EXPERIMENTAL STUDY OF THE AGGRESSIVENESS OF PARALELL SLIDING DOORS ON THE UPPER LIMB.

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In modern systems of public transport the running expenses can be noticeably reduced thanks to a more and more developed automation, whilst flexibility and reliability are increased.

In the VAL°° transport system, with a safety purpose in mind, the access to the vehicle has been made possible as it is for a lift thanks to a fully automatic drive and on account of the precision of stops in stations.
The passengers are kept away from the track by a partition located at the platform edge and provided with sliding doors.
The vehicle is equipped with similar sliding doors which come in front of those of the platform when the vehicle stops in the station (Fig 1).
Under normal working conditions, the axes of vehicle and station doors coincide. However, an offset of 30 cm maximum between the vehicle and platform doors may be tolerated. In this case, the simultaneous closure of vehicle and station doors may induce a shearing type loading on the passenger remaining caught between.

In particular, it could be thought that it would be the case for the upper limb mainly considering the space between door planes (about 20 cm) and the passenger behaviour when coming in and out.
Bending forces, even slight, applied to elbow and wrist joints, induce important loadings which may result in isolated or associated lesions such as sprains, dislocations or fractures.

Therefore, the injury risk for the passenger had to be assessed in this configuration to decide whether the device working had to be modified before putting the vehicle into service.

I. DESCRIPTION AND WORKING OF THE CLOSING SYSTEM.

Each door is made of two folding panels (weighing 40 Kg each for the station and 48 Kg each for the vehicle).
The station doors are plane whereas the vehicle doors are curved so that the space between both doors, which is about 10 cm wide at the ground level reaches 20 cm at 1.4m above the ground.

°° Light automated vehicle for the urban transport system of the city of Lille.

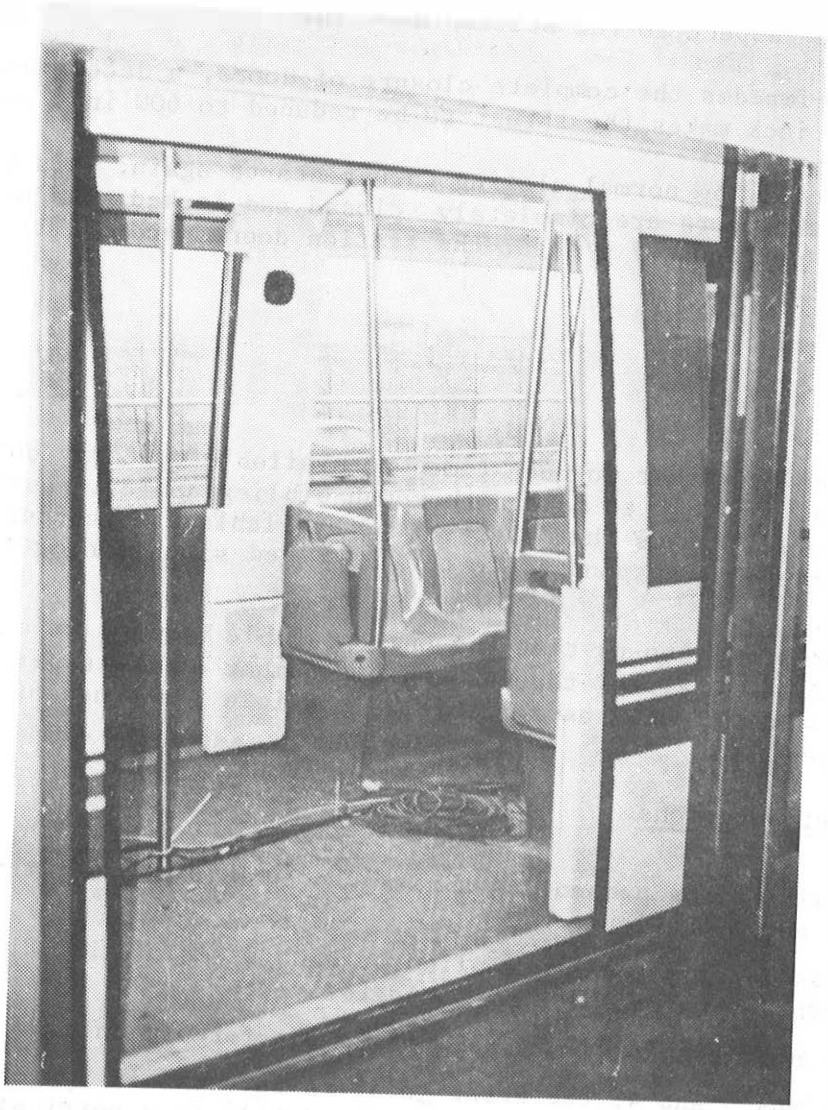

Figure 1 - Communicating sliding doors between station and train.

