Volunteer Shoulder Range of Motion and Stiffness:
Data for Evaluation of Crash Test Dummies and Human Body Models

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Abstract   The shoulder complex has low priority in the development of frontal impact crash test dummies and Human Body Models. It is rarely exposed to injuries in frontal collisions but it does influence belt interaction and, as such, the thorax compression and head kinematics. Therefore, this study establishes response requirements for the shoulder complex in terms of range of motion and stiffness.

Six male volunteers were seated and belted, with minimum belt-clavicle interaction, and shoulders were statically loaded with increasing load; 0 − 200 N/shoulder. Shoulders were pulled straight forward, forward-upward, upward and rearward. Three repetitions per direction were carried out.

Resultant shoulder range of motion, at maximum loads, ranged from 44 to 73 mm. The volunteers provided measurements with reasonable repeatability.

The applied loads were lower than those commonly seen in frontal crashes; however, the shoulder is highly mobile and its response is largely dependent on muscle characteristics. As such, these studies of volunteer responses may be complimentary to tests with post mortem human subjects. Also, the volunteers curved their spines only slightly in these tests. Hence, shoulder motion was successfully isolated and results reflect pure shoulder relative to chest motions. As such the data are suitable for dummy and Human Body Model evaluations.

Keywords   Range of motion, shoulder, stiffness, validation data, volunteer

I.   INTRODUCTION

Frontal collisions are one of the most frequent collision types that lead to injuries as well as fatalities. The thorax and head are the most commonly injured (MAIS 2+) body regions in frontal impacts. To reduce these injuries, the performance of vehicle restraint systems will have to be improved. For evaluation of these systems humanlike test tools, such as crash test dummies and Human Body Models, are needed.

The shoulder complex, including the scapula and clavicle bones, has received rather low priority in the development of these tools. Although the shoulders are rarely exposed to injuries in frontal collisions [1], they influence the belt interaction with the torso [2]. A comparison of the thoracic response of belted dummies and cadavers suggested that well over half of the belt force is directed through the shoulder rather than through the sternum [3]. In addition, the shoulder response may also influence the head kinematics. Shaw et al. [4] reported that the shoulder belt on a THOR Alpha dummy slipped laterally off the shoulder in frontal sled tests. Törnvall et al. [5] found that the Hybrid III and THOR Alpha dummy escaped from the shoulder belt in 45° far side oblique impacts, while the PMHSs did not. It was suggested that the dummy shoulder design, its response to belt loads and a soft lumbar spine contributed to this.

Törnvall et al. [6] developed a new dummy shoulder complex, upper arm, bib and jacket to be mounted to the THOR-NT spine. This shoulder design, denoted SD-1, had a more human-like shaped clavicle, acromion and coracoid process; it had greatly increased shoulder range of motion in the forward-to-upward direction than the THOR-NT shoulder. In the reproduction of a previous PMHS study, the THOR-NT also slipped out of the shoulder belt, while the THOR-NT with SD-1 did engage with the belt in 45° far-side oblique impacts [7].

A "shoulder shielding" hypothesis was proposed as a condition in which the geometry of the shoulder and clavicle results in high belt loads on these structures and relatively lower loads on the upper chest of the THOR-NT [8]. In additional work, the biofidelity of the THOR-NT, with both standard and SD-1 shoulders, was compared to PMHS tests [9-10]. The initial position and forward displacement of the clavicle affected the upper chest deflection, which confirmed the "shoulder shielding" hypothesis. It was shown that the belted shoulder of PMHSs moved backward with respect to T8, while the belted dummy shoulders moved forward. Such shielding

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of the upper chest from belt loads can often invalidate injury risk predictions and hamper the development of advanced restraint systems. To conclude, there is clearly room for improvements to the shoulder-complex of the crash test dummies used to date. However, for these future designs to be humanlike, data that describe the shoulder response in relevant test conditions are required.

In the field of biomedical research, shoulder kinematics during humeral elevation has been well documented since the 1990s [11-14] using a system of transcortical pins and electro-magnetic tracking, photo tracking and MRI scanner techniques. In these studies the volunteers were asked to move their arms actively in abduction [13], raising and lowering the arm in the sagittal, scapular and coronal planes [14]. These studies have been carried out at low velocity. In biomechanics, shoulder range of motion was studied by asking volunteers to move their shoulders in various directions. Values presented were from non-loaded shoulders. However, in crashes the shoulder complexes are influenced by belt forces and by forces due to the deceleration of the arms.

Static forces have been applied to volunteers´ shoulder complexes when seated and restrained by a sternum support [15-16]. Both arms were pulled by 200 N/shoulder in the forward, forward-upward and upward directions. The resulting shoulder displacements were given according to a room fixed coordinate system [15] and relative to T1 [16]. However, in their study no rearward loads were applied to the shoulders and shoulder displacements were poorly isolated from torso bending.

Sled tests with PMHSs have been carried out to simulate car crashes; the shoulder kinematics and interaction with restraints were assessed. In one study, resultant accelerations of the acromion and humerus were reported and proposed as dummy evaluation parameters [17]. Törnvall et al. [7] carried out 0° full frontal, 45° far-side and 30° near-side sled tests with PMHSs restrained by a three-point shoulder-lap belt. Film analysis provided 3-D displacements of photo markers that were rigidly attached to the acromion, T1 and head. Chest deformations were not provided. The University of Virginia conducted full frontal sled tests to study the response of males restrained by a shoulder belt, a lap belt and knee block [18-20]. Instrumentation was comprehensive and enabled the presentation of acromion, spine, head and chest displacements [18-21]. These data will be very useful for validation of future crash test dummies and human body models; the data will enable proper evaluation of shoulder complex kinematics, belt interaction and chest deformation.

To use these sled test data, in evaluations of dummy shoulder kinematics, requires careful reproductions of the test setups that were originally used. It is also crucial that belt slip on the chest and shoulder are very close to that of the PMHSs tested. This means that reproduction of sled tests with PMHSs introduces uncertainties and may be difficult to do in some laboratories. In addition, there is a lack of muscle tone in PMHSs; the scapula is attached to the chest and spine by muscles. This suggests that additional shoulder complex response data, easily reproduced and generated by using volunteers, are made available.

The purpose of this study is to establish volunteer shoulder complex response data in a test environment that can be reproduced easily using crash test dummies and human body models. Preferably, the shoulder response should be isolated from the motion of the torso and spine.

II. METHODS

In brief, six male volunteers were seated in a rigid seat that simulated a driving posture in a specially designed test rig. Forward and upward pulling loads to the shoulders were applied through the arms by means of arm brackets fastened to the elbows. Rearward pulling loads were applied by means of straps that encircled the shoulder complex. Torso movements were prevented by restraining the volunteers with two X-shoulder belts guided close to the neck to avoid interaction with the clavicle. Armrest supports held the arms in the direction of the applied loads. Both shoulders were statically loaded with increasing loads from 0–200 N/shoulder at 50 N/shoulder increments. The volunteer was subjected to four loading angles: shoulders pulled straight forward, angled forward-upward, upward and rearward. Each volunteer was exposed to 3 tests per series. Three cameras were used to record shoulder, spine and head positions.

