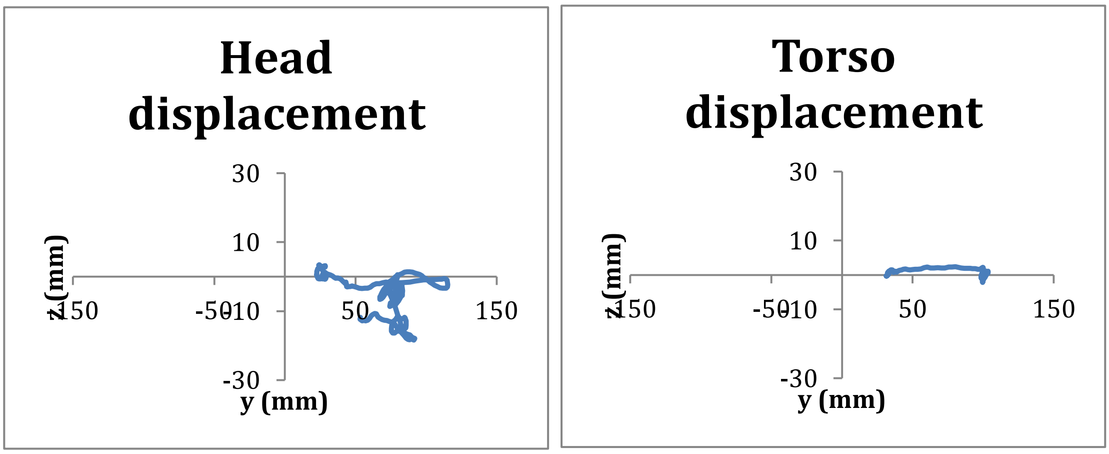

Figure C48 – Head and torso lateral displacement with respect to the centre of the seat for steering 3.

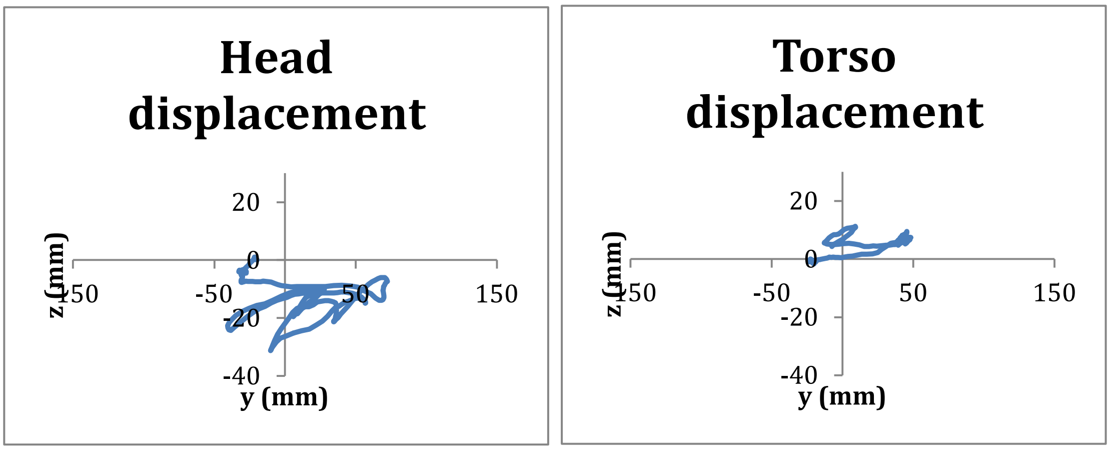

Figure C49 – Head and torso lateral displacement with respect to the centre of the seat for steering 4 (evasive).

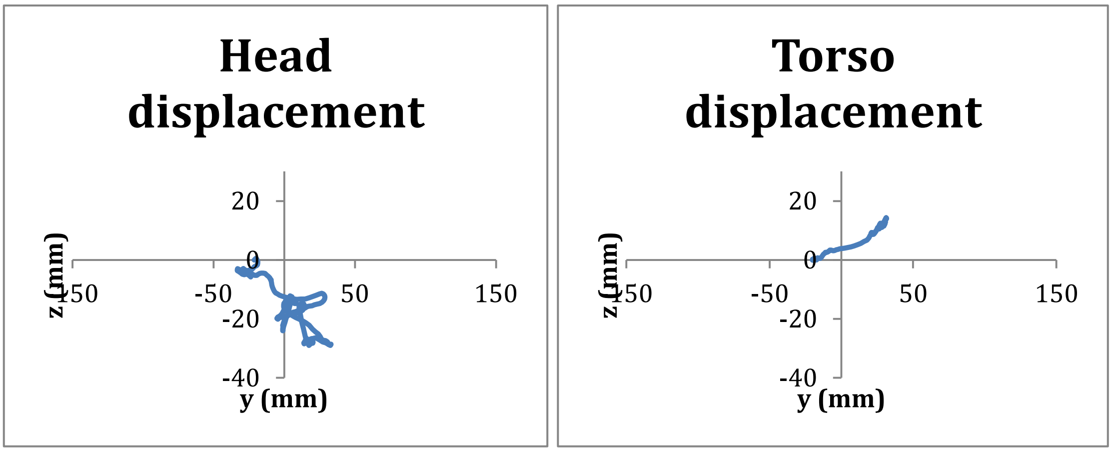

Figure C50 – Head and torso lateral displacement with respect to the centre of the seat for steering 5.

