LATERAL AND OBLIQUE IMPACT LOADING OF THE HUMAN SHOULDER 3D ACCELERATION AND FORCE-DEFLECTION DATA

Sabine Compigne[1,2], Yves Caire[2], Thierry Quesnel[2], Jean-Pierre Verriest[2]
[1]INSAVALOR SA – LMSo, INSA (Institut National des Sciences Appliquées), Lyon, France.
[2]INRETS - Institut National de Recherche sur les Transports et leur Sécurité
LBMC - Laboratoire de Biomécanique et Mécanique des Chocs, Bron, France.

ABSTRACT

The shoulder dynamic response to lateral and oblique impacts was investigated by submitting Post Mortem Human Subjects (PMHS) to three non-injurious impacts delivered on the right shoulder by a rigid guided impactor (m=23.4 kg, v=1.5 m/s) at three different impact angles in the horizontal plane (0°, +15°, -15°). Then, the injury response was investigated with a single injurious lateral impact (m=23.4 kg, v=4 to 6 m/s) on the left shoulder. Triaxial accelerometers and photographic markers were positioned on different shoulder bone locations providing means of 3D response analysis. For all impact directions, the acromion, closest point to the impact, recorded the highest acceleration levels. Different impact force and acceleration signal shapes were obtained depending on impact directions. In terms of deflection, an average of 30 mm and 60 mm of maximum shoulder deflections were measured respectively for non-injurious and injurious impacts. Injurious tests produced fracture to the clavicle but also to the scapula.

Key Words: Biomechanics, cadavers, shoulder, impactors, side impacts

THE DEVELOPMENT OF A BIOFIDELIC SHOULDER ASSEMBLY for future side impact dummies requires a good knowledge of the dynamic behaviour of this complex body area when submitted to a lateral impact. Looking at existing side impact dummies, only global shoulder response is replicated, as dummy shoulder design is very simple in comparison to its human counterpart. In general, only the gleno-humeral joint is modelled as a universal joint allowing decoupled flexion/extension and abduction movements. Additional range of motion is added through clavicle motion, like in the Eurosid-1, or through flexibility of the rib to which the arm is connected, as in the WorldSID. A more humanlike shoulder has been designed for the THOR dummy in which clavicle and scapula are represented, allowing motion in the fore and aft, as well as in the shrugging directions.

Biofidelic behaviour of the shoulder is necessary to ensure a realistic load on linked body areas such as thorax and neck. Previous studies on shoulder behaviour are reported in the technical report of the International Standards Organisation on Anthropomorphic Side Impact Dummy revised in May 1997 (ISO, 1997). Re-analysis of the suitability of the referred data and its relevance to assess side impact dummy biofidelity has been made more recently by the SID 2000 Consortium (van Ratingen, 2000) which identified suitable requirements for dummy shoulders. Focussed shoulder load carried out with an impactor has the advantages of only loading the shoulder joint, limiting the possible influence of attached body areas and reproducing the same initial impact conditions. Since that time, new data or data re-analysed in depth has been published providing shoulder response but also shoulder injury risk prediction. Bolte (2000) finds from padded impactor tests that a deflection of 47 mm between the impacted acromion and the sternum predicts a 50 % risk of AIS 2 shoulder injury, whereas Koh et al. (2001) predict a 50 % risk of AIS 2 shoulder injury for 106 mm of T1-to-shoulder-edge deflection for sled tests with various impact conditions (padding characteristics and pelvic offset).

The aim of this study is to contribute to improve understanding of the behaviour of the shoulder complex through a 3D characterisation of its motion, and add data to existing studies to determine shoulder injury threshold on a larger sample.

METHOD - The test protocol is described more precisely in a previous paper (Compigne, 2002).

SUBJECTS

Post Mortem Human Subjects (PMHS) provided by the department of Anatomy of Medical University of Lyon are fresh corpses of men and women who donated their body to Science. Traditional anthropometry measurements are carried out plus dedicated measurements for shoulder range of motion evaluation in order to check shoulder joint condition. In addition, shoulder flesh thicknesses are measured at the gleno-humeral joint level on both sides. Main subject characteristics are listed in Table 1.

Subject	Age	Sex	Weight [kg]	Height [cm]	Shoulder width [mm]	Shoulder flesh thickness [mm] Left / Right
SIBER 01	77	F	67	161	335	20 / 24
SIBER 02	88	M	33	163	355	10 / 12
SIBER 03	79	F	52	159	355	12 / 10
SIBER 04	82	F	50	155	345	15 / 15

Table 1 : Main subject characteristics

TEST SET-UP

Subject instrumentation (Fig. 1, Fig. 2) – Subjects are instrumented with tri-axial accelerometers (tri-axis) placed at several bony locations:

- In the mid-sagital plane at T1 and sternum locations
- On both sides: tri-axis are mounted on aluminium plates which are bound with metallic wires to the internal and external clavicle extremities and screwed directly into the scapula at both acromion sites.
- On impacted side: two tri-axis are screwed to the scapula at the medial and inferior angles and two tri-axis are screwed laterally onto the humerus, approximately 100 and 250 mm below the humeral head, depending on PMHS anthropometry.

Data acquisition is made according to SAE J211 convention. All data are sampled at 10 kHz.

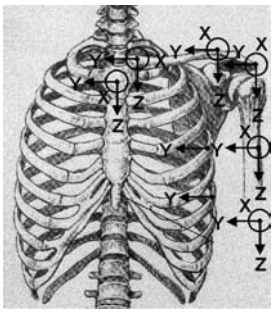


Fig. 1 : Front view of tri-axis locations

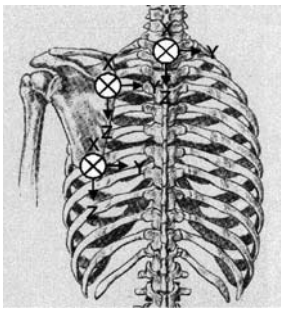


Fig. 2 : Rear view of tri-axis locations

Subject photographic instrumentation – Photographic markers are mounted on accelerometer cubes or directly screwed into the bones. For each shoulder bone, except clavicle, three markers are mounted in order to define technical co-ordinate systems whose motion can be followed during the impact (Fig. 3). Six to seven high speed cameras recording at a rate of 1000 f/s are placed around the impact scene: two to three in the PMHS back and four in the PMHS front (Fig. 3). Three of the seven cameras are high speed digital cameras with fixed time basis. For high speed film cameras, a time marker is processed every 10 ms on the right side of the image. All the cameras are synchronised by a flash lit up at time zero when the impactor contacts the PMHS. The same contact creates the zero on the data acquisition system. The 3D trajectories of the markers are reconstructed using a Direct Linear Transformation (DLT) method with 11 parameters (Abdel-Aziz, 1971)

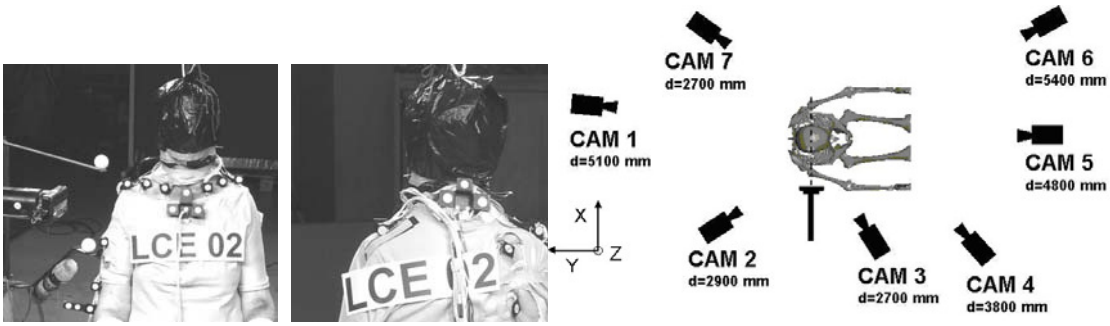


Fig. 3 : Subject photographic markers (front & rear), Camera test set-up

Subject anatomical co-ordinate systems –A local co-ordinate system can be defined for each shoulder bone based on the position of the three anatomical landmarks. These anatomical landmarks are listed in Table 2 and chosen according to van der Helm's study (1995) (Fig. 4). Before the impact, positions of markers and anatomical landmarks are recorded using a 3D measurement arm. When the landmarks cannot be reached easily, as on the scapula and the humerus, three intermediate technical points are materialised by screws into these bones. After the tests, during the autopsy, the two scapulas and the two humerus are removed in order to measure the position of unreachable anatomical points (e.g. humerus head centre) with respect to the local co-ordinate systems defined by the screws. From the trajectories of the photographic targets, the motion of the intermediate technical co-ordinate systems and the motion of the anatomical points can be derived.