Test rig

The basis of the range of motion study was a test device designed to fit average size male persons (Fig. 1). It consists of a rectangular frame made from 45 × 45 mm aluminum profiles. To this frame a seat, a footrest, armrests, restraints and loading systems were attached (Fig. 1).
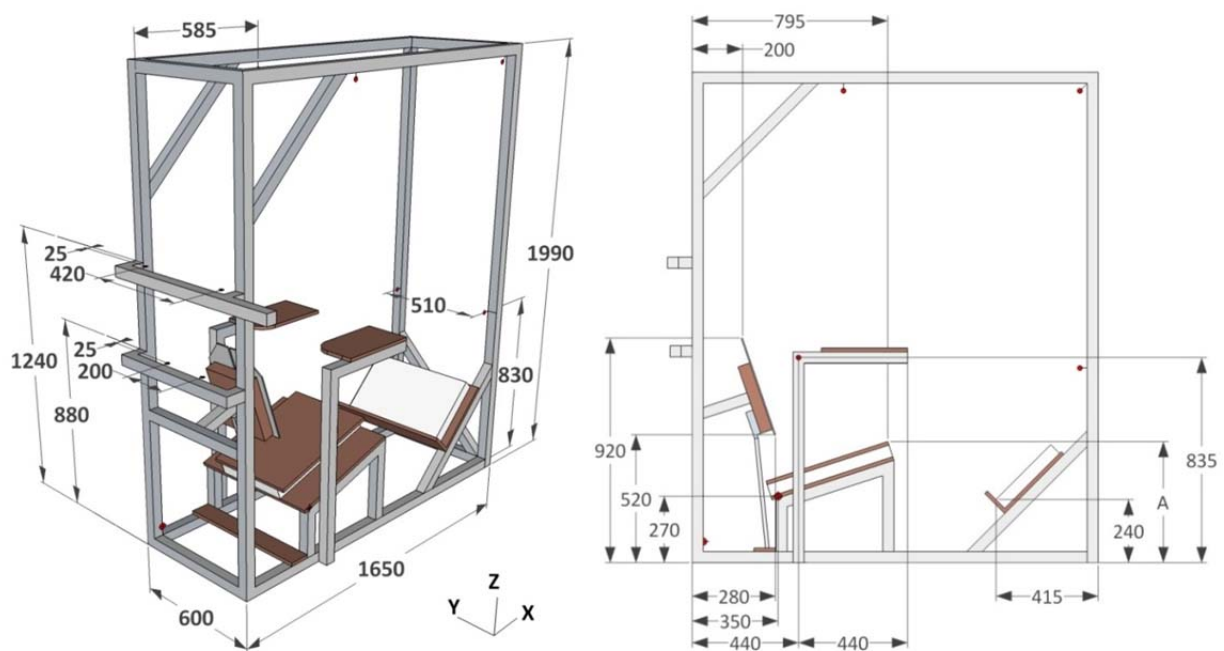
Fig. 1. Schematic of test rig: Left: positions of the belt anchorage points and where the ropes, used to load the shoulders, were rerouted. Middle: Coordinate system used. Right: Test rig dimensions, side view (mm). External dimensions were 1740 × 690 × 1990 mm (L × W × H)

The seat back was constructed from fiber reinforced polyester using a torso surface contour that resembles a seated 50th percentile male [22]. The height of the seat back was 400 mm; its lower edge was approximately at the height of L2 and its upper edge was approximately at the height of T3. The seat back was attached to the base with a low friction linkage system and supported at the rear by a load cell (Fig. 2). The resulting mid-sagittal plane seat back angle was approximately 17°. The volunteers´ backs were in contact with the seat back in all tests and for all shoulder loads; hence also the angle of a vector from L2 to T8 surface landmarks was approximately 17°. In addition, the top left and right corners of the seatback were cut out to avoid scapula interaction (Fig. 2); cut-outs in the mid-sagittal plane facilitated the installation of photo markers along the spine. The seat cushion and the footrest, angled at 18° and 45°, respectively, were rigid. Comfort foam, 12 mm, covered the seat cushion surface. The seat cushion height, dimension "A" in Fig. 1 and in Table I, was adjusted so that all volunteers had their clavicle bone at the same height. The arm rests were made of plywood; they were adjusted in height and angle to provide proper arm support (Fig. 2).
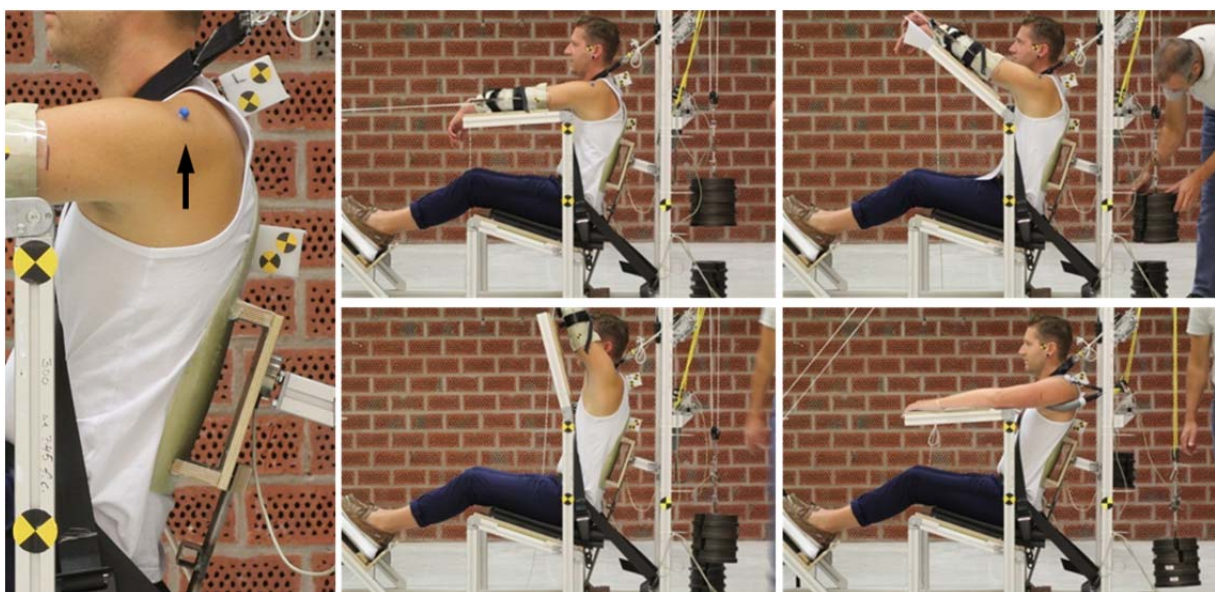

Fig. 2. Left photo: The position of left shoulder photo marker and the spine photo marker mounts. Other photos: Direction of load applied in the study and armrest positions. Top left: 0° series; top right: 45° series; bottom left: 80° series; bottom right: 180° series.

The restraint system consisted of a lap belt and two diagonal belts (crossed) with fixed anchorage points (Fig. 1). The lap belt was tightened until there was a minimum pelvis-to-belt play without being painful. The upper anchorage points for the diagonal belts were arranged so the belt applied loads to the chest and only slightly to the proximal end of the clavicle bones (Figs. 1-2). Each diagonal belt was attached to a load cell which was attached to a rope system that allowed for application of diagonal belt loads.

