VOLUNTEER AND DUMMY TESTS FOR THE VALIDATION OF BIOMECHANICAL ASSESSMENT CRITERIA UNDER THE EURO-NCAP

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ABSTRACT

The Euro-NCAP defines a „green rating" for the 40 mph 40% offset crash test on the basis of certain biomechanical assessment criteria which were suspected of representing perturbations of daily living.

A study was launched to substantiate the criteria for this rating on the basis of 359 volunteer and dummy tests. The tests included jumping and falling experiments as well as impact tests against the chest, the knee and the lower leg.

Main results presented in this paper concern chest deflection, the Tibia Compression Force Criterion (TCFC), the Tibia Index (TI) and the validity of the Hybrid III dummy.

A RANGE OF CRASH TEST PROCEDURES, varying in crash speed, dummy instrumentation, offset, kind of barrier etc., are currently applied by official institutions, insurance companies, car magazines and consumer organisations in order to assess car safety.

In particular, the published crash test results ([3], [4]) according to the European New Car Assessment Program (Euro-NCAP) have created uneasiness among car manufacturers (p.e. [5]). The testing protocol, evaluation of data and assessment of results are described in [15] and [7] respectively. Table 1 gives the Euro-NCAP performance criteria for different body parts (acc. to Hobbs, 1998 [6]).

The lower boundaries, i. e. the boundary between a poor (red) and a weak (brown) rating, mostly correspond to the EEVC threshold values (where existent) according to the crash tests made statutory under ECE R94 and R95.

As long as values remain below the upper boundary, the result is rated 'green' (good). The threshold values are mostly based on research by Mertz (1997, [9]), in which he developed a statistical method for determining the probability of injury risk under mechanical loading of the human body.

Hobbs' 'green' rating (1998, [6]) is based on a probability of 5% for incurring an injury of the same severity (according to AIS) as that on which the legal threshold value is based.

Table 1: Euro NCAP Performance Criteria (acc. to Hobbs 1998, [6])

Body region	Criterion	Lower Boundary	Upper Boundary
Head	HIC	1000	650
	a_{res3ms}	88 g	72 g
Neck	Shear	3.1 kN @ 0 ms, 1.5 kN @ 25-35 ms, 1.1 kN @ 45 ms	1.9 kN @ 0 ms, 1.2 kN @ 25-35 ms, 1.1 kN @ 45 ms
	Tension	3.3 kN @ 0 ms, 2.9 kN @ 35 ms, 1.1 kN @ 60 ms	2.7 kN @ 0 ms, 2.3 kN @ 35 ms, 1.1 kN @ 60 ms
	Extension	Extension 57 Nm	Extension 42 Nm
Chest	Compression	50 mm	22 mm
	Viscous Criterion	1.0 m/s	0.5 m/s
Femur	F_{Femur}	9.07 kN @ 0 ms, 7.56 kN @10 ms	3.8 kN
Knee	Knee slider	15 mm	6 mm
L wer Leg	F_{Tibia} (TCFC)	8 kN	2 kN
	Tibia Index	1,3	0,4
Lower Boundary: rating changes from red (poor) to brown (weak)			
Upper Boundary: rating changes from yellow (adequate) to green (good)			

The aim of this study is an analysis of the Euro-NCAP rating system, especially an investigation of the scientific tenability of the 'green' rating. The course taken here was to test volunteers for a range of loads that could safely be assumed to cause no injury. A number of similar dummy tests (2-3 tests under the same conditions) was to substantiate knowledge about dummy repeatability (scattering of values) and biofidelity.

METHODS

NINE MALE (AGED 23-59) AND SEVEN FEMALE (AGED 22-36) scientists working at this institute volunteered for the experiments (for anthropometric data cf. Table 2) to pursue their research interests. Each of them held sole responsibility for the tests they participated in, discontinued them at their own will or on medical advice in avoidance of persisting injuries. Therefore the appeal to an ethics board was unnecessary. Not all volunteers decided to participate in all test series.