Shoulder bone	Anatomical landmark	Measurement
Thorax	Incisura Jugularis (IJ)	On skin
	Processus xiphoideus (PX)	On skin
	1st thoracic vertebra (T1)	On skin + lateral x-rays
Clavicle	Sternoclaviclar joint (SC)	On skin
	Acomioclavicular joint (AC)	On skin
Scapula	Angulus acromialis (AA)	On scapula after removal
	Trigonum spinae (TS)	On scapula after removal
	Angulus Inferior (AI)	On scapula after removal
Humerus	Head center	On humerus after removal
	Lateral epicondyle	On humerus after removal
	Medial epicondyle	On humerus after removal

Table 2 : Bony landmarks

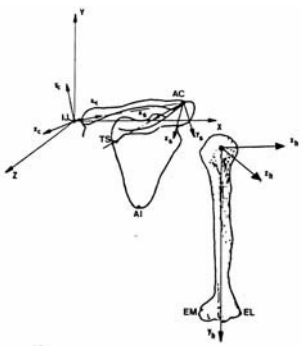


Fig. 4 : Van der Helm's anatomical co-ordinate system definition

IMPACT CONDITIONS

Subject positioning – The subject is placed sideward in front of the impactor in an upright seated posture. It is held in position by a cable attached to an electromagnet and released just before the impact. The time of release is adjusted depending on impact speeds. A 23.4 kg mass impactor fitted with a rigid 150 × 80 mm² rectangular impacting plate is used to deliver impacts concentrated on the gleno-humeral joint. Non-injurious impacts are delivered to the right shoulder at a velocity of 1.5 m/s and at three different angles in the horizontal plane (0°, +15, -15°) (Fig. 5). The 1.5 m/s speed was chosen to prevent any injury and avoid any modification of the shoulder response after several consecutive impacts. Because Bolte found ligament injuries after a single padded test at 3.7 m/s, the tests were conducted here at only 1.5 m/s. On the third subject, a fourth impact, identical to the first one, is delivered in order to check that the repeated impacts do not create slight internal injuries. Then, for left shoulder tests, the subject is pivoted 180° horizontally so that its left shoulder comes in front of the impactor. Cameras are re-located accordingly and a new calibration of the space is performed. Impacts between 4 to 6 m/s have been delivered so far to the left shoulder; the impactor velocity for next tests will be decreased or increased depending on expected injury levels.

Test matrix – The test matrix is presented in Table 3. In general (except for SIBER 01), a pulmonary pressurisation is performed but without recording the pressure level.

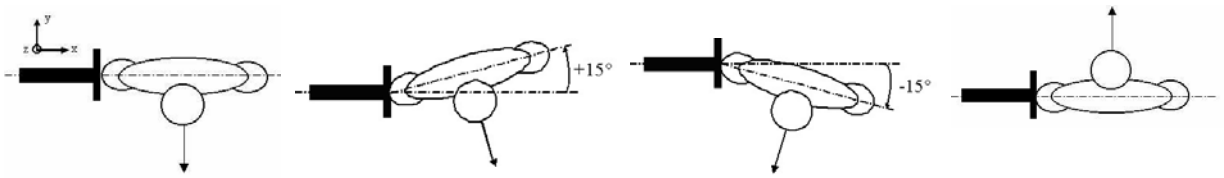


Fig. 5 : Impact directions (to right shoulder: 0°, +15°, -15°; to left shoulder: 0°)[1]

Test	Subject	Impact velocity [m/s]	Impact direction [°]	Test	PMHS	Impact velocity [m/s]	Impact direction [°]
LCE 01	SIBER 01	1.41	0	LCE 12	SIBER 03	1.50	0
LCE 02	SIBER 01	1.43	+15	LCE 13	SIBER 03	1.50	+15
LCE 03	SIBER 01	1.60	-15	LCE 14	SIBER 03	1.53	-15
LCE 04	***SIBER 01***	***5.87***	***0***	LCE 15	SIBER 03	1.56	0
LCE 07	SIBER 02	1.27	0	***LCE 16***	***SIBER 03***	***4.24***	***0***
LCE 08	SIBER 02	1.39	0	LCE 17	SIBER 04	1.54	0
LCE 09	SIBER 02	1.51	+15	LCE 18	SIBER 04	1.54	+15
LCE 10	SIBER 02	1.58	-15	*LCE 19 (*)*	*SIBER 04*	*1.52*	*-15*
LCE 11	***SIBER 02***	***6.07***	***0***	LCE 20	SIBER 04	1.55	-15
				LCE 21	SIBER 04	1.55	0
				LCE 22	***SIBER 04***	***4.27***	***0***

Table 3 : Test matrix (injurious test in italic and bold)

(*) Recordings were lost. Repeated test was conducted as LCE 20.

Post-tests – After the non-injurious tests (right side) and the injurious one (left side), x-rays are taken of both shoulders and thorax. At the end of the shoulder tests, the subject is also submitted to thoracic and pelvic impacts to its right side. Finally, an autopsy is performed for injury survey.

DATA ANALYSIS

All presented data is filtered using a low pass band digital Butterworth filter (CFC 180). Impact force is deduced from the load cell placed between the impactor tube and its impacting plate. The force measurement is corrected by a factor equal to 1.066 for the mass placed in front of the load cell.

At this stage of the research, no normalisation has been conducted. Normalisation influence will be studied once tests on all PMHSs have been carried out.

RESULTS

AUTOPSY FINDINGS

Possible contusions, looseness and tears to shoulder muscles and ligaments as well as bone fractures were searched for by a pathologist during the autopsies. Table 4 shows that the first three subjects sustained a distal fracture of the clavicle. For subjects 2, 3 and 4, coracoid fractures were also found. The third subject which was submitted to a 4 m/s impact on the left shoulder had also a fracture of the glenoid cavity. All subject injuries were rated AIS 2, according to Faverjon (1994). A contusion of the inferior gleno-humeral ligament of the right shoulder was found on the fourth subject but it could not be concluded that it was due to the right shoulder impacts, as the subject fell down on its right side from the table during the last impact (pelvic impact). During the autopsy, the calcaneum bone was also removed for dual energy x-ray absorptiometry (DEXA) in order to get the bone mineral density (BMD) of each subject (Table 4). No rib fracture was found from x-rays after the right shoulder impacts, whereas some could be seen after the left one. However, rib fractures are not reported here as a rather severe impact is also delivered to the right side of the thorax after the whole shoulder tests, inducing a high number of rib fractures, with possibility of induced fractures on the opposite side.

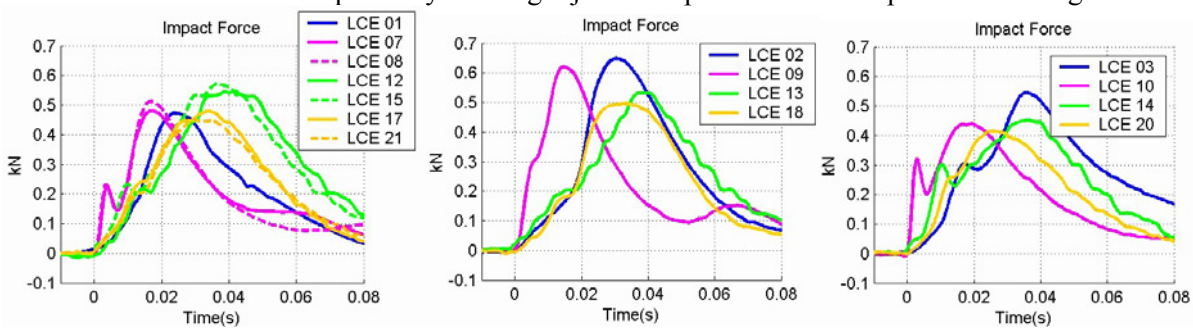
[1] Sign convention (-15° and +15°) has been reversed in comparison with earlier published data (Compigne, 2002).

Subject	Age	Sex	Weight [kg]	BMD [g/cm²]	Right shoulder injuries	Left shoulder injuries	R / L Shoulder AIS
SIBER 01	77	F	67	0.541	None	External clavicle fracture	0 / 2
SIBER 02	88	M	33	0.638	None	External clavicle fracture Coracoid process fracture	0 / 2
SIBER 03	79	F	52	0.591	None	External clavicle fracture Coracoid process fracture Glenoid cavity fracture	0 / 2
SIBER 04	82	F	50	0.375	Contusion of the inferior glenohumeral ligament	Acromion fracture at the junction with the scapula spine Coracoid process fracture	1 / 2

Table 4 : Subject characteristics and injury summary

NON-INJURIOUS IMPACT TESTS (RIGHT SHOULDER IMPACTS)

Impact force – Very low levels of impact force are obtained from 1.5 m/s impacts. An average impact force of 50 daN is obtained from all tests and subjects. For the second subject, the first test (test LCE07) was repeated just after (test LCE 08) because required speed of 1.5 m/s was not obtained. For the third subject, the first shoulder impact (test LCE 12) was repeated at the end of the right shoulder impacts (test LCE 15) to verify that these various impacts, even at low speed, did not have any influence on the shoulder response by creating injuries. Impactor forces are presented on Fig. 6.