The shoulders were pulled straight forward, forward-upward, upward and rearward. These directions are referred to as 0°, 45°, 80° and 180°; the angle is relative to the horizontal plane (Fig. 2). For the first three directions, loads were applied via arm brackets attached to the arms (Fig. 3). For the 180°, loads were applied via straps encircling the shoulder complexes (Fig. 3). Ropes were connected to the brackets/straps and guided through low-friction roller-bearing fitted pulleys to the rear of the test rig where weights were applied.

The arm brackets, made of Plexiglas, were fitted with two straps each to secure to the arm. The arm bracket fixed the elbow at a 45° angle to allow for rope attachments without inducing bending of the brackets and to ensure minimum bicep and tricep muscle activity (Fig. 3). The shoulder straps, a 20 mm wide band covered by ethylene tubing, had a diameter of 35 mm. Arm rest friction was reduced by application of a thin layer of dry Teflon spray to the surfaces and to papers that were introduced between the arms and the surfaces.
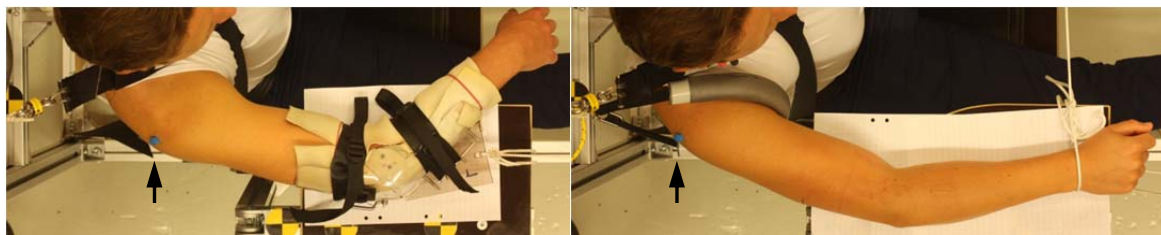

Fig. 3. Arm bracket (left) and shoulder strap (right). Position of shoulder photo marker (arrow).

Instrumentation

Photo markers were mounted on the volunteers´ skin; on the posterior tip of the acromion process, head, T1 and T4 (Fig. 2). The position of the shoulder complex was recorded by digital cameras: from above (Canon EOS 450D, 50 mm lens), from the right (Canon Power Shot S70, lens adjusted to 100 mm) and from the left (Canon EOS 550D, 85 mm lens).

Belt, seat back and applied loads were recorded in these tests. Two load cells that measure tension loads (Futek, LCM300) were connected to the upper end of the diagonal belts. A third tension/compression load cell (Burster 8424-6010) measured the forces normal to the seat back plane (L2-T8 region). A fourth load cell measured the load applied to ropes attached to either the arm brackets or the shoulder straps. All loads were sampled at 200 Hz using an anti-alias filter cut-off frequency of 50 Hz (Brick, GMBH Engineering, Inc.).

Volunteers

Male volunteers with an average stature of 181 ± 7 cm, weight of 79 ± 5 kg and age of 42 ± 13 years, with no record of shoulder injury, were selected for the study (Table I). The volunteers were fit; most of them engaged in weekly fitness activity. The Regional Ethical Review Board in Gothenburg granted the ethical permission, application number 322-10, for this study.

Test procedure

The volunteer was dressed in a cotton sleeveless shirt. The seat cushion height and armrest positions were adjusted to allow the proximal end of the clavicle to be at a given height. Then the photo markers were mounted and the volunteer was belted, arm brackets mounted and attached to the loading ropes.

The volunteers were instructed to relax throughout the tests and to allow for shoulder motions when shoulder loads were applied. The volunteers were instructed that they should call off the test in case they could not remain un-tensed.

The measurement system was started to record loads. A total of 20 kg was added to the system of ropes that were connected to the two diagonal belts. Then these ropes were clamped and the weights removed. Thereafter, the shoulders were loaded to 200 N/shoulder with increments of 50 N/shoulder. Photos of the event were taken after seatbelt loads were applied and after each shoulder load increment. This measurement and the load applications were repeated three times for each series.

To assess the effect of the initial upper arm position, the acromion was palpated and positions were recorded when the upper arm was forward and resting in the lap.

TABLE I
VOLUNTEER AGE, STATURE, WEIGHT, FITNESS, SITTING HEIGHT, AND BIACROMIAL SHOULDER WIDTH.

Volunteer	Age	Stature	Weight	Fitness level	Sitting height	Shoulder width	Dimension A in Fig. 1
	(yrs)	(mm)	(kg)	(times exercises per week)	(mm)	(mm)	(mm)
1	59	1780	83	2-3	930	410	469
2	50	1730	70	1	890	380	507
3	29	1920	82	> 3	970	390	442
4	33	1860	82	2-3	960	430	442
5	50	1820	82	> 3	940	380	457
6	29	1770	77	1	930	380	472

Data processing

A single coordinate system was defined and used in this study (Fig. 1). Film analysis was carried out using TEMA version 3.5-012 (Image systems AB). The right and left acromion processes relative to T1 displacements were used to calculate the shoulder range of motion in three directions.

Range of motion is a function of initial position. Inconsistency in initial position was compensated when the total forward-rearward acromion range of motion did not match the sum of those obtained in tests 0° and 180°. Preferred initial positions for all six tests, in 0° series and 180° series, were compared and the acromion relative to T1 displacements were compensated to account for inconsistency in initial position.

Six volunteers were tested three times each under identical conditions. Data were found to be normal and have similar variances for each tested position and repetition, with the exception of the first series of tests at 0 degrees in which there was a single outlier. For the range of motion data, it was considered appropriate to conduct one-way ANOVAs blocked by volunteer and post-hoc tests using the Tukey-Kramer procedure at a 0.05 significance level [23] in MatLab v7.11, to analyze differences between volunteers and repetitions.

For each condition the acromion process relative to T1 displacement response corridors was established using average ± one standard deviation (S.D.) for all tests (n=18) for a given condition.

An analysis of variance was used to calculate separate coefficients of variation (C.V.) for repeatability and inter-subject variability. The C.V.$_{Repeatability}$ and C.V.$_{Inter-subject}$ for a parameter, y, which are measures of pooled estimates of standard deviation (S_p) and standard deviation between volunteers (τ), respectively, expressed as a percentage of the average peak value ($\overline{X}_g$), are defined below; S_g is the standard deviation for the averages of the results for each volunteer.

$$C.V._{\cdot \text{Repeatability}} = \left[\frac{s_p}{\overline{X}_g} \right] * 100\%$$

$$s_p^2 = \sum_{t=1}^{k} \sum_{i=1}^{n_t} \frac{\left(y_{ti} - \overline{y}_t\right)^2}{N-k}$$

$$C.V._{\cdot \text{Intersubject}} = \left[\frac{\tau}{\overline{X}_g} \right] * 100\%$$

$$\tau^2 = s_g^2 - \frac{s_p^2}{k}$$

$$\overline{X}_g = \sum_{t=1}^{k} \sum_{i=1}^{n_t} \frac{y_{ti}}{N}$$

$$s_g^2 = \sum_{t=1}^{k} \frac{\left(\overline{y}_t - \overline{y}\right)^2}{k-1}$$

where t is the tth to k^{th} test subject, i is the ith to the nth test with the tth subject and N is the total number of tests.