The four folding panels are bordered with a sectional joint of hard rubber all along their inner edge (Figure I).

When closing, a pneumatic jack pushes the folding panels one towards the other till both inner edges come into contact. The jack thrust is of about I70 N. In the closing sequence, there is a slight delay in the vehicle door closure with respect to the station door one.

When an obstacle impedes the complete closure of doors, a detecting device coupled with the jack makes the thrust to be reduced to 60N in a one second period.
After a few seconds, the normal closing thrust starts again. This thrust stops only when the doors are completely closed and locked. The usual closure speed is of about .7 m/s for the station doors, and a little less for the vehicle doors.

2. METHODOLOGY

Owing to the fact that no much time was available to carry out this study, it was not possible to make a thorough bibliographical research. As far as we know, it seems that there is no available data concerning the upper limb tolerance corresponding to the described situation or to any similar one.

This being so,it seemed to us that the only possible way was an experimental evaluation of the injury risk through a small number of tests performed on the real site with a human model as reliable as possible ; the use of volunteers being out of question.

2.I Tested configurations

The main situations presenting a risk can be summed up by the four configurations shown on Figure 2.

In configuration I, stresses are applied to both sides of the elbow joint so that the movement overpasses the physiological stop.

In configuration 2, the torque is applied to the forearm only.

In configurations 3 and 4, the wrist joint is involved in two different positions : the hand first is semi-prone (hand palm in a vertical plane, thumb up), and, second the hand is prone (hand palm horizontal and facing downward).

Since station and vehicle doors are not identical(as to their mass, closing speed, nature of the joint, and so on...) at first it was planned to test the 4 configurations, with the body outside the vehicle, and then inside the vehicle. But after preliminary tests were performed with a dummy arm, the second configuration with body inside the vehicle was given up, since the aggressiveness in this case seemed to be less important than in the first one because of the time lag between the closure of the two types of doors.

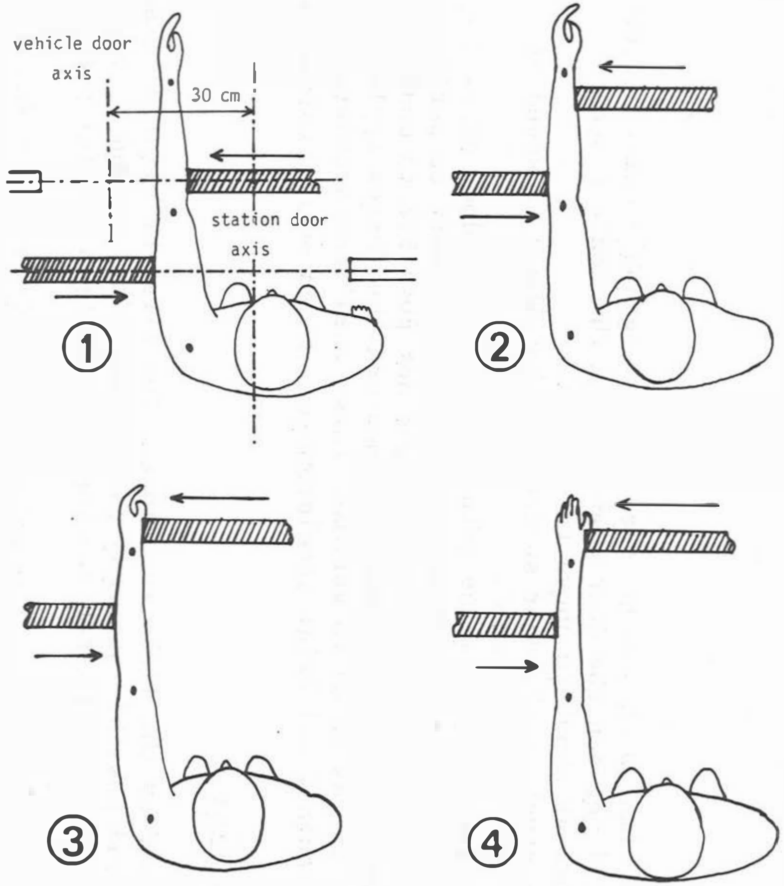

Figure 2 - The 4 configurations of test (the arrows show in which direction the doors move).