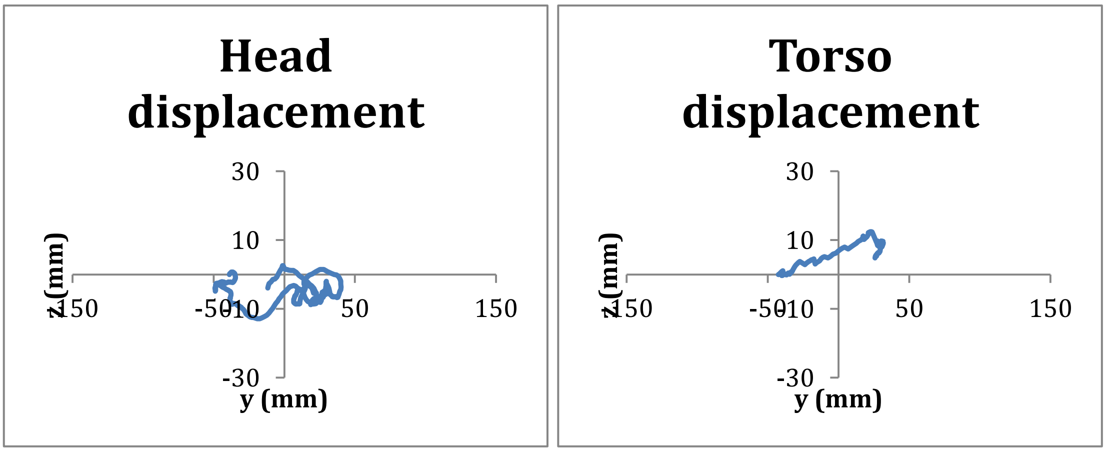

Figure C51 – Head and torso lateral displacement with respect to the centre of the seat for steering 6.

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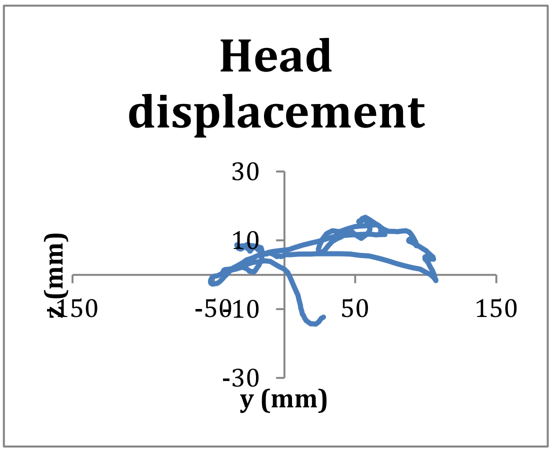


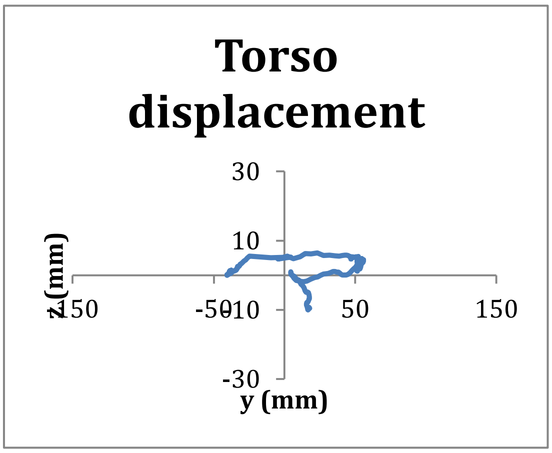
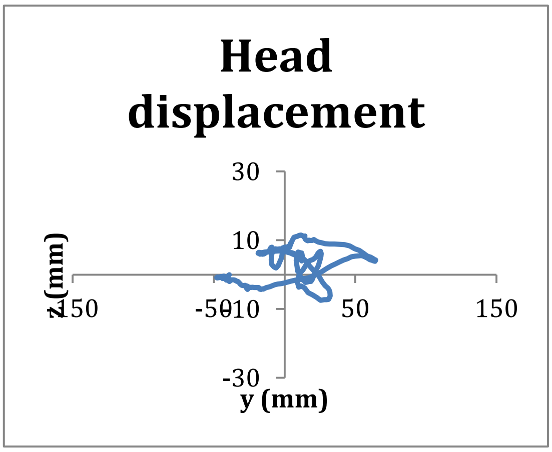


Figure C52 – Head and torso lateral displacement with respect to the centre of the seat for steering 1 (evasive).



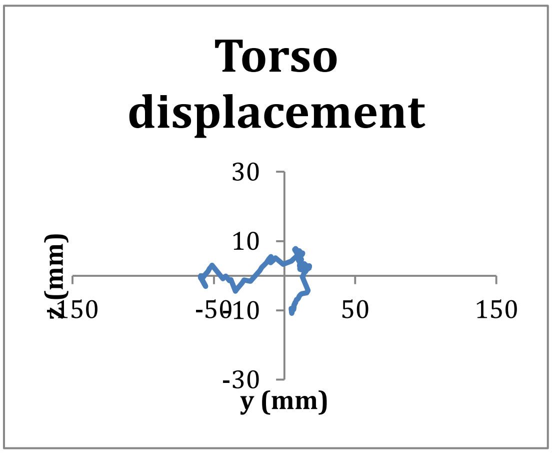
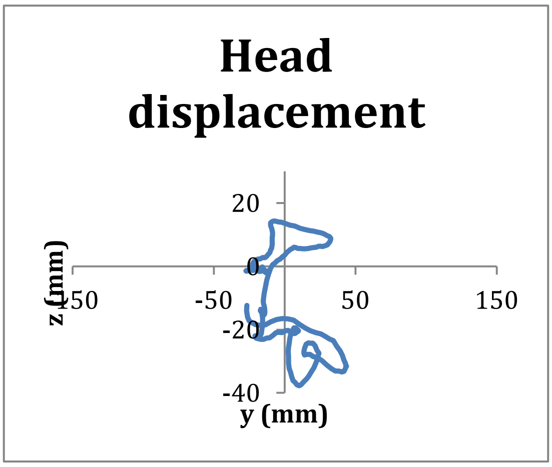


Figure C53 – Head and torso lateral displacement with respect to the centre of the seat for steering 2.



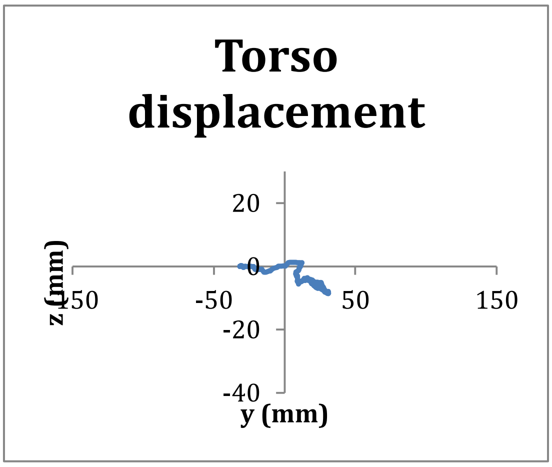


Figure C54 – Head and torso lateral displacement with respect to the centre of the seat for steering 3.