0° *+15°* *-15°*

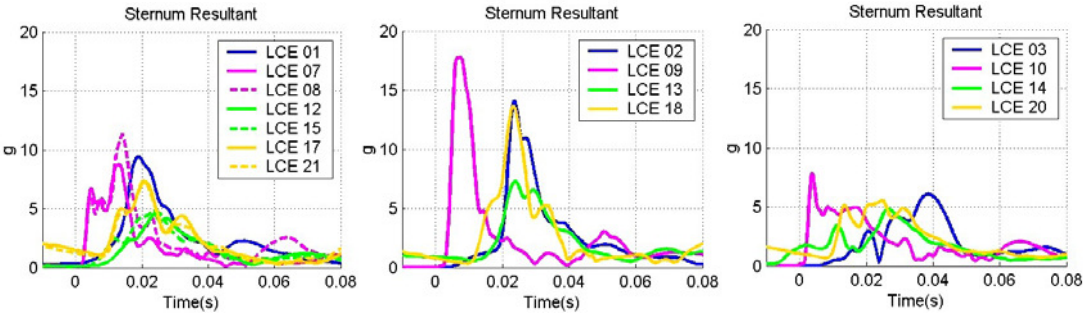
Fig. 6 : Impactor force time history for 1.5 m/s right shoulder impacts

Comparable impactor force levels are reached in the three directions of impact. The impactor force is slightly higher for the +15° oblique impacts, but the biggest difference concerns the curve shapes especially the first peak observed for all the subjects at -15° and for three of them at 0°. Responses at -15° have also a flatter shape. Shoulder complex is loaded in a rather identical manner for the 0° and -15°, whereas at +15°, shoulder joint reacts differently. This first peak happens at different moments during the impact depending on PMHS anthropometry and flesh thickness that has to be compressed before loading the bones. As the gleno-humeral contact surfaces are different in front and rear, the hypothesis of an internal contact between the humeral head and the scapula glenoid rear surface can be made to explain this first peak. The higher congruence of the rear part of the scapulo-humeral articulation explains also for example the higher frequency of shoulder anterior luxation.

The influence of the subject anthropometry on the temporal characteristics of the response clearly appears with the time shift of force peaks ordered according to the body mass. These time shifts are observed on all the subject responses. Here, normalisation of time based on subject weight may help to reduce response variability, especially for subject 2 which only weighs 33 kg. However, it should be noted that this subject achieved one of the best BMD score and did not sustain more injuries than the other subjects.

Close force curves for tests LCE 07 and LCE 08 and also tests LCE 12 and LCE 15 show that test to test repeatability is quite good. This repeatability will also be verified on subject responses.

Subject shoulder acceleration measurements – Only some acceleration responses are presented here and compared for the four subjects and the three impact conditions.

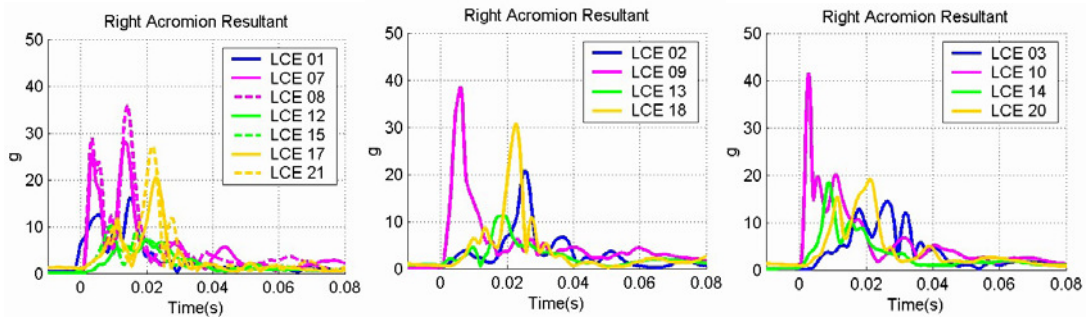


0° *+15°* *-15°*

Fig. 7 : Sternum Res. acceleration for 1.5 m/s right shoulder impacts

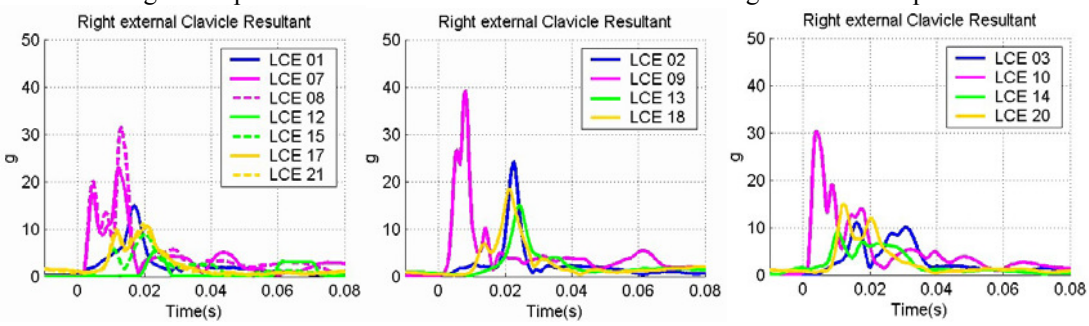
Some variations between subjects are observed for sternum accelerations measurements. From the different impact directions, lower sternum accelerations are seen for -15° impact direction and highest ones for the +15° impacts. At -15°, rear shoulder complex is more loaded whereas at +15°, it is the front shoulder (clavicle and sternum).

On the impacted side, acromion and clavicle are loaded differently depending on impact directions. Comparable resultant accelerations are recorded on acromion and external clavicle. For the three impact directions, the external and internal clavicle resultant accelerations are also comparable, showing very little signal attenuation between the two ends of the clavicle. On the contrary, the comparison of internal clavicle resultant acceleration and sternum one, shows an attenuation (sternum resultant accelerations are twice lower than that of the internal clavicle) certainly due to dissipation into the sterno-clavicular articulation. For +15° impacts, acromion lateral acceleration exhibits only one single peak that shows that the acromion is uniformly pushed by the impactor. At 0° and -15° impacts, acromion lateral responses have two peaks. The first peak occurs at the same time as the little peak already noticed from the impactor force. From film analysis it will be showed that for these two impact directions, the acromion is pushed backwards. Analysis of marker trajectories will also show that at +15°, the acromion motion is in line with that of the impactor. However, its motion is still limited, perhaps due to the arm position along the thorax, which doesn't allow the shoulder to move so much (cf. Fig. 12 to Fig. 17). This reinforces our previous hypothesis, i.e. the shoulder reacts differently in +15° tests as compared to 0° and -15° ones.



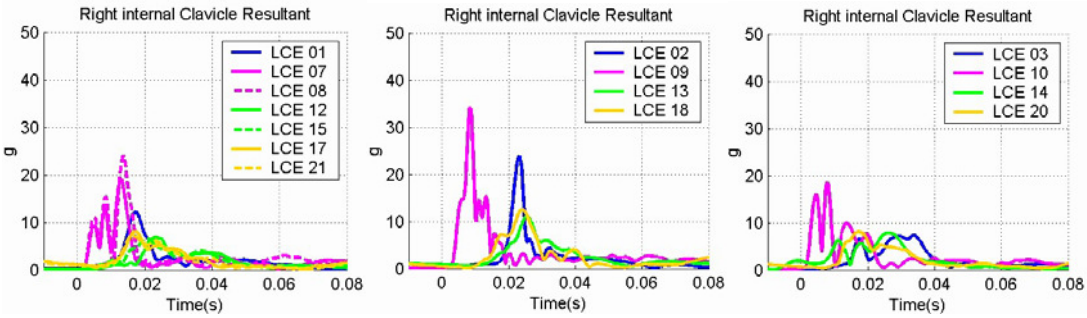
0° *+15°* *-15°*

Fig. 8 : Impacted acromion Res. acceleration for 1.5 m/s right shoulder impacts



0° *+15°* *-15°*

Fig. 9 : Impacted external clavicle Res. acceleration for 1.5 m/s right shoulder impacts

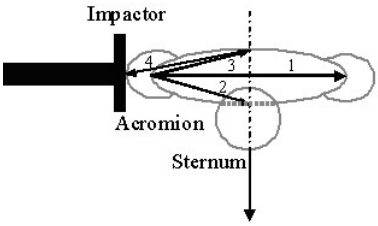


0° *+15°* *-15°*

Fig. 10 : Impacted internal clavicle Res. acceleration for 1.5 m/s right shoulder impacts

Looking more generally to subject 03 responses in tests LCE 12 and test LCE 15 and to subject 04 responses in tests LCE 17 and test LCE 21, it can be concluded that the three impacts conducted at 1.5 m/s do not modify the way the shoulder reacts. The effects of the three impact directions can be assessed without suspicion of shoulder modifications after each of these impacts.