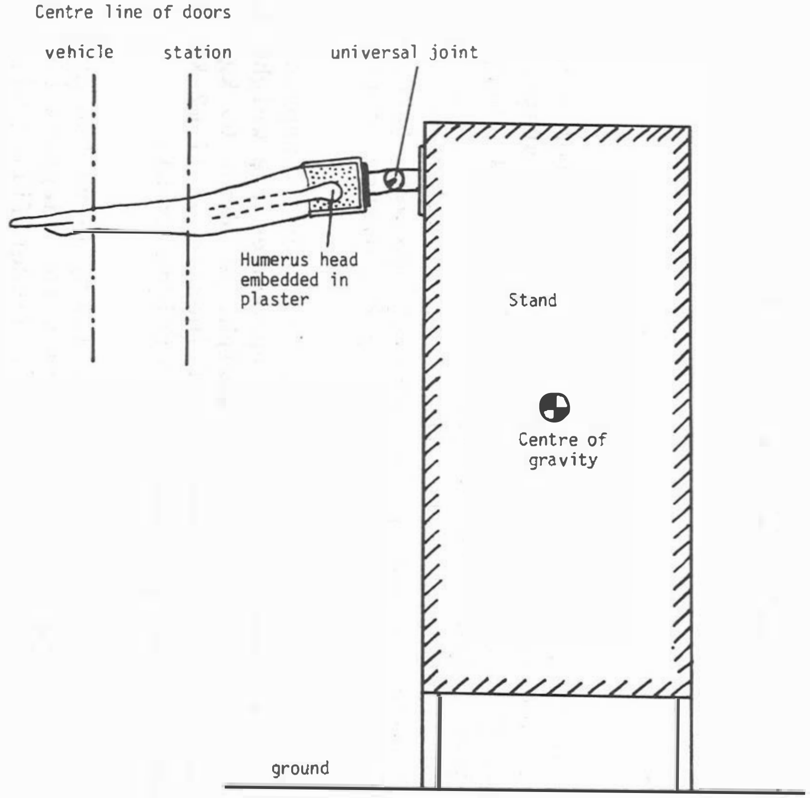

Figure 3 - Arrangement of the arm and stand.

The off-set between the door axes was set at 30 cm on one side or the other depending whether a left or a right arm was used.

2.2. Experimental model.

Owing to the lack of data to predict the injury level from a physical parameter the model used should directly indicate the damage sustained by the passenger. In this case, the best model is a limb taken off a human body.
On an average, the subjects were 70 years old.
On the whole, 8 left and right arms coming from 4 fresh cadavers were used (2 female : 1 and 4 - 2 male : 2 and 3). All precautions were taken so that no previous disease could have an incidence on the resistance of the limbs used.

The model part corresponding to the rest of the body is represented by a support, made of wood and sheet steel, which reproduces the weight and inertia characteristics of an average person (weight of about 65 kg, centre of gravity at 90 cm above the ground, moments of inertia of I7 m2 Kg around both horizontal axes and of I m2 Kg around the vertical axis).

The support and limb are joined together at I.40m above the ground through an universal joint which provides the arm with 3 degrees of freedom. On the arm side, the joint is bolted to a steel cylinder filled with plaster into which the humerus head is embedded (Fig 3). The arm remains horizontal by means of a string to the vehicle ceiling.

2.3. Measurements

The tests were filmed with a high speed cinephotographic camera (200 frames/second) located between the door planes above the contact area between doors and limb at about 2m above the ground.
Optical targets were stuck on the door surface so that the door speed at the contact moment could be calculated.
Since obstacle detection is made at the actuator level, the door edges are not fitted with force detectors ; moreover as it was necessary to perform these tests under real working conditions, it was not possible to modify the doors (the joints could not be removed) to measure the forces applied to the limb. Therefore, it was tried to estimate these ones from acceleration measured on doors through 4 uni axial accelerometers fixed on the folding panels.

2.4. Research of injuries :

Injuries sustained by the limbs were looked for first by clinical examination in order to find possible abnormal passive mobility, second by comparing X ray pictures taken before and after the tests, third by a careful post-mortem examination.
This one was carried out by Professor MORIN from the Laboratoire d'Anatomie de la Faculté de Médecine de Lyon.

II. RESULTS

2.I Film data.