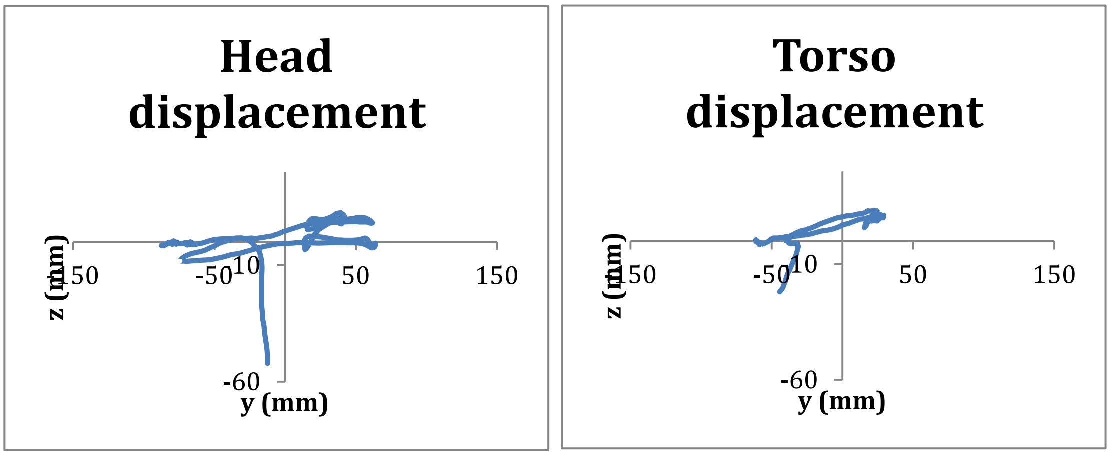


Figure C55 – Head and torso lateral displacement with respect to the centre of the seat for steering 4 (evasive).

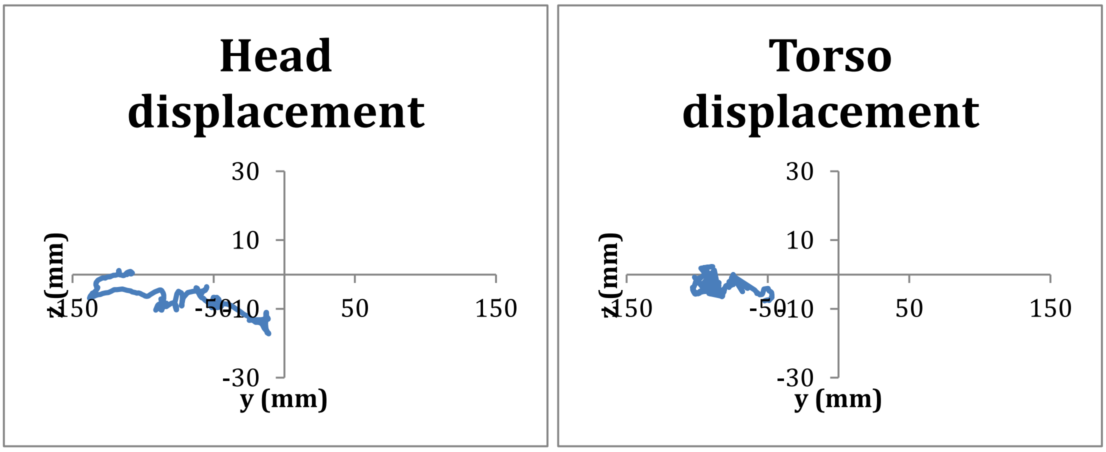


Figure C56 – Head and torso lateral displacement with respect to the centre of the seat for steering 5.

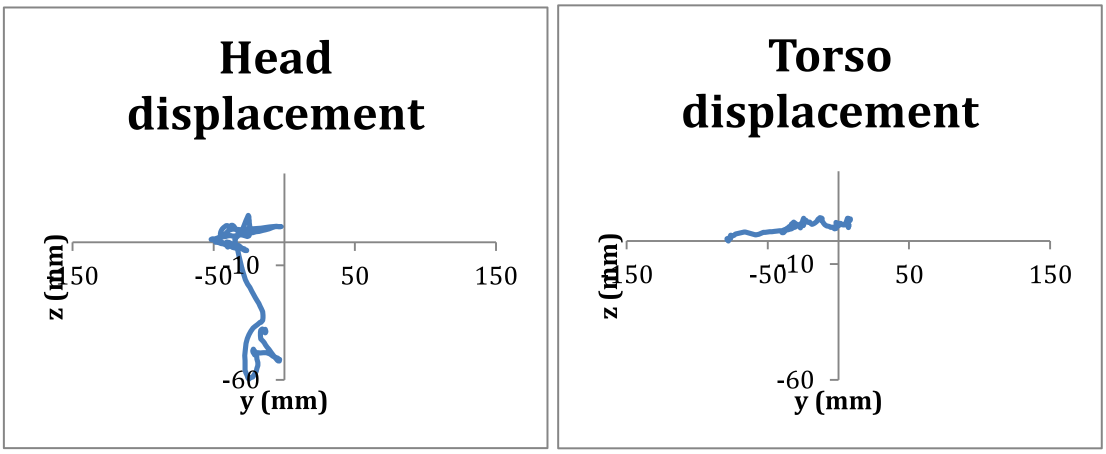


Figure C57 – Head and torso lateral displacement with respect to the centre of the seat for steering 6.