III. RESULTS

Shift in acromion relative to T1 position when the arms were adjusted and belt tension application

When the volunteers elevated their arms prior to test, from resting in the lap to the different initial positions used for the four series, the acromion moved relative to T1. For the 0° series and 180°, the preferred acromion position relative to T1 was shifted on average 7 mm rearward and 29 mm upward. When the armrest was set for the 45° series, the acromion relative to T1 shifts were on average 26 mm rearward and 1 mm downward

from the position preferred in the 0° series. Adjusting for the 80° series, these shifts were on average 24 mm rearward and 7 mm downward from the 45° series.

Tensing the belts made the volunteers move slightly into the seat. It also resulted in an acromion relative to T1 rearward motion that was rather small; less than 7 mm for all volunteers.

These acromion relative to T1 motions have not been used to compensate the motions reported in the following sections. Nevertheless, these motions are reported because they can be used to assess initial posture of human body models.

Compensation of initial acromion position

The preferred initial acromion relative to T1 positions were expected to be identical in the 0° series and 180°. However, for the restrained subjects, the preferred initial acromion relative to T1 position in the 0° series was on average 16 mm further forward and 4 mm further above than those in the 180° series. The individual differences in preferred initial acromion relative to T1 positions were in general small but varied considerably between volunteers (Table II). These differences in preferred initial positions could be due to anticipation of the tests, the influence of the arm brackets for the 0° series or the straps that encircle the shoulder complexes for the 180° series. Regardless of the reasons for these variations, the measured differences in preferred initial positions in the 0° series and 180° were used to compensate for the ranges of motion. A single starting position in the x-z plane was used for each volunteer in all six tests; three repeated 0° series tests and three 180° series tests. For the 45° series and 80° no such compensations were carried out.

TABLE II
INITIAL AVERAGE (N=3) ACROMION RELATIVE TO T1 POSITION DIFFERENCES BETWEEN THE 0° OR 180° SERIES (FOR POSITIVE VALUES THE PREFERRED POSITION WAS FORWARD AND ABOVE IN THE 0° SERIES AS COMPARED WITH THE 180° SERIES).

Volunteer	x-direction (mm)	z-direction (mm)	Movements observed
1	15	10	Forward prior to the 0° series
2	40	6	Forward 20 mm prior to 0° series
3	-9	2	Rearward prior to 0° series
4	6	6	Forward 6 mm prior to 0° series
5	31	3	Forward 20 mm prior to 0° series
6	10	-1	Rearward prior to 180° series

Belt, seat and shoulder loads

Seat belt and seat back loads and directions of the applied shoulder loads are useful data when these tests are reproduced. These loads and directions are presented in the Appendix. In brief, the belt loads, after the weights that applied them were removed, were approximately 65 N for all series. The seat back load was on average 430 N prior to application of shoulder loads. When the shoulder loads were applied, these belt and seat back loads changed as a function of the loading conditions. The directions of the applied shoulder loads varied slightly between the subjects due to anatomical differences and preferred shoulder trajectory but had minor influence on the results; the armrest prevented the elbow from moving downward relative to the intended plane of motion.

Torso angle

When loads were applied to the shoulders, either through the arm brackets or the shoulder straps, the seat flexed, the torso may have rotated and the volunteer may have curved or straightened their backs somewhat. Average torso angle change, as measured between the T1 and T8 skin photo markers, was 3° forward for the 0° series at maximum load. For the 45° series, 80° and 180° corresponding rotations were 2° forward, 2° rearward and 5° rearward, respectively.

Another measurement of spine curvature is the T1 skin photo marker rotation. For the 0° series, this marker rotated forward on average 2° at maximum load. For the same load increase, the T1 skin photo marker rotated rearward by 2° in the 45° and 180° series and rearward by 7° in the 80° series.

Range of motion

When loading the volunteers' shoulders in any of the four directions, the ranges of motion were mainly a combination of anterior-posterior (x) and superior acromion (z) relative to T1 displacements. Individual range of

motions in the x-z plane are presented in Fig. 4 (uncompensated for initial acromion relative T1 position) and Fig. 5 (compensated for initial acromion relative T1 position).

The 0° and 45° series showed the greatest volunteer ranges of motion in the anterior-posterior direction followed by 180° series. Both 0° and 180° series showed small medial and superior ranges of motion (Table III). The 45° series also showed large ranges of motion in the superior direction, almost as large as in the anterior direction. The 80° series showed the largest superior range of motion and, despite the guidance by arm supports, large variability in the anterior direction. The range of motion increased slightly when initial acromion relative to T1 positions were compensated for in 0° series and 180° (Fig. 5). The most apparent changes, introduced by this compensation, were the spread in initial position at zero shoulder loads and that the range of motion at maximum shoulder loads appeared to be more consistent in-between volunteers.
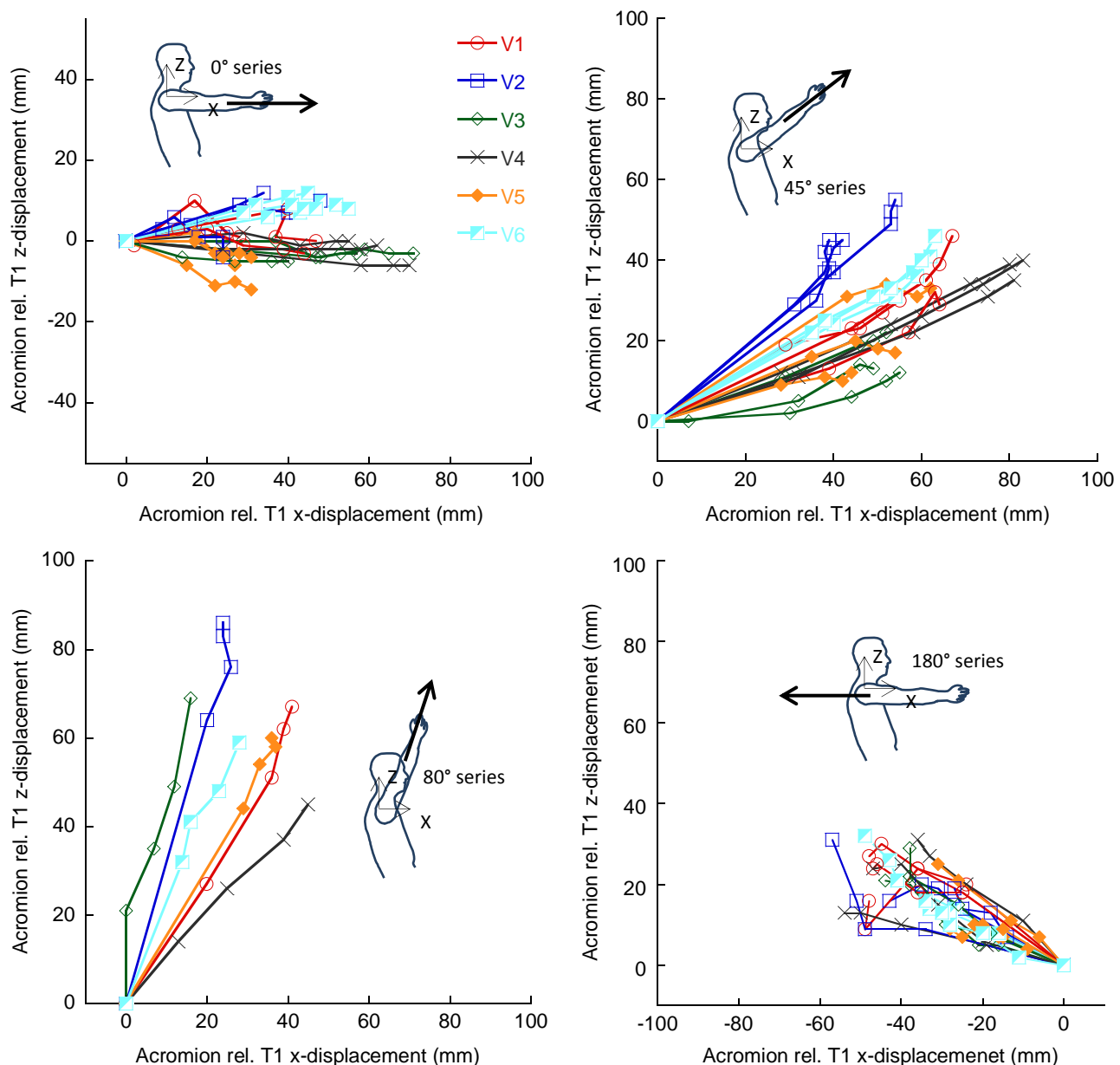