Subject shoulder kinematics – So far, only trajectories of the technical markers screwed into the bones have been analysed. The motion of anatomical points will be derived in the next step. In this first analysis, several deflections (acromion-to-acromion, acromion-to-sternum, acromion-to-T1, impactor-to-T1) have been calculated from marker 3D-motions (Fig. 11). The 3D reconstruction of marker positions is checked at time zero by comparing reconstructed co-ordinates to those obtained from the 3D measurement arm just prior to the impacts. The average error made on distance estimation by the film analysis is less than 1% when these distances are compared to initial static values. Film analysis has not been conducted for tests LCE 17 to LCE 21 yet.



1: acromion to acromion,
2: acromion to sternum,
3: acromion to T1,
4: impactor to T1

Fig. 11 : Analysed deflections

The shoulder marker trajectories are presented on Fig. 12 to Fig. 17 at discrete times (0, 20, 40 and 60 ms). The trajectories are reported in the laboratory co-ordinate system defined, for a right hand impact at 0°, as X along the impactor axis, Z vertical and Y pointing backwards to the subject. For oblique impacts, the co-ordinate system has been rotated by ±15° with the subject's body for a better comparison between the different tests. The graphs from left to right correspond to subject 01 to 03 respectively.

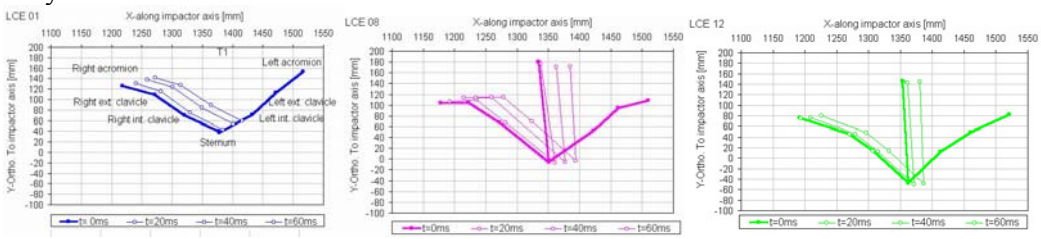


Fig. 12 : Acromion, clavicle and sternum motions in the laboratory XY plane, origin at impactor – (0°)

NB: T1 trajectory not available for test LCE 01.

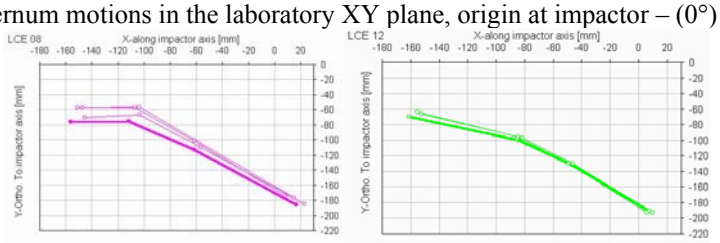


Fig. 13 : Acromion, clavicle, sternum motions in the laboratory XY plane, origin at T1 – (0°)

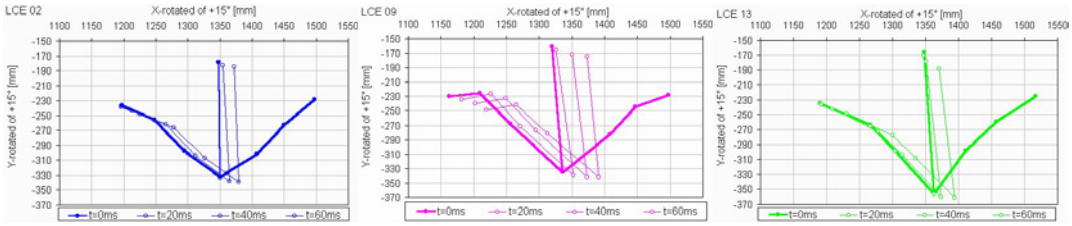


Fig. 14 : Acromion, clavicle, sternum and T1 motions in the laboratory XY plane origin at impactor – (+15°)

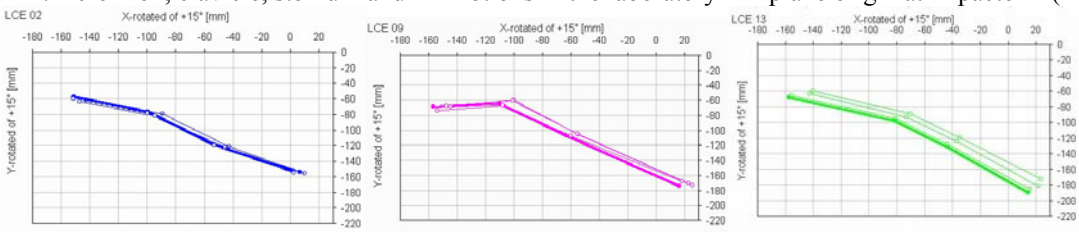


Fig. 15 : Acromion, clavicle, sternum motions in the laboratory XY plane, origin at T1 – (+15°)

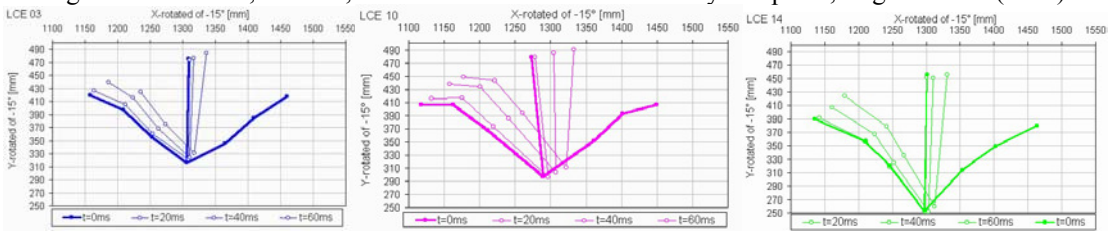


Fig. 16 Acromion, clavicle, sternum and T1 motions in the laboratory XY plane origin at impactor – (-15°)

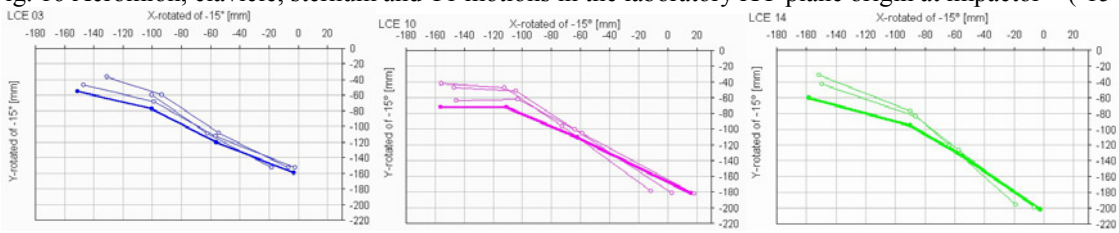
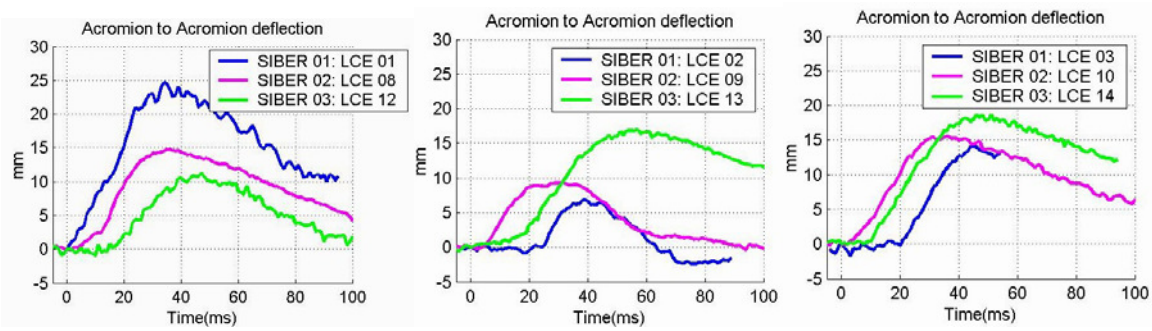


Fig. 17 : Acromion, clavicle, sternum motions in the laboratory XY plane, origin at T1 – (-15°)

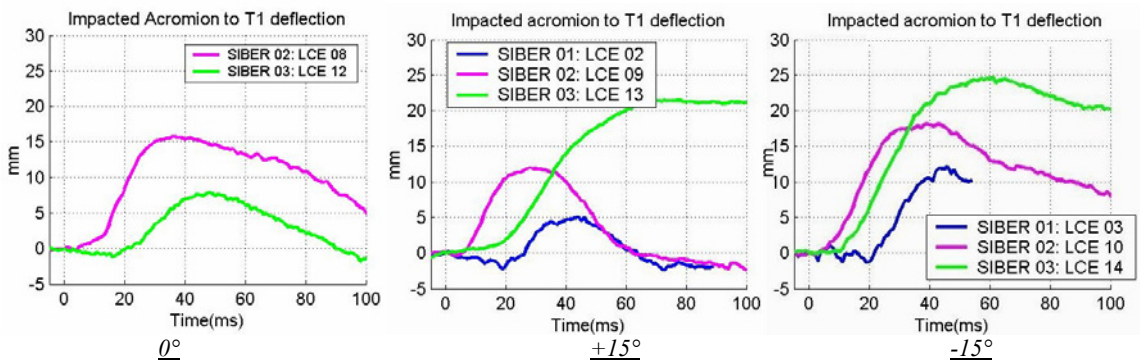
The acromion-to-acromion deflection was between 7 to 25 mm. The lowest deflections are generally found for the +15° impact direction.