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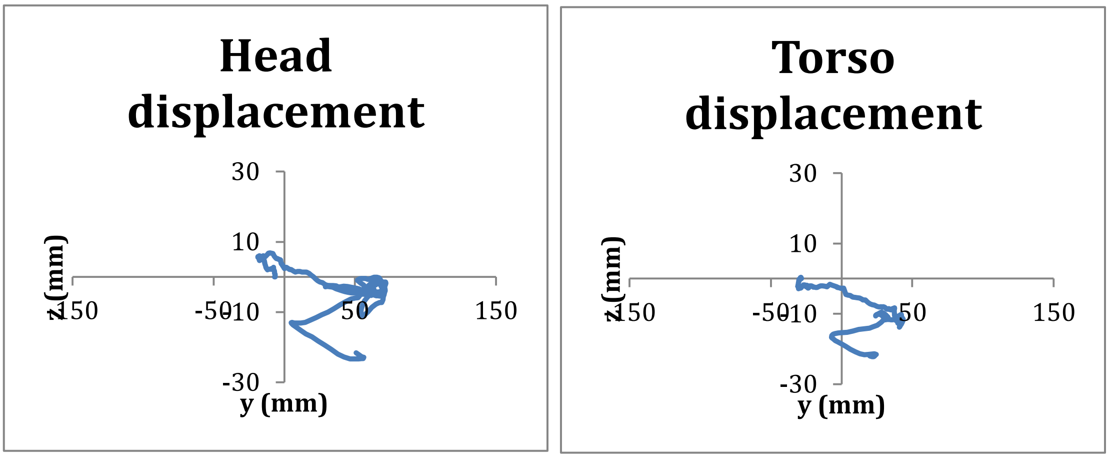

Figure C58 – Head and torso lateral displacement with respect to the centre of the seat for steering 1 (evasive).

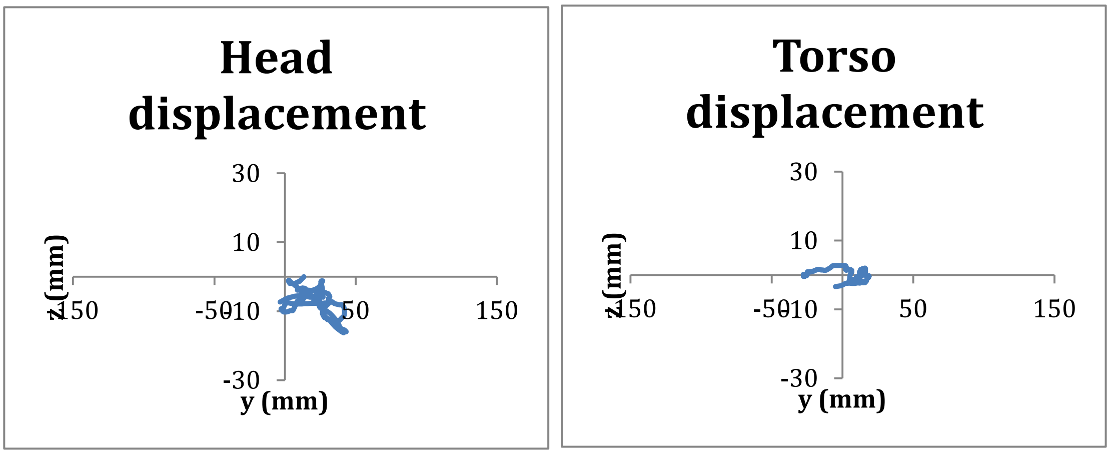

Figure C59 – Head and torso lateral displacement with respect to the centre of the seat for steering 2.

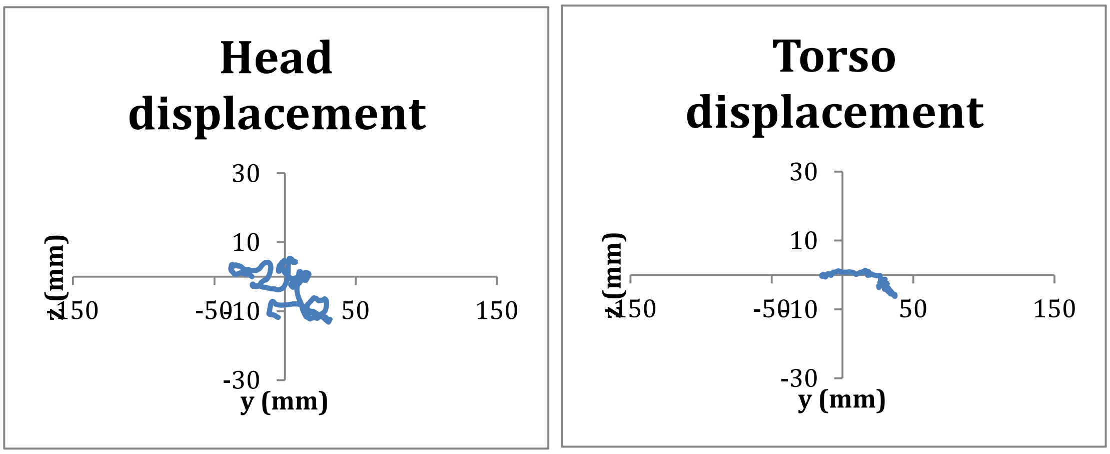

Figure C60 – Head and torso lateral displacement with respect to the centre of the seat for steering 3.

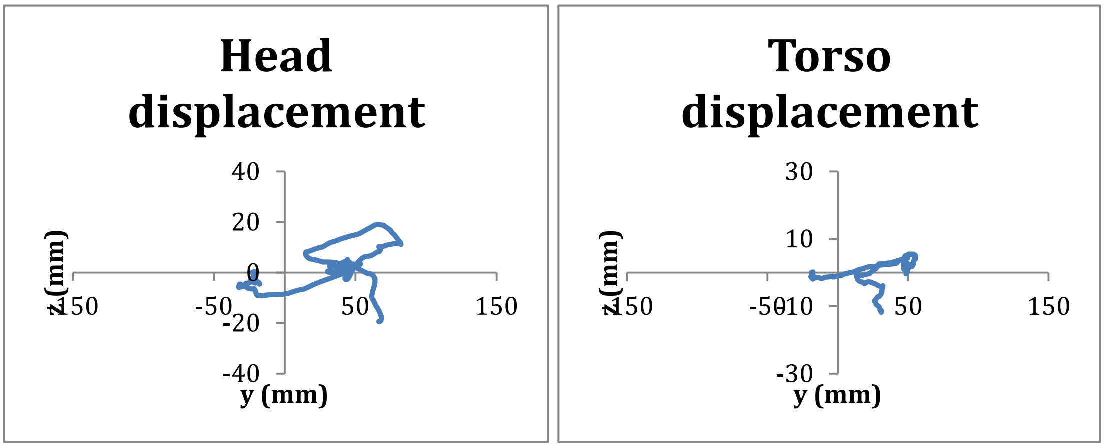

Figure C61 – Head and torso lateral displacement with respect to the centre of the seat for steering 4 (evasive).