Fig. 4. Individual volunteer acromion relative to T1 displacements. No compensation for initial acromion position was introduced. Values in origin correspond to zero shoulder loads. Successive points correspond to shoulder load increments of 50 N/shoulder.

Figs. 4 and 5 show that there were individual differences in the resistance of shoulder relative to T1 motions. On average volunteer V2 produced the largest motions. Volunteers V3 and V5 produced smaller motions than the average for all four loading conditions, although none of the differences were significant. Volunteer V2 produced significantly larger shoulder motions compared to volunteers V3 and V5 when loads were applied in the rearward direction. In addition, it was noted that this volunteer produced more upward-rearward oriented

motions for the other loading directions. Volunteer V4 produced slightly large forward shoulder motions for the 0° series and significantly larger for the 45° series when compared to V2, V3 and V5.
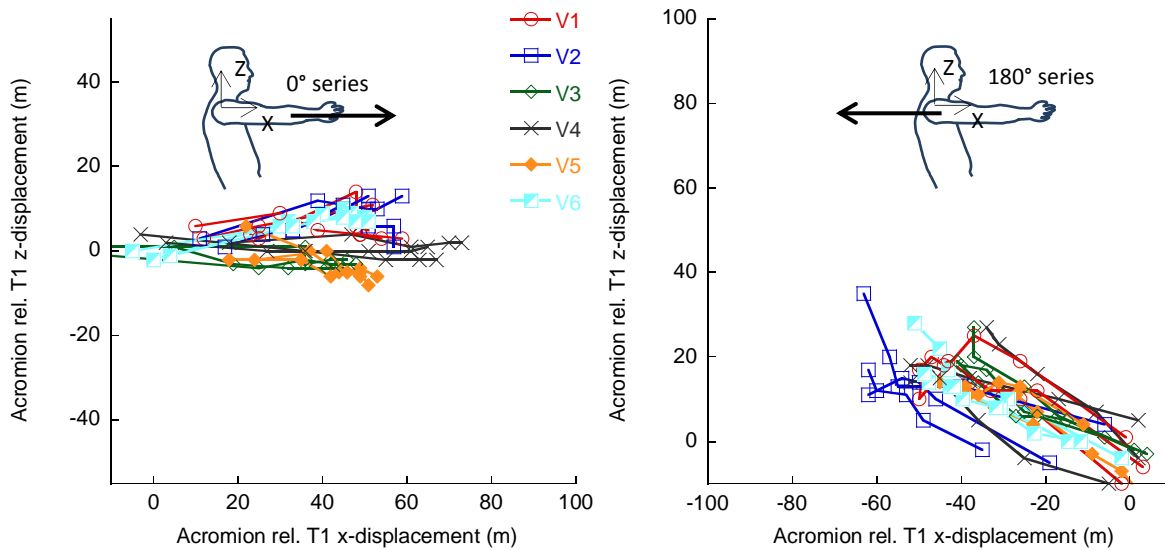

Fig. 5. Volunteer acromion rel. to T1 displacements, compensated for initial acromion position.

Average ± S.D. compensated acromion relative to T1 x-displacement was 54 ± 8 mm for the 0° series, 59 ± 13 mm for the 45° series, 32 ± 11 mm for the 80° series and -47 ± 10 mm for the 180° series at maximum shoulder load (Table III). The associated z displacements were 2 ± 6 mm for the 0° series, 33 ± 13 mm for the 45° series, 64 ± 13 mm for the 80° series and 18 ± 6 mm for the 180° series.

TABLE III
AVERAGE (AV.) AND S.D. COMPENSATED ACROMION RELATIVE TO T1 DISPLACEMENTS (MM) AS A FUNCTION OF THE LOAD APPLIED TO THE SHOULDERS (N/SHOULDER).

Shoulder load	0° series						45° series						80° series						180° series					
	x		y*		z		x		y*		z		x		y*		z		x		y*		z	
	Av.	S.D.	Av.	S.D.	Av.	S.D.	Av.	S.D.	Av.	S.D.	Av.	S.D.	Av.	S.D.	Av.	S.D.	Av.	S.D.	Av.	S.D.	Av.	S.D.	Av.	S.D.
50	33	8	2	2	3	5	33	8	-1	4	18	10	16	10	2	2	34	18	-25	12	-1	4	7	6
100	44	8	1	2	3	6	49	8	-2	6	26	11	24	11	1	2	47	17	-35	11	-2	6	12	6
150	50	8	0	3	3	6	56	11	-4	5	31	12	29	11	0	3	56	16	-43	10	-4	5	15	5
200	54	8	-1	3	2	6	59	13	-6	5	33	13	32	11	-1	3	64	14	-47	10	-6	5	18	6
n	6 volunteers, 3 tests each						6 volunteers, 3 tests each						6 volunteers, 1 tests each						6 volunteers, 3 tests each					

* NEGATIVE DISPLACEMENTS WERE IN THE MEDIAL DIRECTION.

Response requirements

The volunteers were slightly taller and heavier than the average male. To prepare for an adjustment for this acromion process relative to T1, resultant displacements were plotted as a function of volunteer weight, stature, seating height and acromion to acromion distance (Appendix, Fig. A-2). Based on an analysis of these plots, displacement data (x) were normalized, to be representative of an average male person, using acromion to acromion distance (L) and the formula below. The 50th percentile male acromion to acromion distance (406 mm) was taken from Schneider et al. [22].

$$x_{scaled\ for\ 50M} = x_{volunteer} \times \frac{L_{average\ M50}}{L_{volunteer}}$$