The sequence of events is practically the same for all the tests. The station doors begin to open first and then are the first to impact with the limb. In most of the cases, the contact between the limb and both folding panels of the station doors occurs just as (or slightly before) the folding panel of the vehicle door touches the arm. What happens then depends on the position of the impact points on the limb. In configurations I and 2, the vehicle door is stopped by the forearm and the whole swings round a balance position due to the successive thrusts exerted by the vehicle door actuator. In configurations 3 and 4, the vehicle door is slackened and even sometimes stopped by the wrist, but when the loading starts again, either hyperflexion or hyperextension of the wrist occurs and then the door goes on closing.
For two tests, (4 and 5), the initial (t=0 at the first contact), intermediate and final positions of the limbs and doors are shown on figure 4 and 5.

2.2 Acceleration data

The trends of acceleration curves are different for station doors and vehicle doors. These are schematically shown on Figure 6.

When considering the station door, after a long acceleration phase, of low amplitude, the contact with the limb only results in a small deceleration owing to the high ability of motion of the limb and to the ratio of the involved masses. The highest deceleration peak is related to the impact with the 2nd folding panel. In this case, only a transverse compressive load is applied to the limb.

Sometimes, there is a second peak resulting from a rebound. In some cases (tests 2 and 6), both folding panels (vehicle and station) impact with the limb at the same time. Then, the door loadings give rise to an important torque at the elbow level.

When considering the vehicle door, the motion is slightly delayed (≃200 to 300 ms). The deceleration due to the stop by the limb is more or less high according to the configuration. Then, one or several acceleration phases followed by stop decelerations may occur. At last, a deceleration peak due to the complete door closure is observed if the limb escapes.

To estimate the level of the load (force and torque) applied to the limb, aiming at establishing a relation ship with the severity of injuries, all the involved mechanical actions should be measured. For that purpose, the geometrical arrangement and the inertial properties of the various components, the propelling force of the door actuators and the frictional forces would have to be known precisely.
Since these data are not available, only a rough value of the load can be calculated using the mass x acceleration cross product of the door. Values measured during the tests and corresponding load values are given in table 1.