0° *+15°* *-15°*

Fig. 18 : Acromion-to-acromion deflection for 1.5 m/s impacts

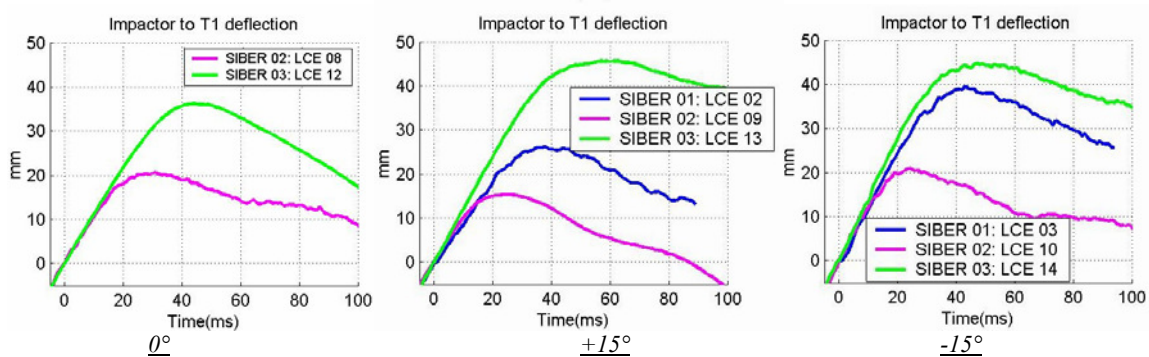
The acromion-to-T1 deflection is equal or slightly inferior to the acromion-to-acromion deflection, except for the -15° impacts.



0° *+15°* *-15°*

Fig. 19 : Acromion-to-T1 deflection for 1.5 m/s impacts

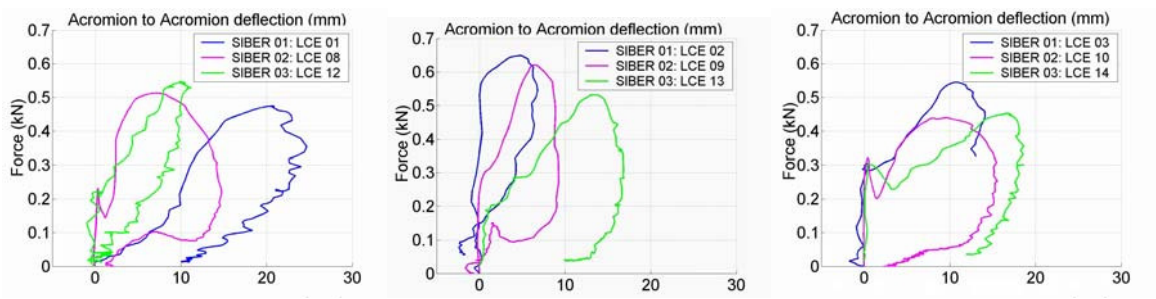
The impactor-to-T1 deflection represents the deflection of the impacted shoulder. It takes flesh compression, bone motion and joint compression into account. While subject 2 has the largest skeletal deflections (acromion-to-acromion), it has the lowest global shoulder deflection. This result is related to its anthropometry (body mass of only 33 kg) and almost all deflection is due to internal structures deformation or compression and not to soft tissues. The global shoulder deflection for subjects 1, 2, 3 is equal to 30, 20 and 45 mm, respectively (average values for the three impact directions). Except for subject 2, 65 % of the deflection is approximately due to the arm flesh deflection and the rest comes from internal shoulder structure motion.



0° *+15°* *-15°*

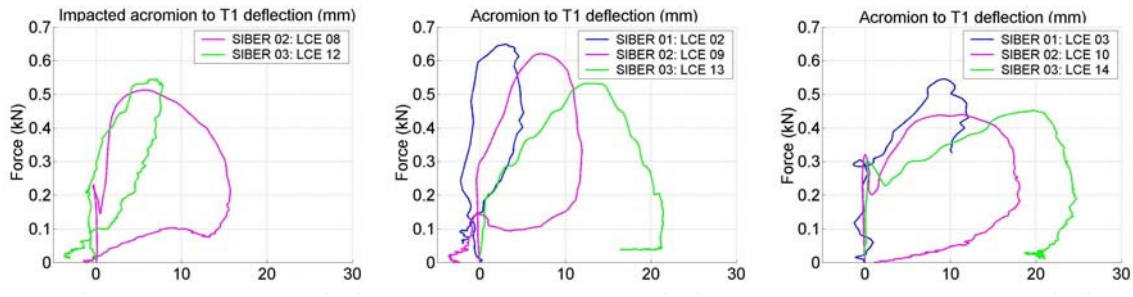
Fig. 20 : Impactor-to-T1 deflection for 1.5 m/s impacts

Subject 2 shows force-deflection responses with very steep initial slope during the loading phase. The deflection continues to increase after the impact force has reached a maximum and decreases. Subject 1 shows lower initial slope because of its larger flesh thickness. On Fig. 21 and Fig. 23, the first peak seen of the impact force curve gives its shape to the force-deflection response.



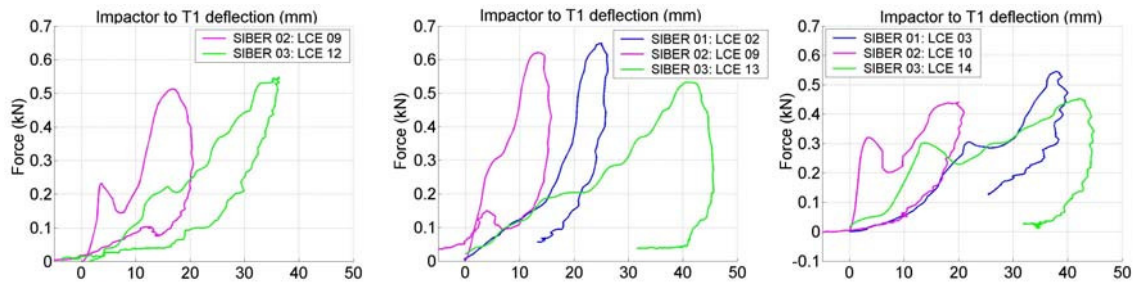
0° *+15°* *-15°*

Fig. 21 : Force vs acromion-to-acromion deflection response for 1.5 m/s impact



0° *+15°* *-15°*

Fig. 22 : Force vs acromion-to-T1 deflection response for 1.5 m/s impact



0° *+15°* *-15°*

Fig. 23 : Force vs impactor-to-T1 deflection response for 1.5 m/s impact

INJURIOUS IMPACT TESTS (LEFT SHOULDER IMPACTS)

Impactor responses– As high velocity tests conducted on the first two subjects led to fractures, the third subject was impacted at 4 m/s (test LCE 16). Subject 2 and 3 who sustained clavicle and coracoid process fractures experienced a very similar impact force, rather flat with two little peaks. In both cases, the coracoid process was fractured at its base, eliminating the role of the coraco-acromial and coraco-clavicular ligaments. From this point, the shoulder (scapula and humerus) was not linked anymore to the clavicle and sternum and fell down under arm weight as already explained by Irwin et al. (2001). The flat shape might be a consequence of this; the shoulder had no more resistance and impactor was free to move inside it.

Impact force from tests LCE 16 and LCE 22 conducted at 4.2 m/s were aligned with the ISO corridor lower bound given for 4.5 m/s impacts. The responses of these two tests would be within the corridor after normalisation.