Normalized shoulder range of motion requirements, which can be used for evaluation of dummies and human body models with anthropometry close to an average male, are presented in Fig. 6.
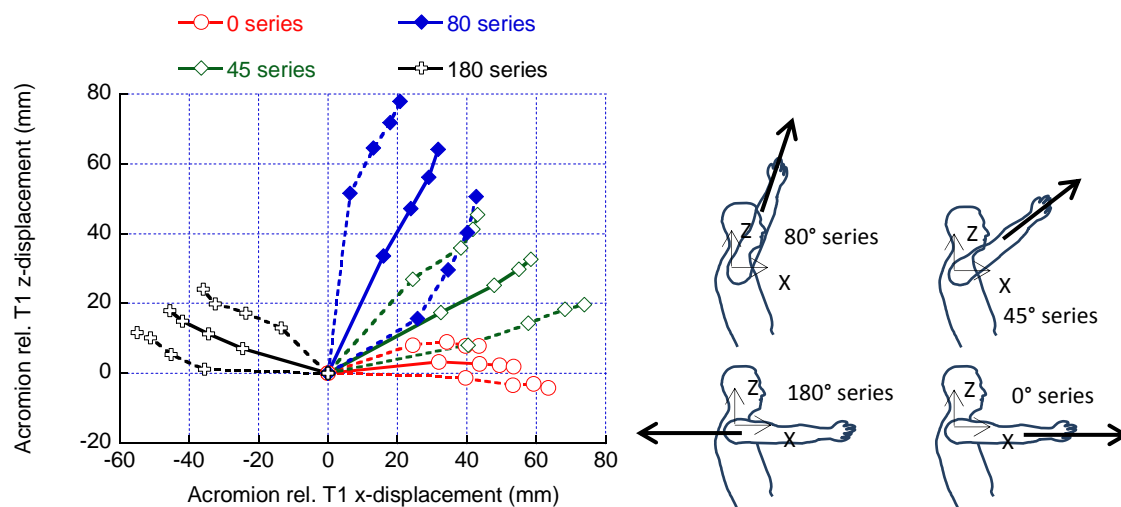

Fig. 6. Average ± S.D. volunteer acromion relative to T1 x- and z-displacements. Data were compensated for shift in initial acromion rel. T1 to position and normalized to represent an average male.

Stiffness

The stiffness was calculated as the load build-up per resultant acromion relative to T1 displacement. The average stiffness was slightly higher in the rear direction than in the forward direction (Table IV). There was less resistance to upward motion than to horizontal motion of the shoulder.

TABLE IV

AVERAGE AND S.D. VOLUNTEER SHOULDER STIFFNESS (N/MM) AS A FUNCTION OF APPLIED LOAD (N).

Load	0° series		45° series		80° series		180° series	
	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.
50	1.5	0.4	1.3	1.4	1.3	1.5	1.8	1.4
100	2.2	0.4	1.8	0.4	1.9	2.0	2.7	2.0
150	3.0	0.4	2.3	0.5	2.3	1.0	3.3	0.9
200	3.7	0.5	2.9	0.6	2.7	1.1	4.0	0.9

Habituation and effect of age

A one-way ANOVA blocked by subject and Tukey-Kramer post-hoc tests did not reveal any significant differences in resultant range of motion between repetitions or age, data grouped to two age groups being 30 and 50 years of age, at the 0.05 level in any of the three series tested multiple times.

Repeatability

The test with volunteers provided measurements with reasonable repeatability; repeatability C.V. for resultant acromion relative to T1 ranged from 6 to 13%. The C.V. for inter-subject variability was slightly higher than the repeatability (Table V).

TABLE V

REPEATABILITY AND INTER-SUBJECT VARIABILITY FOR ACROMION RELATIVE TO T1 RESULTANT DISPLACEMENT AT MAXIMUM LOAD.

	0° series	45° series	80° series	180° series
C.V.$_{Repeatability}$ (%)	6	11	13	12
C.V.$_{Intersubject}$ (%)	14	18	n.a.	17
No. of repeated tests for each volunteer	3	3	1	3
No. of volunteers	6	6	6	6

IV. DISCUSSION

Range of motion

The range of motion of the shoulder, assessed as acromion relative to T1 displacement, has been studied for non-injurious loads applied to the shoulder via arm brackets or straps encircling the shoulder complex. The largest absolute range of motion was for loading applied upward for a seated volunteer: on average 70 mm for a load of 200 N/shoulder.

This study differs from many others on shoulder range of motion because loads were applied to force the shoulder complex to move relative to the thorax. It provided larger ranges of motion than studies on voluntary posture changes. Ash et al. [20] provided acromion displacements as recorded in their frontal impact sled test series with PMHSs. The average maximum acromion displacements relative to T1 for the non-belted and belted shoulder were approximately 130 mm forward and 140 mm rearward, respectively. The motions of the unbelted shoulder, which are a combination of forward and upward motions in T1 fixed coordinate system, are larger than those presented by the volunteers; the resulting volunteer acromion relative T1 displacement was on average 75 mm. There are several reasons for this difference; e.g. the inertia induced loads on the shoulder were higher in the sled tests (maximum belt forces were close to 6.5 kN) than the static forces applied to the arms in the volunteer tests, and the PMHSs lacked muscle tissue tonus. In addition, in these sled tests single shoulder belts were used, large torso rotations were present, and to a large degree undermine the comparison of the results obtained in the current study for which the loading was symmetrical.

Törnvall et al. [7] also applied loads to the arms in their study of shoulder range of motion. For identical shoulder loads they reported larger acromion relative to T1 displacements. This could be due to differences between the boundary conditions used. Törnvall et al. [7] did not restrict torso bending; only a sternum support and a soft seatback restricted these motions. In this study, the volunteers did not curve their spines excessively forward or rearward when loads were applied to the shoulder complex.

Stiffness

The average stiffness of the shoulder complex was estimated as the load divided by the resultant displacement of the acromion relative to T1. The stiffness increased when higher loads were applied. For 50 N/shoulder the shoulder complex produced a stiffness of approximately 1.5 N/mm whereas for 200 N/shoulder the stiffness ranged from 3 to 4 N/mm. The higher stiffness was measured in the 0° and 180° series. This finding may be due to the design of the shoulder complex; the shoulder moves rather freely in the plane tangential to the exterior surface of the upper right and left regions of the ribcage. However, in the 0° and 180° series the loads applied to the shoulders are somewhat normal to this plane. This could partly explain the difference in stiffness between the 0° and 180° series and the 45° and 80° series in which the applied load was more vertical.

The stiffness was expected to be a function of age; however no significant effect of age could be observed. One reason for this could be that the older volunteers included in this study were rather fit.

Repeatability

The repeatability and inter-subject variability was fair; CV at maximum shoulder load ranged from 6% to 13% for an average volunteer. The reason for this probably originates from variation in the initial position of the shoulder relative to T1. However, the preferred initial starting position of the shoulder varied only slightly between the four load conditions. In conclusion, other sources may also be present, e.g. minor muscle tension.

Inter-subject variability was, as expected, larger than the variation for each subject, ranging from 14% to 18%. A reason for this variation between subjects may be the difference in past physical activities. Volunteer V4 had, for a prolonged period, on a regular basis trained front-crawl which loosened up his shoulder complex. This volunteer had an average range of motion of 125% of the average for all volunteers in the 0° and 45° series. Differences were smaller for the other two series. Another volunteer, V5, exhibited only 75% of the average range of motion in the 180° series.

Limitations of the study

The loads applied to the shoulder complex in this study were quasi static and lower than those commonly seen in frontal crashes. However, the shoulders are highly mobile and their responses to loads are largely dependent on muscle characteristics. As such, studies using volunteers may be complimentary to studies with PMHSs despite the fact that low loads must be used for volunteers.

Joints used in crash test dummies are rarely rate-dependent but non-linear. For human body models, rate dependency is commonly included in the model of joints; however, joints are frequently modeled linearly. For these reasons some additional analysis may be required when the data presented here are to be used to evaluate these models.