Table 2: Anthropometric data of the volunteers

Volunteer	Sex	Age	Body mass	Body height	Thorax circumf.	Th. depth	Th. breadth	foot lenght
			m_B	l_B	$circ_{Th}$	h_{Th}	b_{Th}	l_F
		[J]	[kg]	[cm]	[cm]	[cm]	[cm]	[cm]
1	m	59	72	173	98	22,6	34,5	26,5
2	m	35	74,5	177,5	95,5	23,2	31,8	27
3	m	29	80	178	101	24,5	32,2	
4	f	23	59,5	164,5	84	19,3	26	
5	f	25	70	173	91	19,8	28,5	
6	f	36	57	165	83	19,2	27,3	25
7	f	22	54,5	164,5	83	17,9	26,9	
8	m	52	68	169	94	23,4	30,4	24,5
9	m	32	75	170	101	25	33	25
10	m	23	62	180				25
11	m	38	93	192				28,5
12	m	31	64	172				24,5
13	f	29	60	160				23,3
14	m	32	75	170				24
15	f	29	53	160				
16	f	31	48	160				

Two 50th-percentile male HIII dummies were also used for the load tests. The drop tests were accomplished using a 50th-percentile male pedestrian dummy equipped with Instrumented Legs (IL).

THE TEST SERIES CONSISTED OF A TOTAL OF 359 experiments (238 volunteer tests, 121 dummy tests) as shown in the following matrix (Table 3).

Table 3: Test matrix

Body Part Loaded	Number of Tests	
	Dummy	Volunteers
Chest frontal	33	36
Femur axial (Knee)	21	50
Sliding Knee	46	62
Tibia axial (drop tests)	21	10
Tibia axial (jump tests)	-	80
Total	121	238
Total	359	

THE PENDULUM TESTS were conducted at ENDEVCO Germany Ltd., Heidelberg. A pendulum used for dummy calibration ($m_{Pd} \approx 14$ kg, $\varnothing_{Pd} = 154$ mm) was adapted for the experiments by padding with 30 mm of Ensolite fixed with adhesive tape. A microswitch was fastened half-way between the surface of the pendulum and that of the padding in order to show the optical moment of impact (t_0) by flash-light.

The impact velocity v_{imp} and the acceleration in x-direction a_{Pd} were measured on the pendulum. Calculated pendulum force F_{Pd} was based on the mass of the pendulum m_{Pd} and its acceleration a_{Pd}.

The tests were recorded photographically with a standard video camera and, occasionally, a 500 frames-per-second high speed camera.

THE IMPACT OF THE PENDULUM was directed at the middle of the sternum. Dummies and volunteers were positioned accordingly with the aid of an adjustable height platform. Fig. 1+2 show the test setup and the impact configuration for volunteers.

Frequently, only the lower edge of the pendulum instead of the whole surface made contact in volunteer tests, which is why dummy tests, too, were conducted in two different impact configurations.

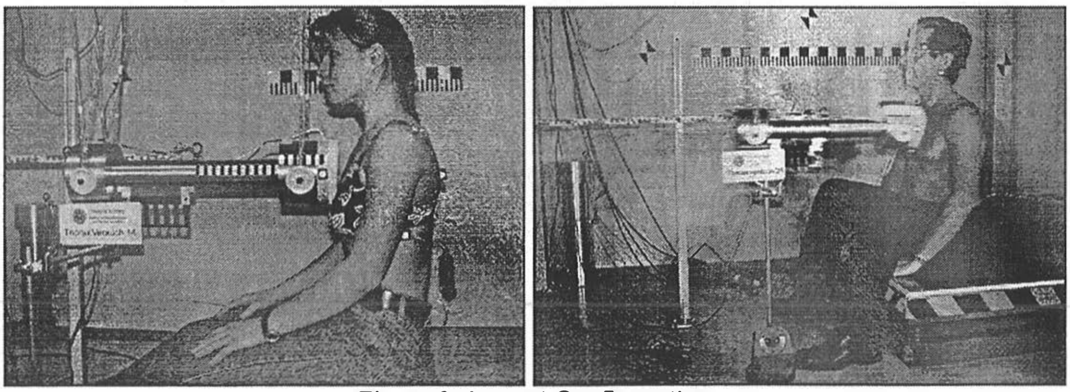

Fig. 1+2: Impact Configuration

Throughout one test series, the impact was flat against the chest (Fig. 3), in the second one, the dummy had a slight backward pitch (Fig. 4) which was meant to test the behaviour of the potentiometer (deflexion transducer).