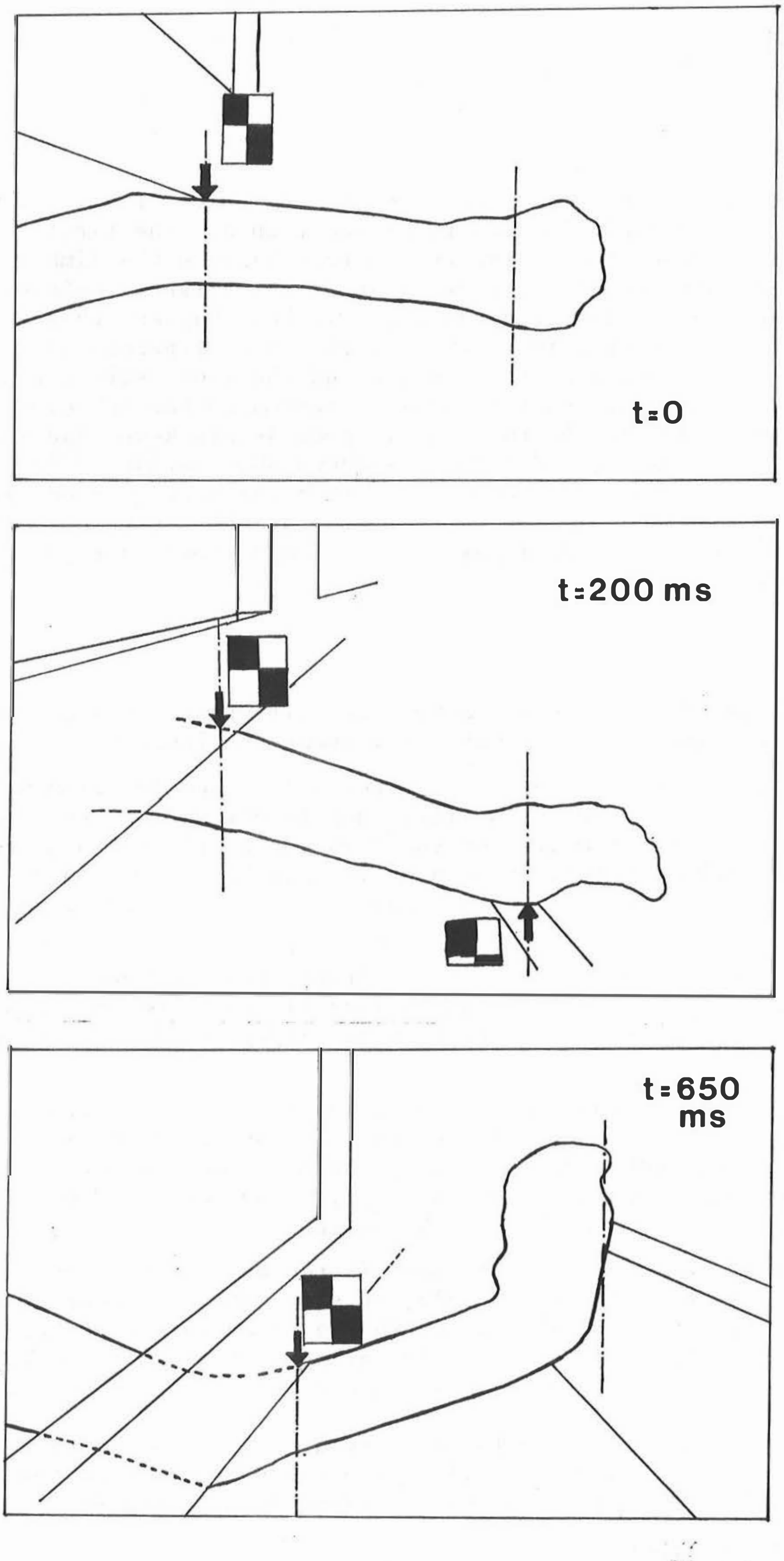

Figure 4 - Cinephotographic data from test 4.