This study relies on the verdict from the volunteers that they managed to relax in all tests. An independent measurement of muscle activation, such as the measurements of EMG signals, would have been preferred. However, no habituation could be detected and repeatability was fair for all volunteers; these observations indicate that the volunteers did manage to relax in all tests.

The number of volunteers is limited and may not be representative of the average vehicle occupant. Only male volunteers with an average stature and weight slightly above the average male vehicle occupant were included in this study. All the volunteers were fit for their age. Additional volunteer studies should be carried out to study shoulder response of females and of less fit males.

The main source of error in this study arose from differences in preferred shoulder posture. Shifts in preferred initial position of the acromion relative to T1, when the arms were moved to test positions, were determined; they can be used when human body models or crash test dummy performance are assessed.

The belts applied some load to the proximal end of the clavicle bone, which may have influenced the forward displacements of the acromion relative to T1. This effect was judged to be minor because the belt did not change its curvature near the clavicle bone.

Ranges of motion were assessed by using photo markers mounted on the skin of the volunteers. This induces some uncertainty since the markers can move relative to the bony landmarks of interest. This uncertainty is considered small because all of the volunteers were fit and no loads were introduced to the skin near the photo markers. Previous studies have shown that skin markers are accurate enough for this type of study [24].

Film analysis introduces errors due to lens properties, tracking errors and photo markers that move normal to the used reference plane. In this study high resolution cameras, well defined photo markers and telephoto lenses of superior quality, were used in combination with an extraordinary long distance between the film planes and the volunteers. The error introduced by the film analysis was estimated to be less than 3 mm.

V. CONCLUSIONS

The range of motion of the shoulder assessed as the acromion relative to the T1 was studied for loads applied to the shoulder via arm brackets or straps that encircled the shoulder complex. The repeatability and inter-subject variability was satisfactory. The average stiffness of the shoulder complex when subjected to loads of 200 N/shoulder was about the same in all directions tested. The complex was slightly more flexible when exposed to upward loads than for forward, forward-upward and rearward loads. These stiffness values can be used in developing mathematical models of the human that take rate dependency and nonlinearity into account.

VI. ACKNOWLEDGEMENT

VII.   REFERENCES

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VIII. APPENDIX

The directions of the applied shoulder loads varied slightly between the subjects due to anatomical differences and preferred shoulder trajectory but had minor influence on the results (Table A-I). For the 0° series, the rope pulled the elbows slightly downward. However, the armrest restricted the downward motions. For the 45° series, the angle was slightly smaller but also here the armrest restricted the arm forward motion; the resulting arm trajectory was approximately 45°. For the 80° series, the armrest did not sufficiently support the arms which were pulled at an angle of approximately 72°. For the 180° series, the shoulder straps and ropes pulled the shoulders upward by an average 3° relative to horizontal.

TABLE A-I

LOADING ANGLES FOR EACH VOLUNTEER AND FOR THE STUDIED TEST SERIES (°).

	Direction of applied load relative to horizontal			Direction of applied load relative to sagittal plane	
Volunteer	Series 0°	45° series	80° series	180° series 0° series (pulling outward)	180° series (pulling inward)
1	-2	43	75	179	2	9
2	-3	41	71	174	3	13
3	-3	44	69	178	2	12
4	-3	41	73	179	3	14
5	-2	40	72	175	2	14
6	-2	41	71	177	4	13

The average belt load for each volunteer, when no shoulder load was applied and when the shoulder load was increased, varied between volunteers (Fig. A-1 and Table A-II). The average belt loads were rather consistent for zero shoulder loads, approximately 65 N for all series, with the exception of one volunteer, V2. When shoulder loads were applied, the changes in belt loads appear to be a function of the loading conditions (Fig. A-1). Elevated initial belt load commonly resulted in elevated belt loads at maximum shoulder loads: clearly for 0° series and 45° series and less for the other two series (Fig. A-1).

TABLE A-II

AVERAGE AND S.D. RIGHT BELT LOADS FOR EACH VOLUNTEER AT MAXIMUM SHOULDER LOAD (THREE TESTS FOR EACH VOLUNTEER FOR THE 0°, 45°, 180° SERIES AND ONE TEST FOR EACH VOLUNTEER FOR THE 80° SERIES)(N).

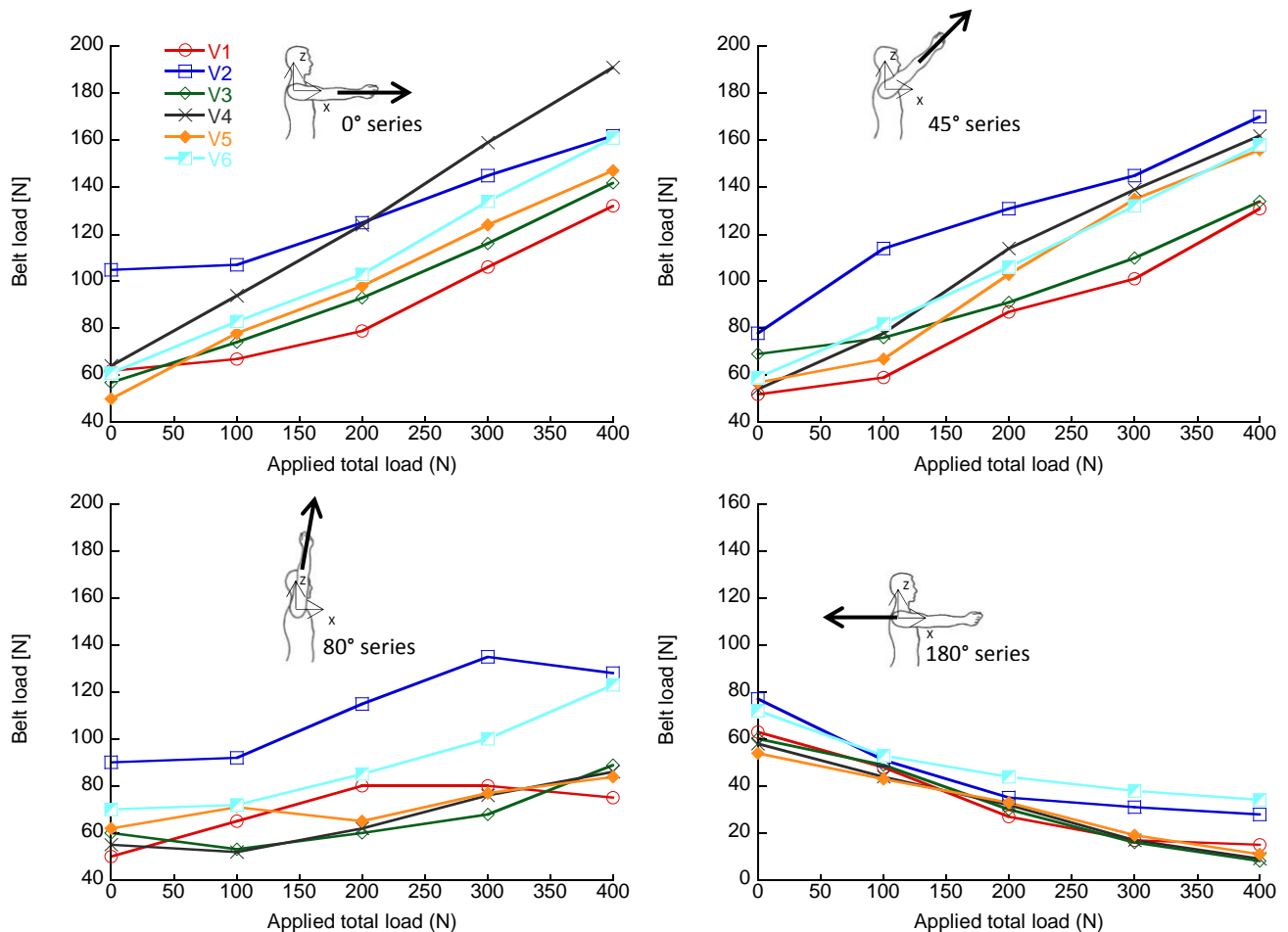|	0° series		45° series		80° series	180° series	
Volunteer	Average	S.D.	Average	S.D.	Average	Average	S.D.
1	132	14	131	8	75	15	1
2	162	20	170	3	128	28	9
3	142	7	134	10	89	8	2
4	191	12	162	8	86	9	1
5	147	18	156	7	84	11	4
6	161	1	158	3	123	33	32