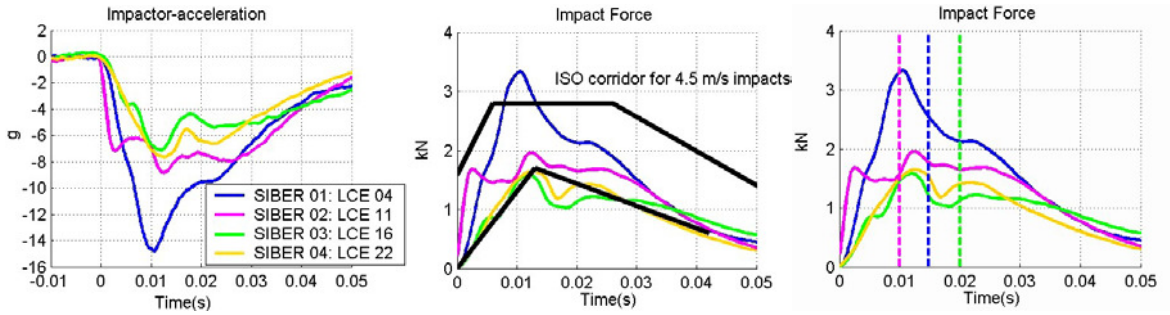


Fig. 24 : Impactor acceleration (left) and impact force (middle & right) for injurious tests to the subject left shoulder

Subject shoulder acceleration measurements – For these impacts, rather high acceleration resultants are observed. Again, responses of the second subject are earlier and higher because of its small stature and weight. Sternum accelerations are very similar for the four subjects. Equivalent accelerations occur in the longitudinal direction, resulting from the forward motion of the sternum under shoulder compression.

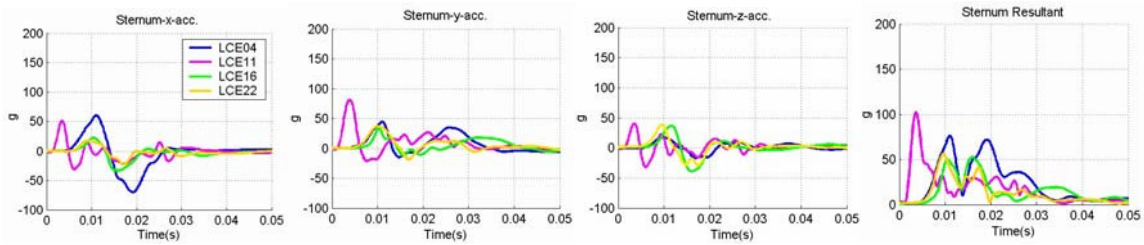


Fig. 25 : Sternum accelerations

The acromion is submitted to a transversal acceleration equal to almost ten times that of the impactor.

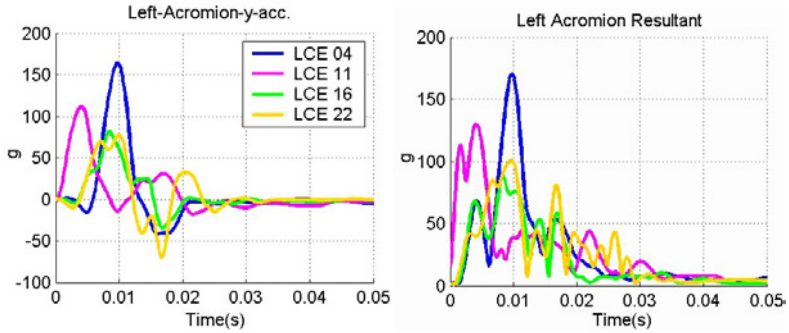


Fig. 26 : Lateral and resultant impacted acromion accelerations

The acromion and the clavicle receive similar accelerations in the three directions. Fluctuation is seen on transverse accelerations at the external and internal clavicle locations. For the second and third subjects, the clavicle fracture occurs at the distal third of the clavicle, between the external tri-axis of the clavicle and the acromio-clavicular joint. For the first subject, tri-axis was screwed into the clavicle and the fracture occurred at the screw. Opposing polarities as described by Bolte (2000) on accelerometer traces placed around the fracture site (in the present case, acromion and external clavicle) are not identified here. In tests LCE 04 and LCE 16, the large oscillations seen on the transverse accelerations at around 10 ms may be due to the fracture. A distal clavicle fracture is also found for the test LCE11 but neither the clavicle readings, nor the impact force (Fig. 24-right), give much evidence of this. The vertical lines drawn on the curves for the three subjects represent the time at fracture occurrence. This time is identified from the marker motion analysis (next section). As the marker positions are given every 5 ms time step, the fracture "time window" is equal to 5 ms before this time line. However, a correlation with clavicle acceleration recordings is not so straightforward.

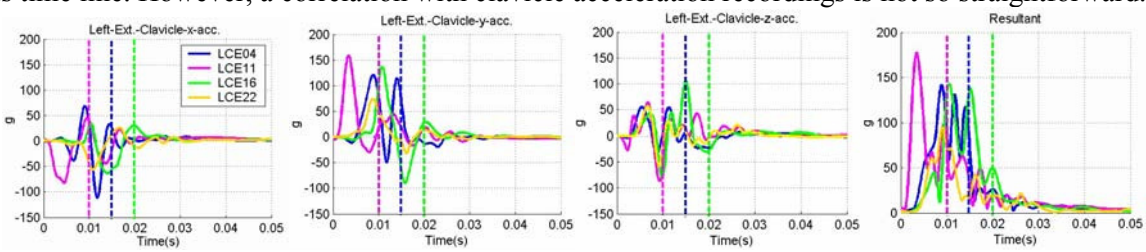


Fig. 27 : External clavicle accelerations

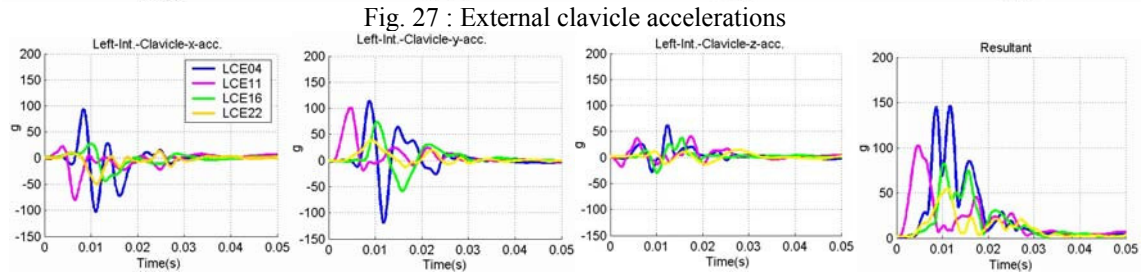
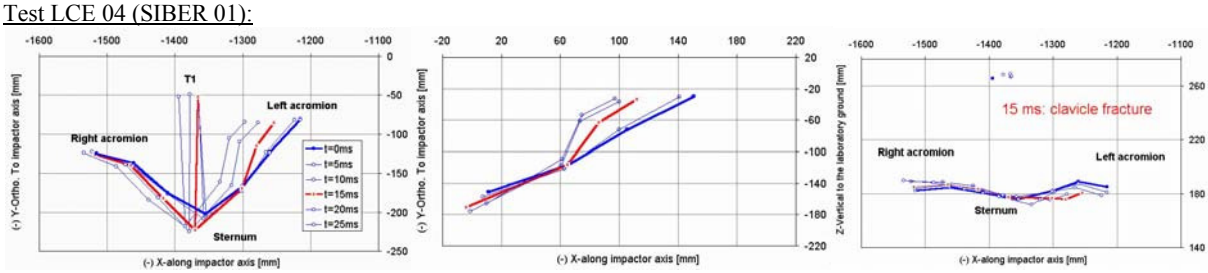


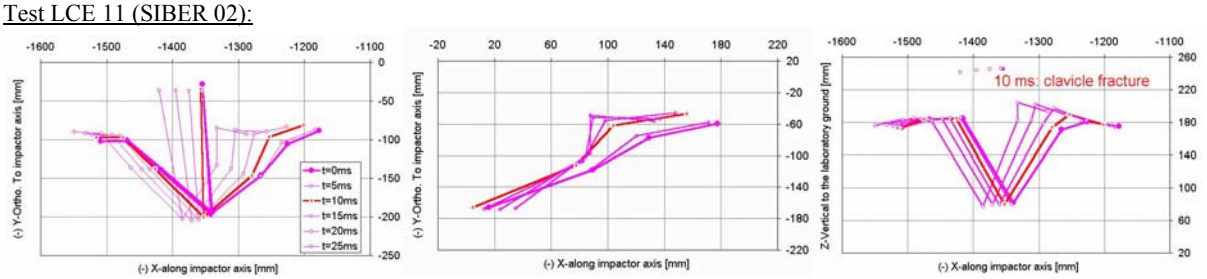
Fig. 28 : Internal clavicle accelerations

<u>Subject shoulder kinematics</u> – As for the non-injurious impacts, a 3D reconstruction of marker motion is conducted in the same way. Motions of acromions, clavicles, sternum and T1 are presented at discrete moments during the impact (0, 5, 10, 15, 20, 25 ms) (Fig. 29).