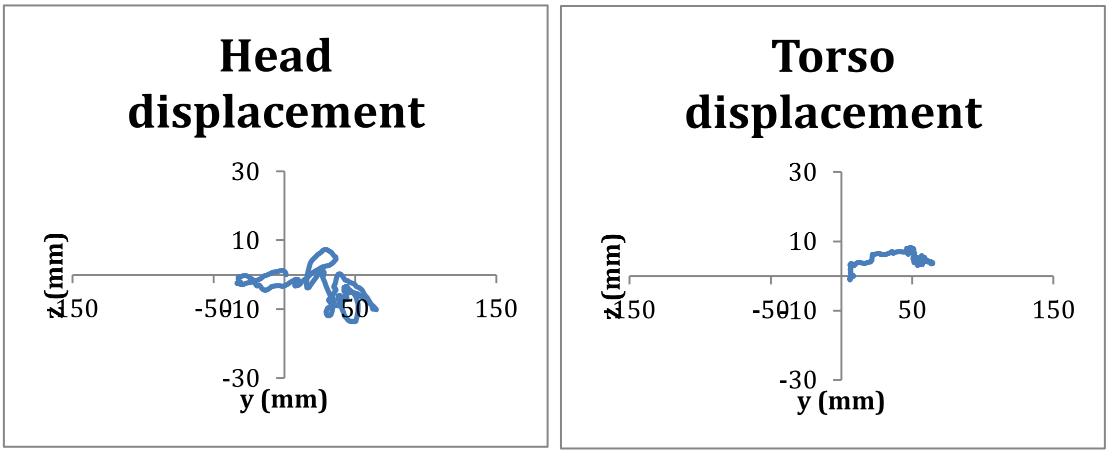

Figure C62 – Head and torso lateral displacement with respect to the centre of the seat for steering 5.

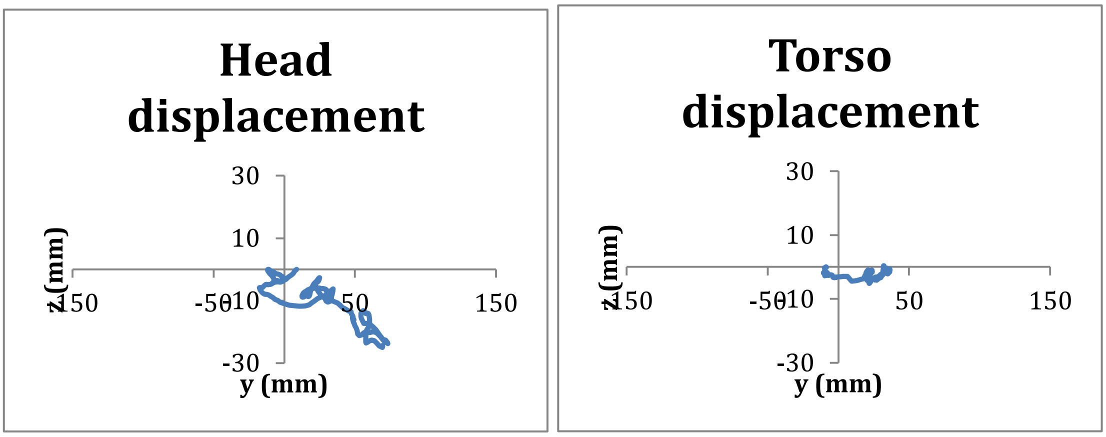

Figure C63 – Head and torso lateral displacement with respect to the centre of the seat for steering 6.

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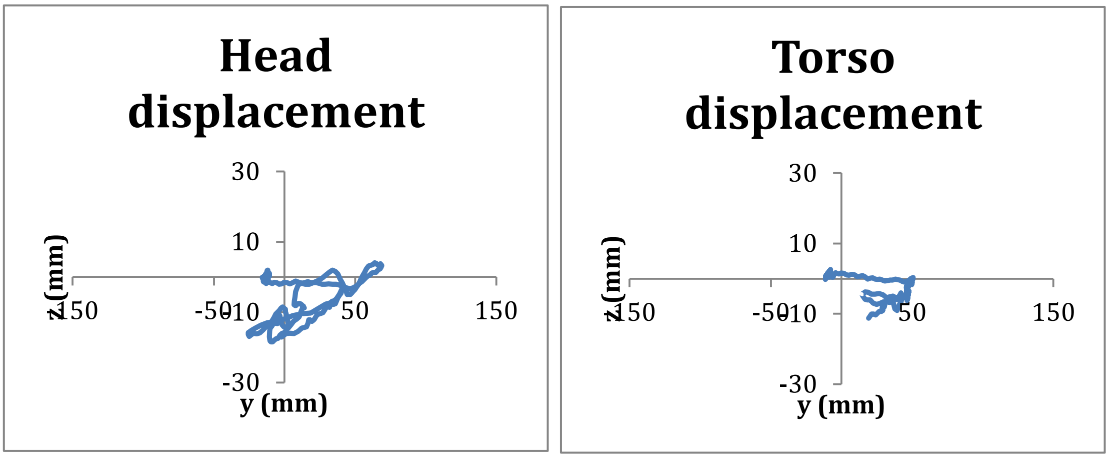

Figure C64 – Head and torso lateral displacement with respect to the centre of the seat for steering 1 (evasive).