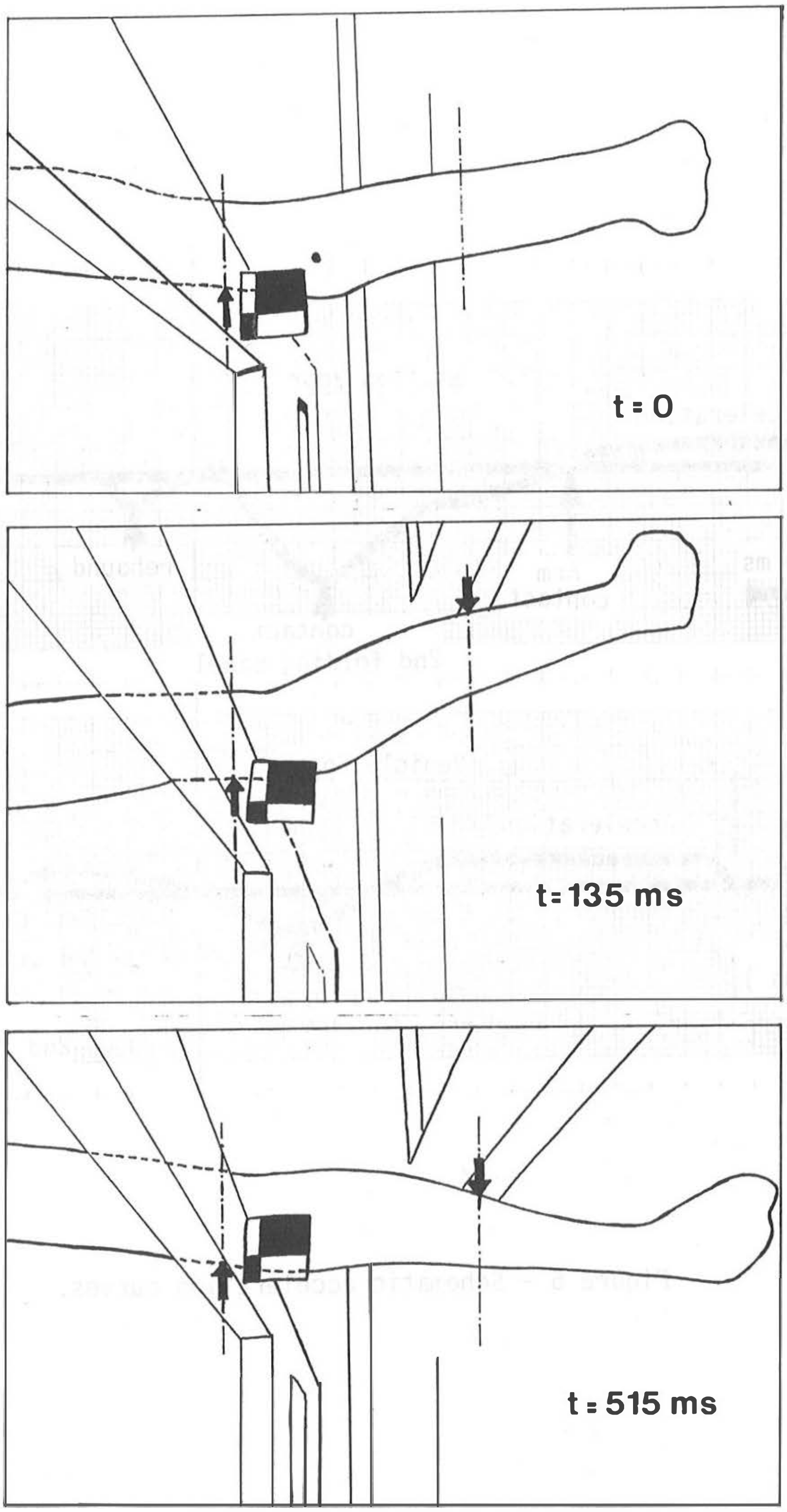

Figure 5 - Cinephotographic data from test 5.

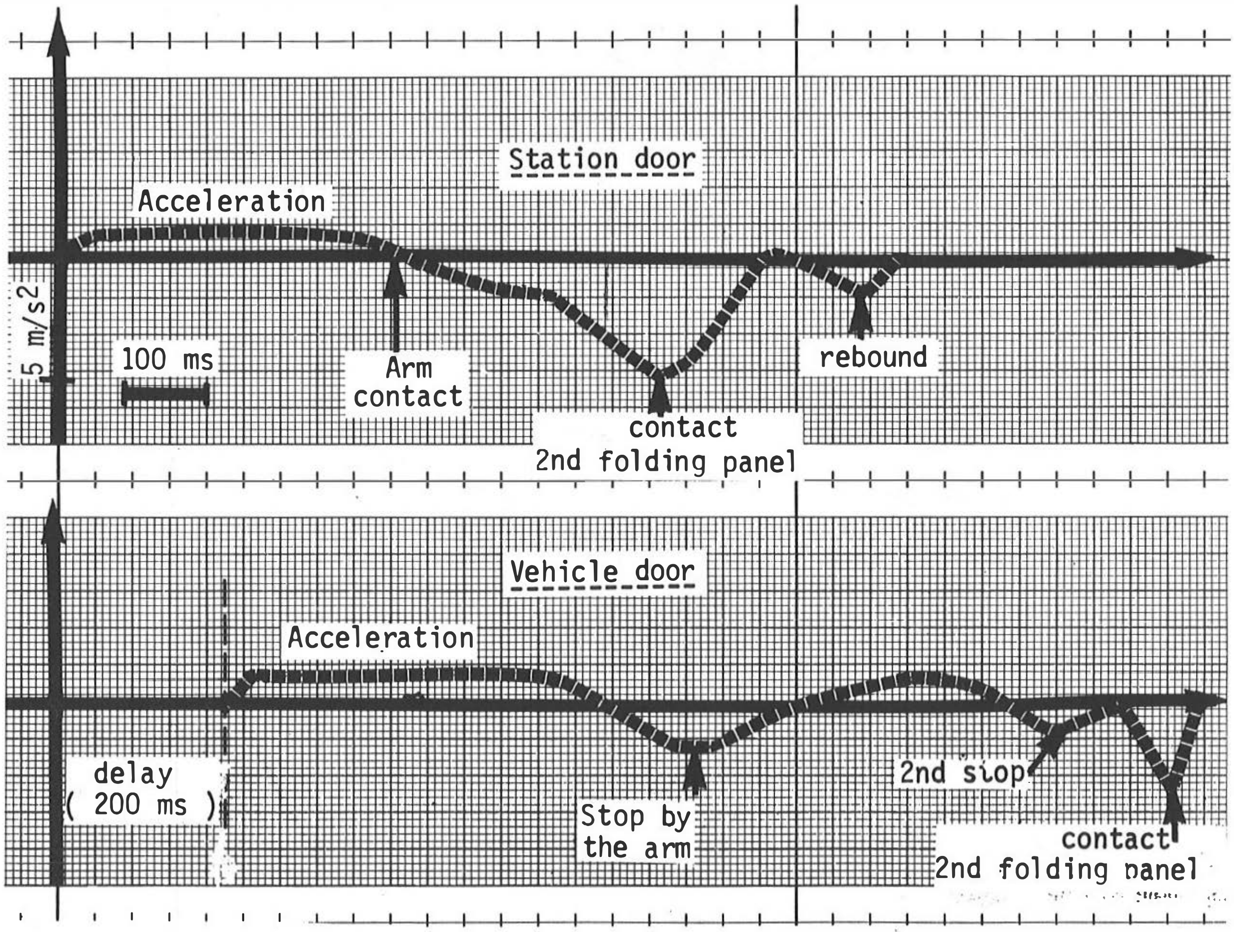

Figure 6 - Schematic acceleration curves.