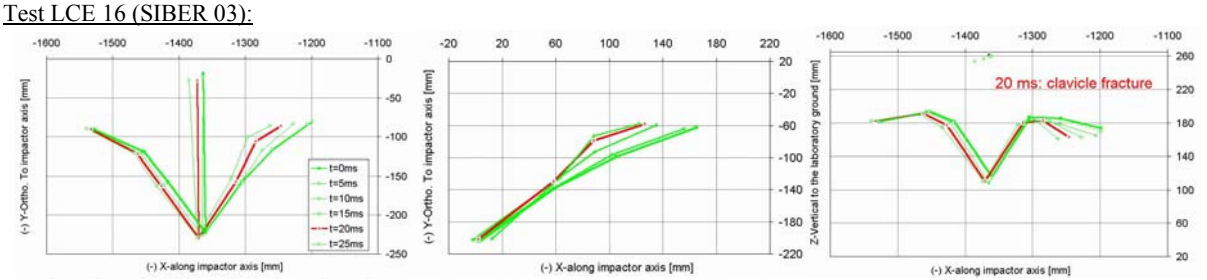
Test LCE 04 (SIBER 01):



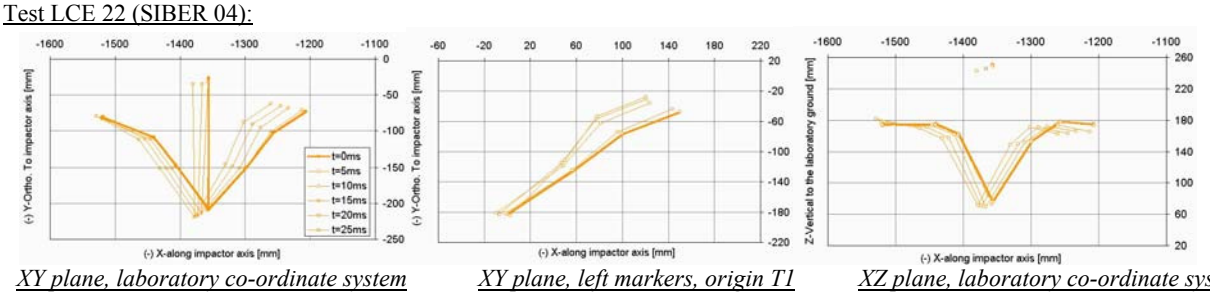
Test LCE 11 (SIBER 02):



Test LCE 16 (SIBER 03):



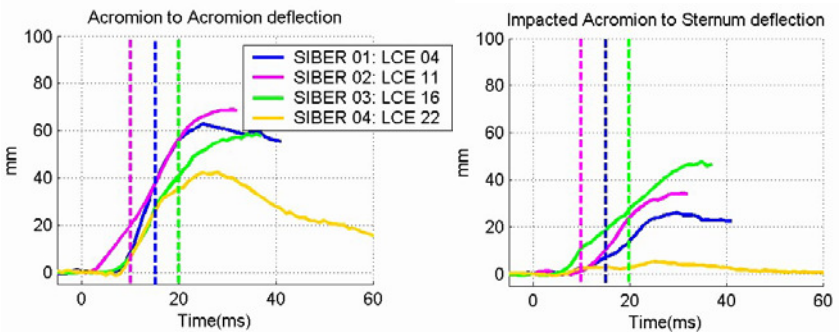
Test LCE 22 (SIBER 04):



XY plane, laboratory co-ordinate system *XY plane, left markers, origin T1* *XZ plane, laboratory co-ordinate system*

Fig. 29 : Motion of the acromion, clavicle, sternum and T1 markers

From Fig. 30, acromion-to-acromion deflection values between 60 and 70 mm are obtained for the three impacts in which subject's clavicle is fractured. This represents almost 20% of compression of the initial bi-acromial width. A smaller deflection (40 mm, 10% of compression) is obtained for subject 4 for which no clavicle fracture was found. A very small acromion-to-sternum deflection is also measured for this subject whereas its impactor-to-T1 deflection is equivalent to that of subject 3 submitted to an impact at the same velocity level. As on clavicle acceleration responses, end of the fracture "time window" is indicated by the vertical lines. It seems that the fracture occurs for very low acromion-to-sternum deflection, for acromion-to-acromion deflection between 20 and 40 mm and for impactor-to T1-deflection between 40 and 60 mm.



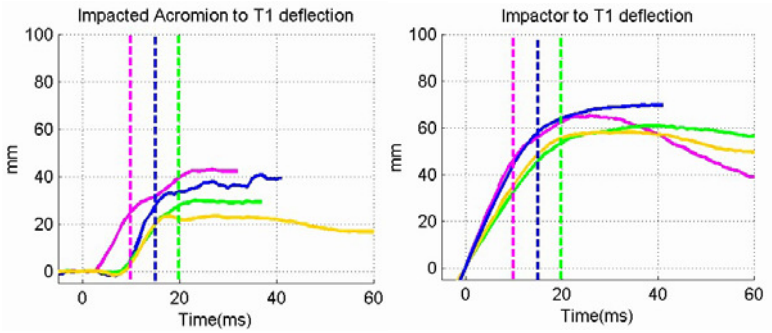


Fig. 30 : Shoulder deflections for high speed impacts

The slope of the force deflection curves of the skeletal structure is very steep (Fig. 31). This reflects the rigid loading due to the absence of padding on the impactor face. For subject 2, the flat response after the loading phase is typical from fractures: increase of deflection for a constant force level.

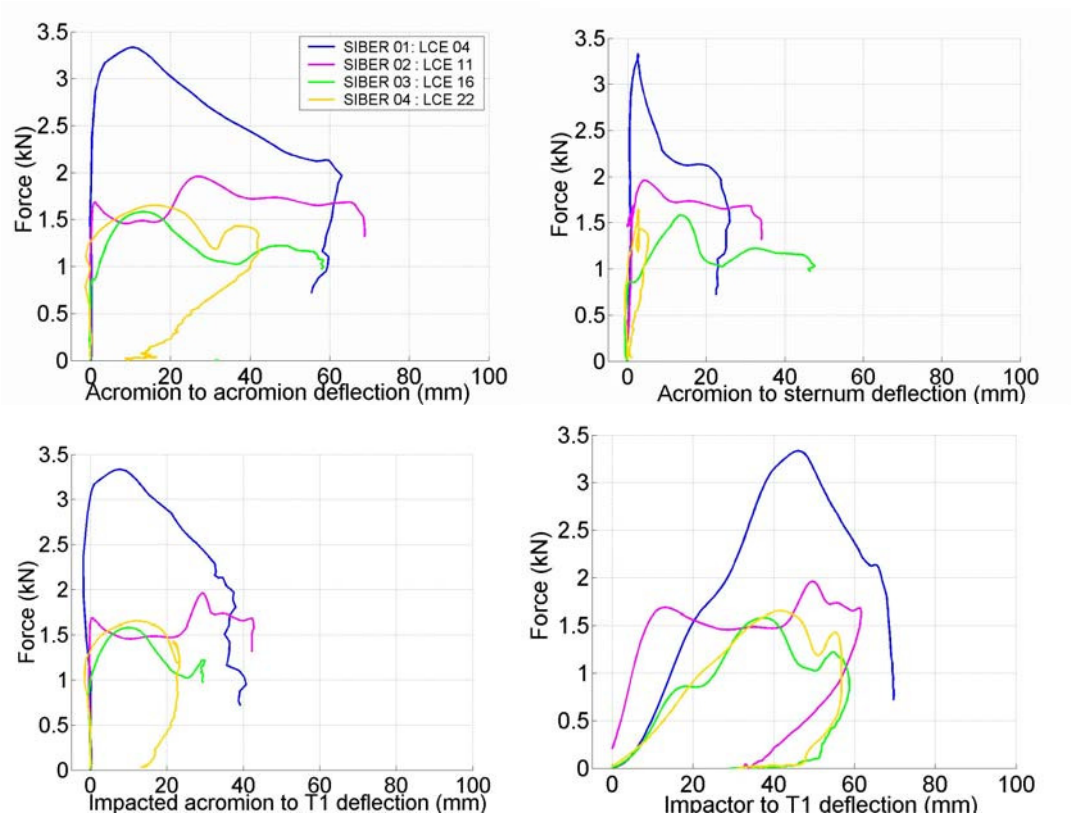


Fig. 31 : Force-deflection responses for high speed impacts

DISCUSSION

Most of the test protocol used in this study is based on Bolte's (2000). Main addition to his test protocol is the analysis in three dimensions of the marker trajectories, shoulder deflection and, in a future step, the analysis of the shoulder bone relative motion. Similar limitations of this study due to the use of PMHS can also be highlighted. More specifically, the lack of muscle tone may have influenced the response of the shoulder for which muscles have a stabilization role. Some injuries such as ligament looseness are difficult to identify since they are not as obvious as a rupture. Some of them may not have been considered.