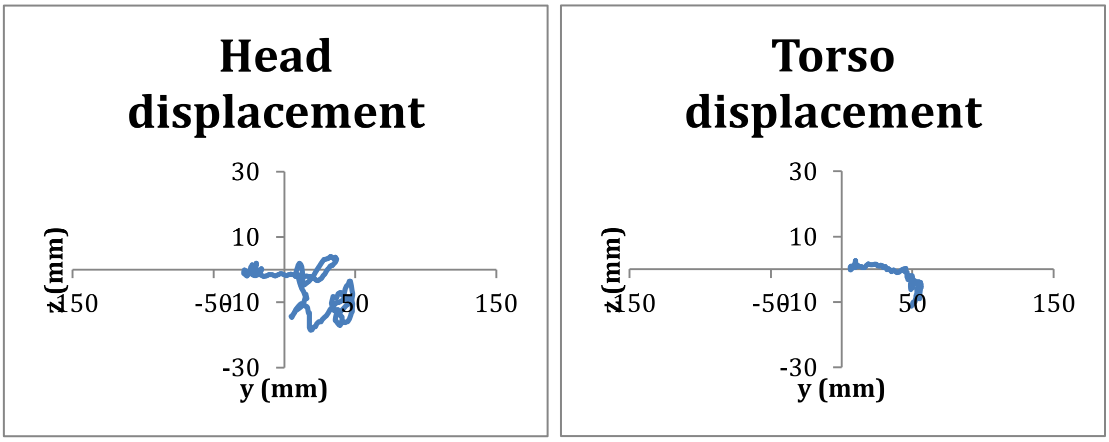

Figure C65 – Head and torso lateral displacement with respect to the centre of the seat for steering 2.

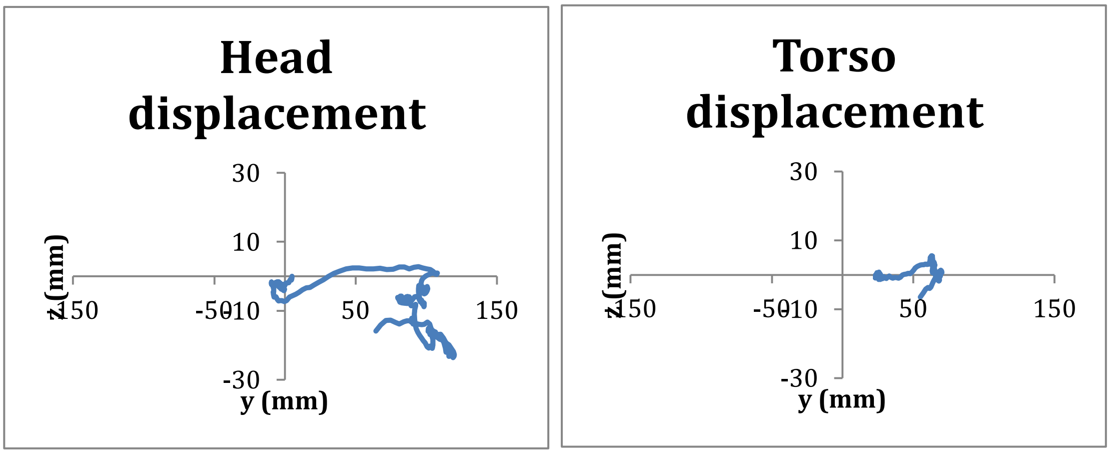

Figure C66 – Head and torso lateral displacement with respect to the centre of the seat for steering 3.

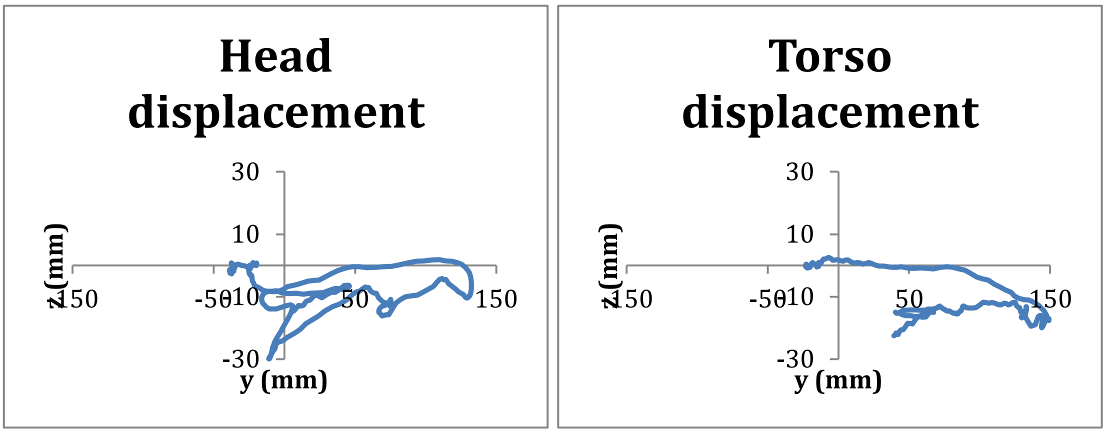

Figure C67 – Head and torso lateral displacement with respect to the centre of the seat for steering 4 (evasive).

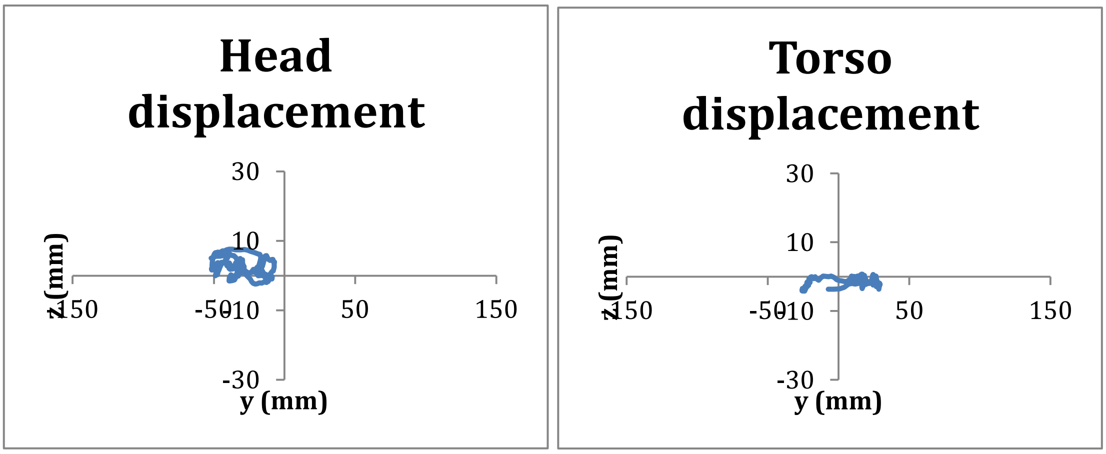

Figure C68 – Head and torso lateral displacement with respect to the centre of the seat for steering 5.