2.3. Necropsy data (Table 2)

When considering the results from post-mortem examination, on the whole 4 out of the 8 limbs do not show any lesion. For the others the examination reveals injuries of elbow and wrist mainly.

Elbow injuries :

The elbow articular capsule of limb 1D was injured, which, a priori, does not seem to correspond to the conditions specified for this test (the load should have been applied at the forearm level). As a matter of fact, the film analysis shows that, at first, the limb was correctly positionned (as planned), but it slipped during the test, so that the load was applied at the elbow level, which, at last, resulted in an important angle between arm and forearm. A similar although less important elbow injury was found in limb 2G. This type of injury is shown on Fig 7.

As far as there is no ligamentary lesion, these elbow injuries are reduced to capsulary lesions which are to recover spontaneously ; they are of the same type as the common "housemaid's knee" that every body knows.

Wrist injuries :

They were found in 3 tests (2G, 2D, 4G). They are more serious than elbow injuries because beside capsular lesions, they include ligamentary tears constituing sprains responsible for an abnormal mobility between the articular surfaces and resulting in a subluxation. Sprains of the lower radio-ulnar ligaments with interarticular fibro-cartilage involvement (see Fig 8), are commonly due to a wrist hyperextension (which corresponds in fact with our test conditions). It seems often difficult to restore the ligament function and according to COLEMAN, (°°) the exeresis is sometimes necessary.

Concerning wrist, it can be then noted that it is at least necessary to keep it at rest in a plaster cast because of the important mobility due to the ligament tear and sometimes surgical repair is needed.

The muscle bruise area seen on the forearm 2G is not by itself an important factor of severity. So, this lesion will not be overstressed.

CONCLUSIONS :

Results of the 8 tests performed on the site with human arms show that, according to the tested configurations. the more aggressive factor of the door closing device in VAL system is the thrust exerted by the doors and not as it could be thought, the dynamic loading due to the door impact.

(°°) COLEMAN N.E. J.Bone and Joint Surgery, 1960, 42-B, 3, p.p. 522-529.

TEST NUMBER	ARM NUMBER	Vehicle door measured accelerations and calculated forces						INJURIES
		1st IMPACT		RESTARTING DOOR		2nd IMPACT		
		DECELERATION (m/s^2)	FORCE (N)	ACCELERATION (m/s^2)	FORCE (N)	DECELERATION (m/s^2)	FORCE (N)	
1	1-L	3.3	158	2.3	110	-	-	no injury
2	3-L	4.5	216	2.0	96	3.9	187	ELBOW
3	4-L	2.3	108	1.5	72	4.5	216	WRIST
4	2-L	2.1	100	-	-	4.5	216	ELBOW + WRIST
5	3-R	2.3	108	2.8	134	-	-	no injury
6	1-R	-	-	-	-	-	-	ELBOW
7	2-R	0.7	34	-	-	3.7	178	WRIST
8	4-R	0.2	24	-	-	-	-	no injury

Table 1 - Data from acceleration measurements.

TEST NUMBER	ARM	AUTOPSY FINDINGS
1	1L	No lesion.
2	3L	No lesion
3	4L	Elbow and forearm : no lesion. Wrist : rather important mobility of the lower radio-ulnar joint resulting from tears of the anterior ligaments joining the two bones without fibro-cartilage involvement.
4	2L	Elbow : tear of 2mm length on the front capsular plane. Forearm : muscle bruise at the level of pronator quadratus muscle. Wrist : small anterior tear of capsule and ligament, crush and dilaceration of radio-ulnar ligament and interarticular fibro-cartilage.
5	3R	No lesion.
6	1R	Elbow : tear of about 3cm length on the front capsular plane in front of the humeroulnar joint. Forearm and wrist : no lesion.
7	2R	Elbow and forearm : no lesion. Wrist : small anterior tear of capsule and ligament, tear and crush of radio-ulnar ligament and interarticular fibro-cartilage giving a high abnormal mobility of the proximal carpal row, cartilage avulsion at the convexity of the lunate.
8	4R	No lesion.