Due to the use of a rigid impactor in the current study, some more severe but also different injuries have been found compared to Bolte's work. The fracture at the external site of the clavicle is still found as in Bolte's study, but also scapula injuries at coracoid process and glenoid cavity. No ligament injury is found whereas Bolte identified commonly sterno-clavicular and, in more severe cases, acromio-clavicular looseness. This may be explained in our case by rigid impacts which fracture the

bones directly. Koh et al. (2001) who performed rigid and padded lateral sled tests showed that different injuries were created depending on the use or not of paddings. Furthermore, 100% of the subjects (four subjects in total) had shoulder injuries in rigid impacts against 50% (nine subjects in total) in padded impacts for almost the same velocity. In padded and rigid tests, acromio-clavicular separation was the most common injury, but acromion fracture was only found in rigid impacts and clavicle fracture was more often obtained in padded tests. Padding thickness and type was demonstrated by Koh as having a great influence on shoulder deflection and therefore on shoulder injury. Indeed, it was statistically demonstrated by Bolte and Koh that shoulder deflection was a significant parameter to evaluate the risk of injury, unlike the impact force.

Looking at the existing shoulder impact tests, authors have investigated the influence of the arm position: passenger arm position (arm along the thorax, the hands on the laps), driver position (arm in antepulsion), and also the influence of the impact level along the humerus. Bolte conducted his tests in a similar arm position as the current study (slightly antepulsion), whereas Meyer (1994) and Thollon (2001) performed tests in both passenger and driver arm position using subjects preserved in a Winckler's preparation. Impacts were delivered at two different speeds: 5.5 and 7.5 m/s with a 37 kg impactor and foam interfaces or paddings were placed between the impactor and the subject's shoulder. Meyer and Thollon found also a rather flat response shape of the shoulder impact force curve showing two peaks. They analysed the first peak as an end stop of the humeral head into the glenoid cavity of scapula and the flat shape also showed that the shoulder is well loaded and did not escape the impactor face. Fracture of the external clavicle was frequent in both driver and passenger arm position, as also looseness in the sterno-clavicular joint. As in the present study, coracoid process and glenoid cavity fractures were also found in some cases. This type of injury was analysed as a consequence of a direct impact of the humeral head.

The consecutive impacts delivered to subject's right shoulders did not appear to have an influence on the response of the shoulder as it still behaved in the same way after several impacts. The angles of ±15° for the direction of impact were chosen in line with previous tests performed by APR and reported in the ISO DTR 9790 document (ISO, 1997). They showed slight variations in the shoulder response.

The injurious tests on the third and fourth subjects were conducted at 4 m/s in very similar test conditions than that of APR, with close subject masses (respectively for the APR and the present study, 48 to 56 kg and 50 to 52 kg). Equivalent impact forces were recorded: between 1.5 and 2.4 kN for the APR and 1.7 kN in average for this study. ISO reported from APR tests a maximum 36 mm normalised shoulder deflection, while a 60 mm maximum raw deflection and 40 mm raw deflection at impact force peak were calculated from subjects 03 and 04 of this study. According to Bolte, for non-displaced fractures, the maximum of deflection of the shoulder can be used as a predictor of the fracture even if the time of fracture occurs before the maximum deflection. Here, a maximum acromion-to-sternum deflection of 25 mm led to fracture, whereas Bolte found that an acromion-to-sternum deflection of 47 mm gave a 50% probability of an AIS 2. The use of padding seems to reduce considerably the risk of a shoulder injury by increasing the maximum deflection level that shoulders can sustain before fracture.

For dummy development, this study will give biofidelity guidelines and required measurements to assess shoulder injury risk in case of a lateral impact. Dummies do not need to replicate all the details of the human anatomy, but global responses, such as shoulder deflection and impact force have to be humanlike. In terms of injury assessment, and more particularly clavicle fracture, acromion-to-sternum deflection may be one of the relevant factors which need to be directly measured or correlated with other available dummy deflection measurements.

CONCLUSION

Four to five tests have been conducted on each of four PMHSs in order to study shoulder behaviour in case of non-injurious and injurious impacts. The non-injurious impacts carried out at very low speed were performed at three different angles in the horizontal plane (0°, +15°, -15°). In order to analyse the deflection in oblique impacts, as well as being able to take into account subject rotation during the impact, a three dimensional analysis of the subject motion was performed. Deflections reported in this paper were relative 3D displacements between markers.

The results showed a good repeatability for same impact conditions and consecutive tests at 1.5 m/s did not damage the shoulder, as same response was still observed after four impacts. Slight modifications of the response were seen when angle changed, as different areas of the shoulder complex were loaded. It may be useful to explore other impact conditions, i.e. ± 15° oblique tests at higher velocity and/or keep the same velocity and increase the angle up to ± 30° to reinforce this analysis.

In injurious tests, it was not possible to detect the time of the fracture using acceleration signals around the fracture site as described by Bolte (2000). A maximum acromion-to-acromion deflection between 60 and 70 mm was reached for the two tests conducted at 6 m/s; the range was 40 to 60 mm for the two tests conducted at 4 m/s. A fracture "time window" was estimated from sternum, external and internal clavicle, and acromion marker motions. Comparison of injury results from rigid and published padded tests showed large difference in severity but also on injury thresholds.

The analysis of these tests is not completed as the final goals are to build response corridors for the shoulder and define injury risk curves. The next step will also be to define anatomical landmark motions and relative bone rotations deduced from marker motions and static measurements taken prior to tests or on the removed bones after the autopsy. This data could be used for numerical human model validation, as well as for the evaluation of the biofidelity of the shoulder/thorax complex of dummies.

ACKNOWLEGMENTS

The authors would like to thank the INRETS/LBMC staff for their valuable contribution to this work: A. Maupas, co-ordinator of experiments, P. Lapelerie for preparing PMHSs, G. Goutelle, J. Lardière, M. Callejon for collecting films and photos, M. Marais and S. Serindat for measurements taken during the tests.

The authors thank also the department of Anatomy of Lyon-Nord (Medical University of Lyon), the Radiology laboratory of the Sainte Marie-Thérèse Clinic, Bron.

The SIBER project, co-ordinated by the TNO and involving ACEA, BAST, FTSS-UK, MIRA, TRL, TRW, WUT, is funded by the European Commission under contract G3RD-2000-00365.

REFERENCES

ABDEL-AZIZ, Y.I., KARARA, H.M., Direct linear transformation from comparator coordinates into space coordinates in close-range photogrammetry. Proc of the Symposium on Close-Range Photogrammetry, 1971, Falls Church, VA: American Society of Photogrammetry, pp. 1-18.

BOLTE IV, J.H., HINES, M.H., Mc FADDEN, J.D., SAUL, R.A, Shoulder response Characteristics and injury due to lateral glenohumeral joint impacts, Proc. of the 44th STAPP Car Crash Conference, SAE Editor, Nov. 2000, Atlanta-Georgia, paper n°2000-01-SC18, pp. 261-280.

COMPIGNE, S., CAIRE, Y., VERRIEST, JP., Three dimensional dynamic response of the human shoulder submitted to lateral and oblique glenohumeral joint impacts, Proc. of the IRCOBI Conference, Sept. 2002, Munich-Germany, pp. 377-379.

FAVERJON G., FORET-BRUNO, J.Y., GOT, C., MORVAN, Y., PAGE, M., PORTIER, L., THOMAS, C., VALLEE, H., Abbreviated Injury Scale – 1990 Revision, abbreviated impairment scale – 1994 Revision French translation, June 1994.

van der HELM, F.C.T., PRONK, G.M., Three-dimensional recording and description of motions of the shoulder mechanism, Journal of Biomechanical Engineering, Feb. 1995, Vol. 117-pp. 27-40.

ISO/TC22/SC12/WG5, Road Vehicles - Anthropometric side impact dummy – Lateral impact response requirements to assess the biofidelity of the dummy, TR 9790, 1997.

KOH, S-W., CAVANAUGH, J.M., ZHU, J., Injury and response of the shoulder in lateral sled tests, Proc. of the 45th STAPP Car Crash Conference, SAE Editor, Nov. 2001, paper n°2001-22-0005, pp. 101-141.

MEYER, E., Le choc latéral sur l'épaule: Mise en place d'un protocole expérimental en sollicitation dynamique, Mémoire de D.E.A., Université Paris Val de Marne, Faculté de Médecine Pitié-Salpetrière, Ecole National Supérieure des Arts et Métiers de Paris, 1994.

van RATINGEN, M., HOOFMAN, M., WISMAN, J., ROBERTS, A., LOWNE, R., COMPIGNE, S., BOUQUET, R., CAIRE, Y., VERRIEST, JP., Review of Side Impact Response Requirements, SID 2000 report, Task 1.1, BE-7-4355, Oct. 2000.

THOLLON, L., Modélisation du membre thoracique dans le cadre d'un choc latéral – Approche expérimentale et numérique, rapport de thèse, Université de la Méditerranée Aix-Marseille-II, Ecole Supérieure de Mécanique de Marseille, Juin 2001.