Fig. A-1. Average right belt loads for each volunteer in the 0°, 45°, 80° and 180° series (three tests for each volunteer).

The belt loads were rather consistent for each volunteer at zero shoulder load but varied between volunteers (Table A-III). At higher shoulder loads the variations in belt loads, in absolute terms, increased in amplitude for all series except 0° series. Higher initial belt load commonly resulted in elevated belt loads at maximum shoulder loads.

TABLE A-III

AVERAGE AND S.D. OF ONE SIDE BELT LOADS FOR EACH LOAD INCREMENT (SIX VOLUNTEERS, THREE TESTS EACH FOR THE 0°, 45° AND 180° SERIES AND ONE TEST EACH FOR THE 80° SERIES)(N).

Shoulder load	0° series		45° series		80° series		180° series	
	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.
0	66	22	61	10	65	14	64	10
50	84	17	79	19	68	15	48	11
100	104	20	105	15	78	21	33	14
150	131	21	127	17	89	25	23	15
200	156	22	152	16	98	22	17	15

Seat back loads are provided in Table A-IV. As for the belt loads, the seat back loads were a function of the applied shoulder load direction and amplitude.

TABLE A-IV

AVERAGE AND S.D. SEAT BACK LOADS FOR EACH LOAD INCREMENT (SIX VOLUNTEERS, THREE TESTS EACH FOR THE 0°, 45° AND 180° SERIES AND ONE TEST EACH FOR THE 80° SERIES) (N).

Shoulder load	0° series		45° series		80° series		180° series	
	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.
0	377	34	451	30	496	53	395	28
50	338	51	383	44	407	50	458	46
100	284	55	327	60	366	42	540	67

| 150 | | 239 | 64 | 279 | 63 | 332 | 54 | 624 | 83 |
| 200 | | 202 | 72 | 232 | 71 | 309 | 62 | 706 | 106 |

Normalized acromion relative to T1 x-displacements as function of volunteer stature, weight, seated height and volunteer acromion to acromion distance (Fig. A-2). These plots reveal that range of motion may be a function of acromion to acromion distance and appear not to be a function of stature, body weight, or seated height.
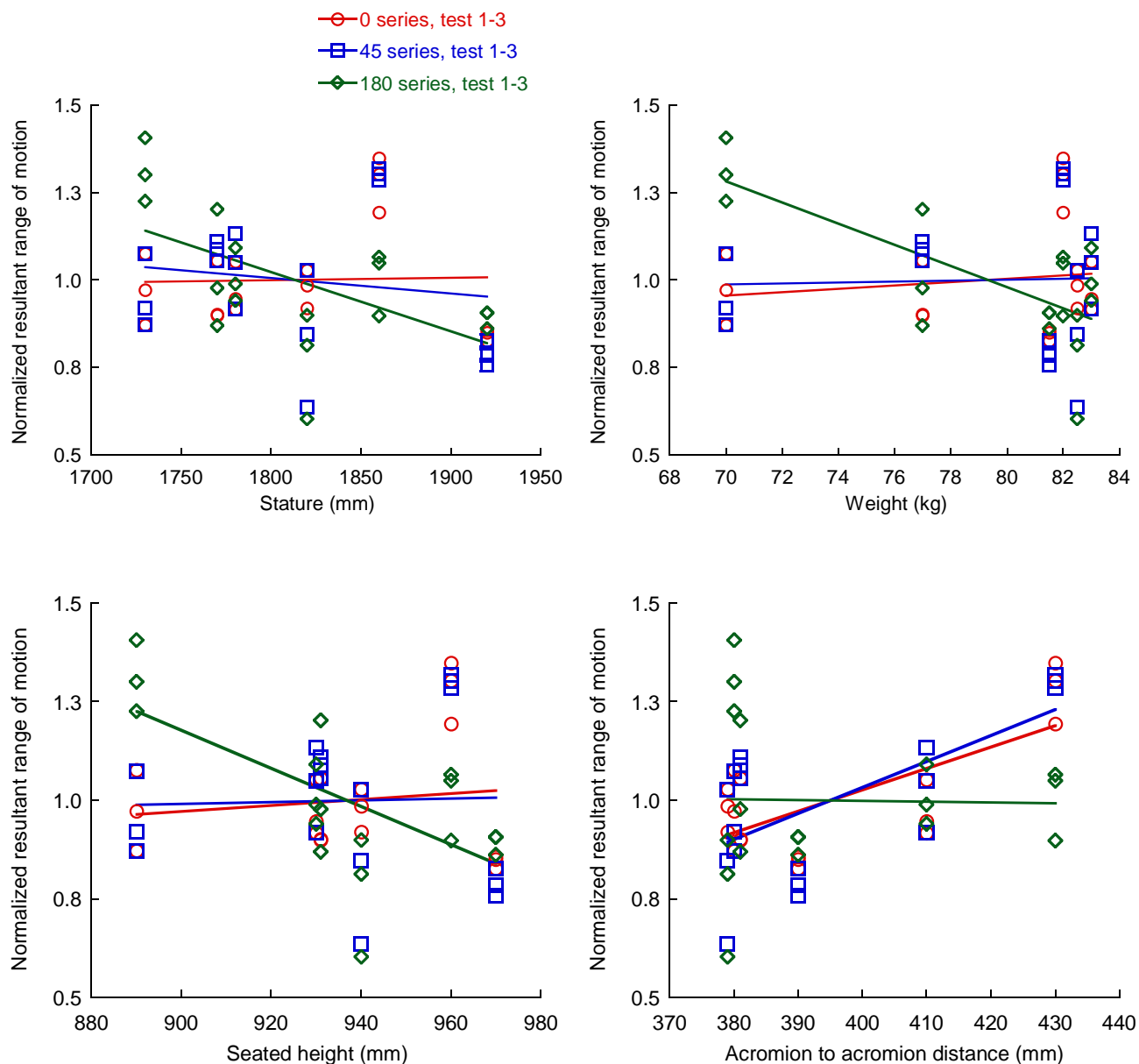

Fig. A-2. Normalized acromion relative to T1 resultant displacements (range of motions) as function of volunteer stature, weight, seated height and acromion to acromion distance.