Table 2 - Data from autopsy.

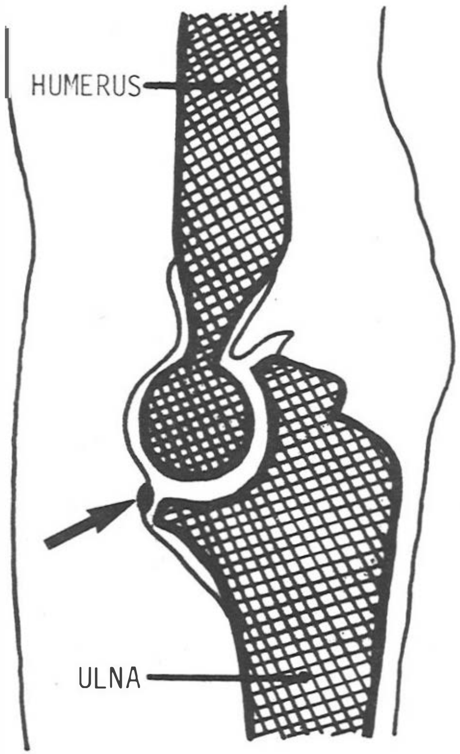

Figure 7 - Sagittal section of the elbow showing the site of the capsular lesions.

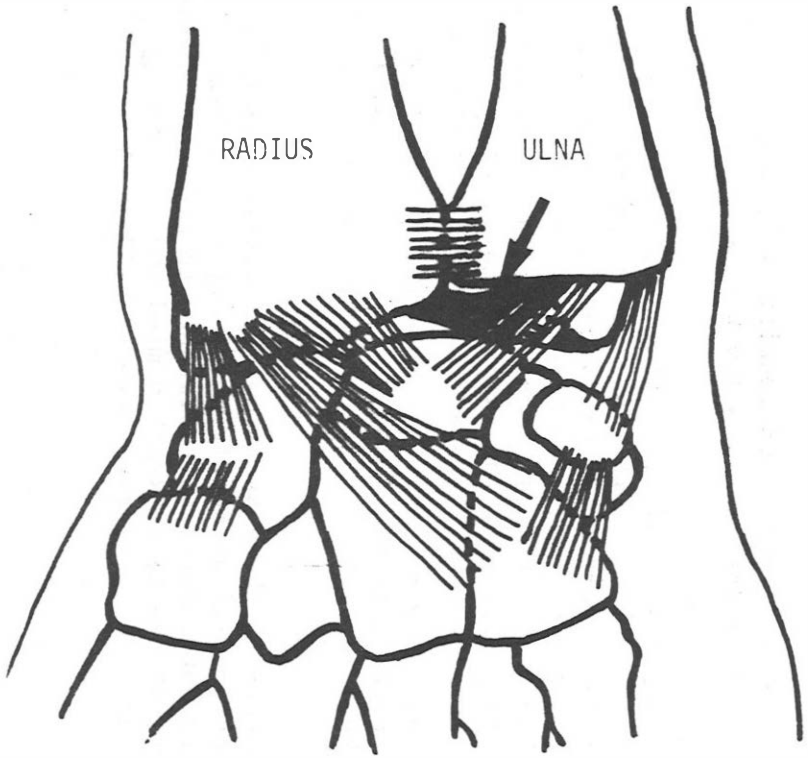

Figure 8 - Front view of the wrist showing the main site of injury (radio-ulnar ligaments with interarticular fibro-cartilage involvement).

The injuries sustained by the tested arms consist in sprains of the wrist for the most part and in elbow lesions to a lower extent.

It seems difficult, from these results, to draw a tolerance value for the human upper limb first, because the static load was not measured during the tests and second, because the number of tests is not sufficient considering the scatter of resistive characteristics of bones and ligaments.

Moreover, the used subjects are too old to make the sample representative of the passenger population. A priori, the experimental subjects probably show a more pessimistic behaviour compared with a healthy adult person.

This is not necessarily true for children whose resistance is not well known, but for whom the after-effects of an arm injury may be less severe ; besides , they can be injured in a different way considering their smaller height.

At last, the subjects used in these tests were of course perfectly inert. A passenger placed in the same conditions surely would try to free himself and at least would oppose a co-ordinated muscular resistance to preserve his hand from the door action. However, it has to be kept in mind that a limb may remain caught for example because of a luggage which is held in hand.

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