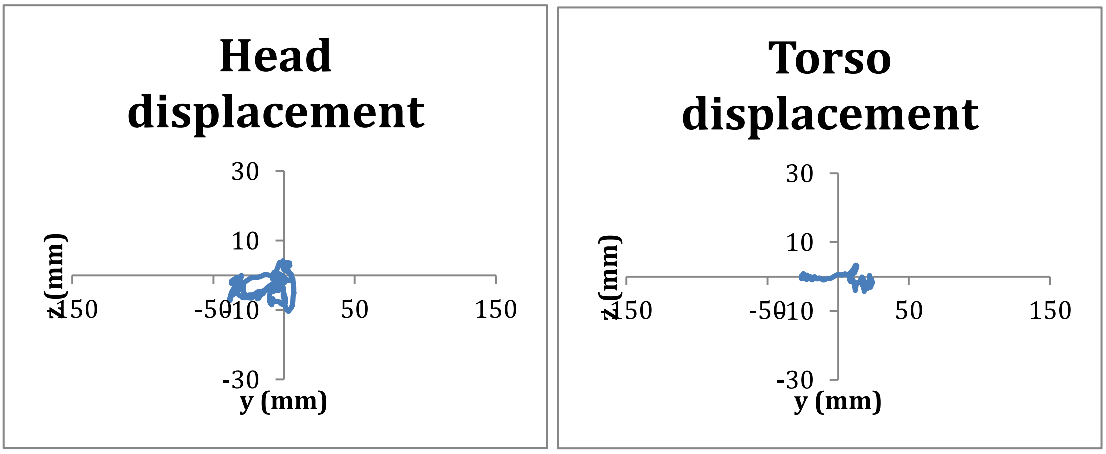

Figure C69 – Head and torso lateral displacement with respect to the centre of the seat for steering 6.

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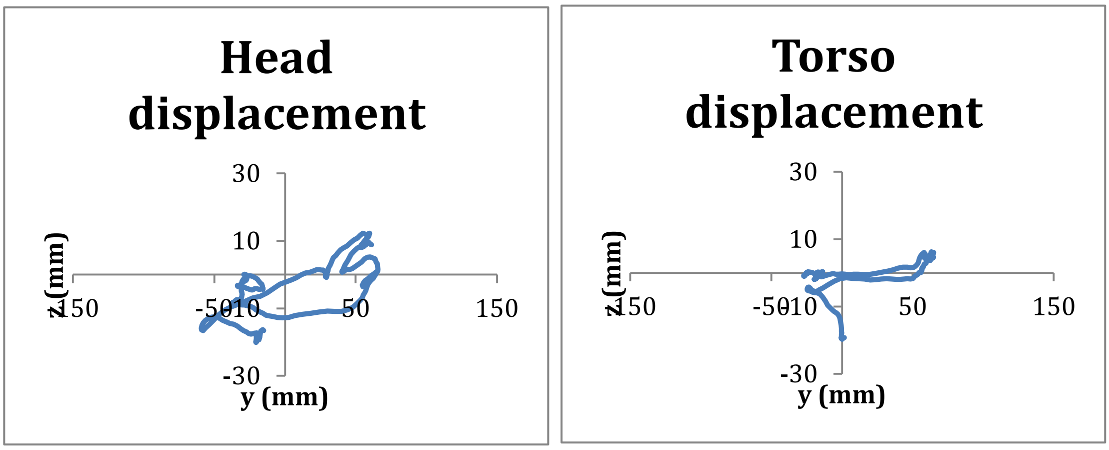


Figure C70 – Head and torso lateral displacement with respect to the centre of the seat for steering 1 (evasive).

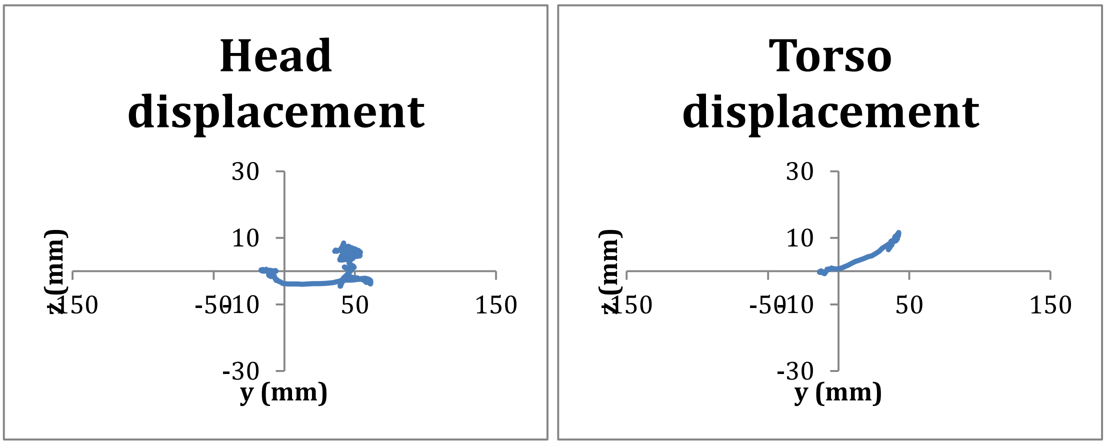


Figure C71 – Head and torso lateral displacement with respect to the centre of the seat for steering 2.

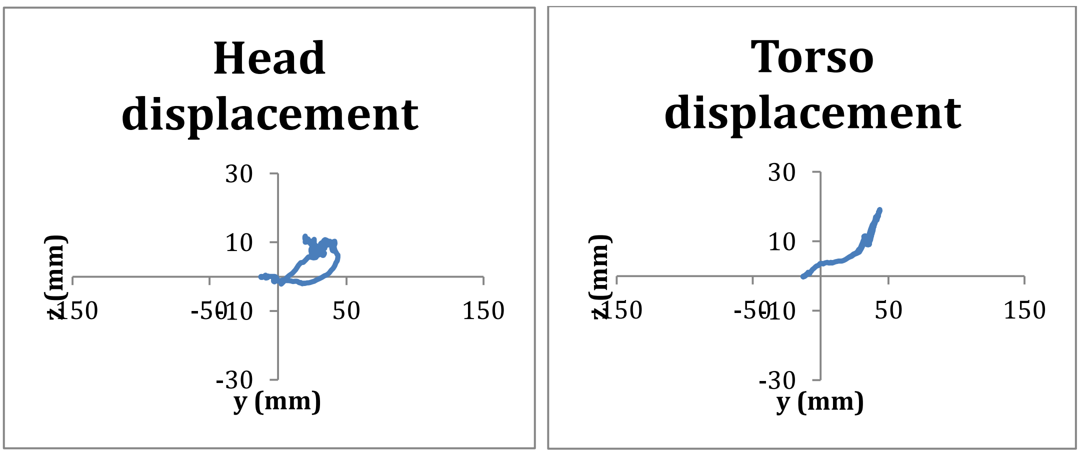


Figure C72 – Head and torso lateral displacement with respect to the centre of the seat for steering 3.

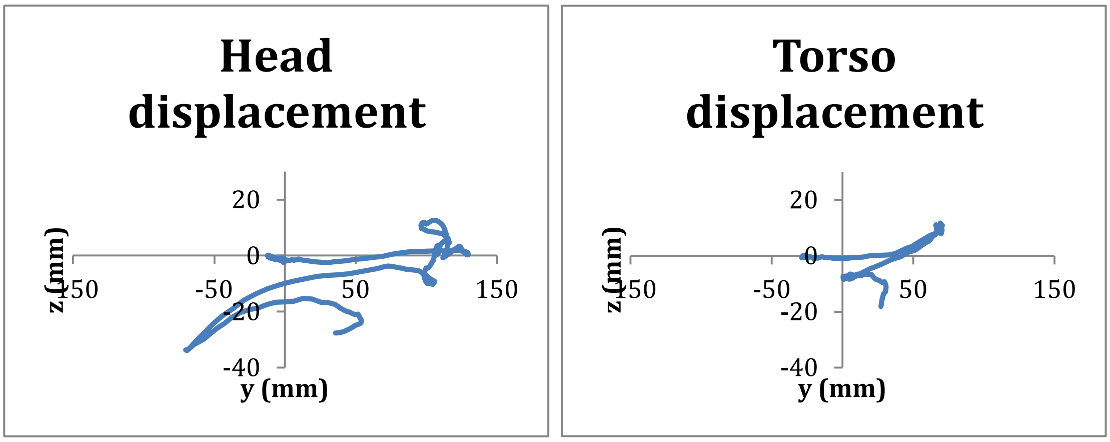
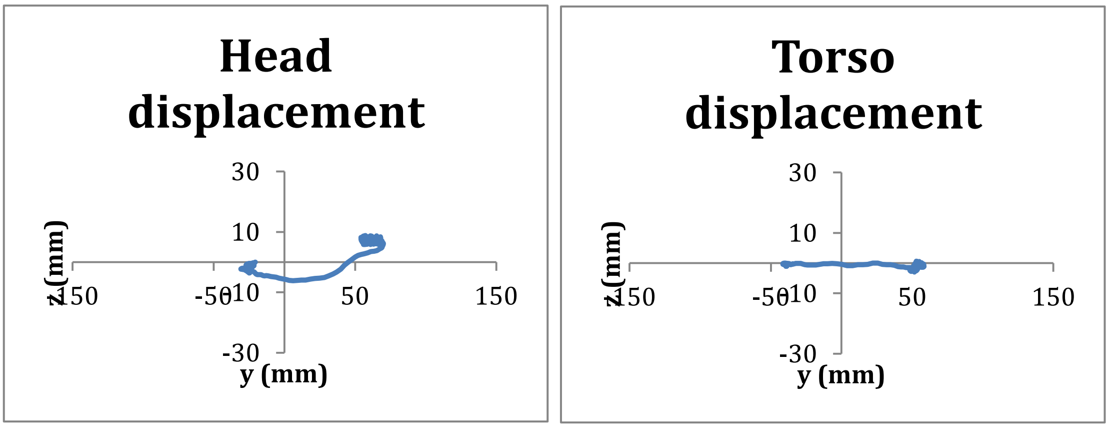


Figure C73 – Head and torso lateral displacement with respect to the centre of the seat for steering 4 (evasive).



Figur C74 – Head and torso lateral displacement with respect to the centre of the seat for steering 5.

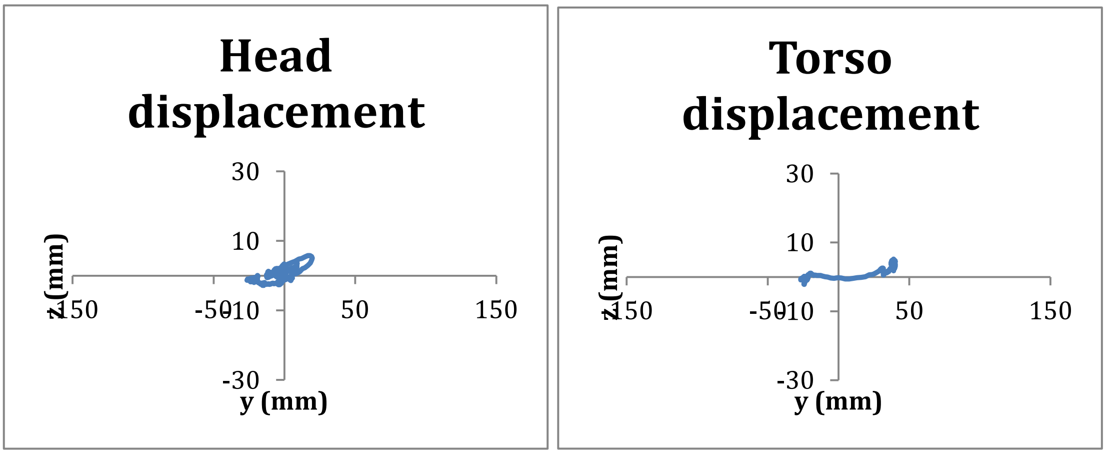


Figure C75 – Head and torso lateral displacement with respect to the centre of the seat for steering 6.