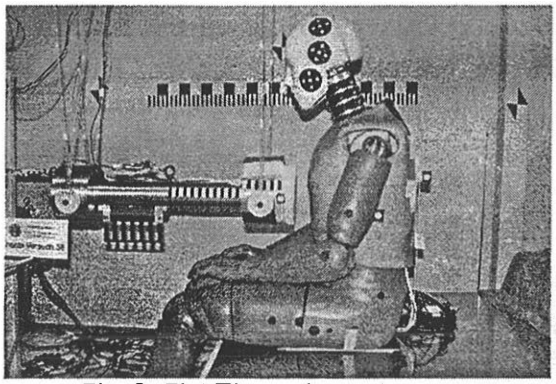

Fig. 3: Flat Thorax Impact

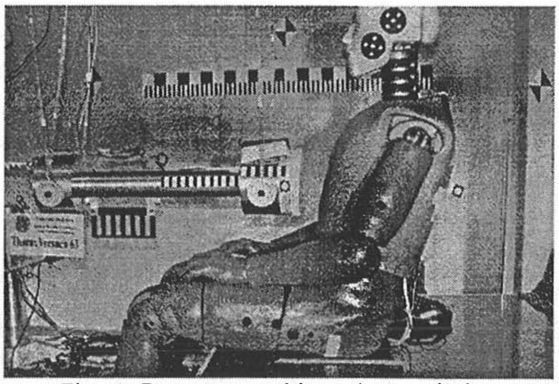

Fig. 4: Dummy positioned at a pitch

The measurements recorded on volunteers were back acceleration along the x-axis a_{BX} and, in some tests, head acceleration a_C in x-, y- and z-directions. Both were measured by transducers individually adapted to each volunteer. Thermoplastic dorsal adapter plates (Fig. 5) (Cellaform®, 2,4 mm thick), were moulded to the volunteers' backs, with paying special attention to the spine (spinous processes) in order to ensure a good fit with bone structures. The back adapter bearing an aluminium U-profile with uniaxial accelerometers and a target was attached to volunteers' backs using adhesive tape (Strappal®).

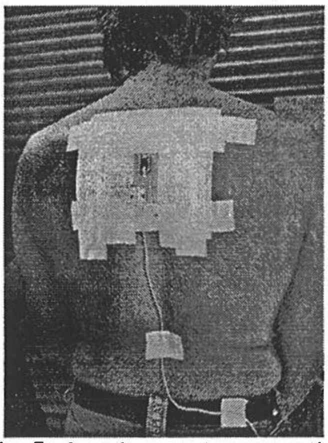

Fig. 5: Accelerometer mounting

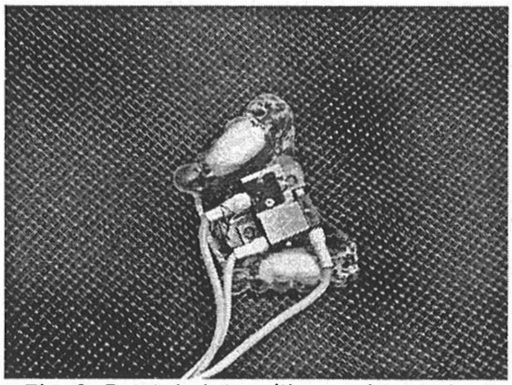

Fig. 6: Dental plate with accelerometers

Head acceleration was recorded using dental plates. According to individual dental impressions of the upper jaw taken tightly fitting adapters were manufactured and equipped with screw threads to which a set of three uniaxial accelerometers could be attached (Fig. 6). The dental plates were used for runs No. 6.26 ff (cf. Table 1 in the appendix).

Thorax acceleration a_{Th} (x-, y- and z- direction), thorax deflexion d_{Th}, head acceleration a_C (x-, y- and z- direction), neck moment M_{NY} and neck force F_N (x- and z-direction) were measured on the dummy during thorax impact tests. In addition back accelerations a_{Bx} in x-direction were measured using a similar kind of adapter plates as for volunteers.

IN ORDER TO DETERMINE FOOT LOADS for a fall or jump from a small height, 80 jump tests were performed with 8 volunteers (2 f, 6 m; subjects 1, 6, 8-13, cf. Table 2) as well as 21 dummy drop tests and 10 volunteer drop tests with three different subjects (1 f, 2 m; subjects 9, 13, 14).

Both dummy and volunteers were wearing measuring shoes for assessing foot loads. The make and function of the measuring shoes is described more closely in Schueler et al. (1996, [13]) and Lorenz (1997, [8]). There were also some tests using the standard H III-shoes (Tests FB 16-21).

THE TEST SETUP FOR DUMMY DROP TESTS is shown in Fig. 7 and 8. The dummy was suspended on standard car safety belt straps connected by a belt buckle. The lower end of the strap was screwed onto the dummy head (thread for dummy hook). The upper end was tied into a loop and hooked up in a pulley also used to adjust drop height. The dummy was dropped through manual opening of the belt buckle. The tests were conducted with varying heights h_{drop} and leg positions.

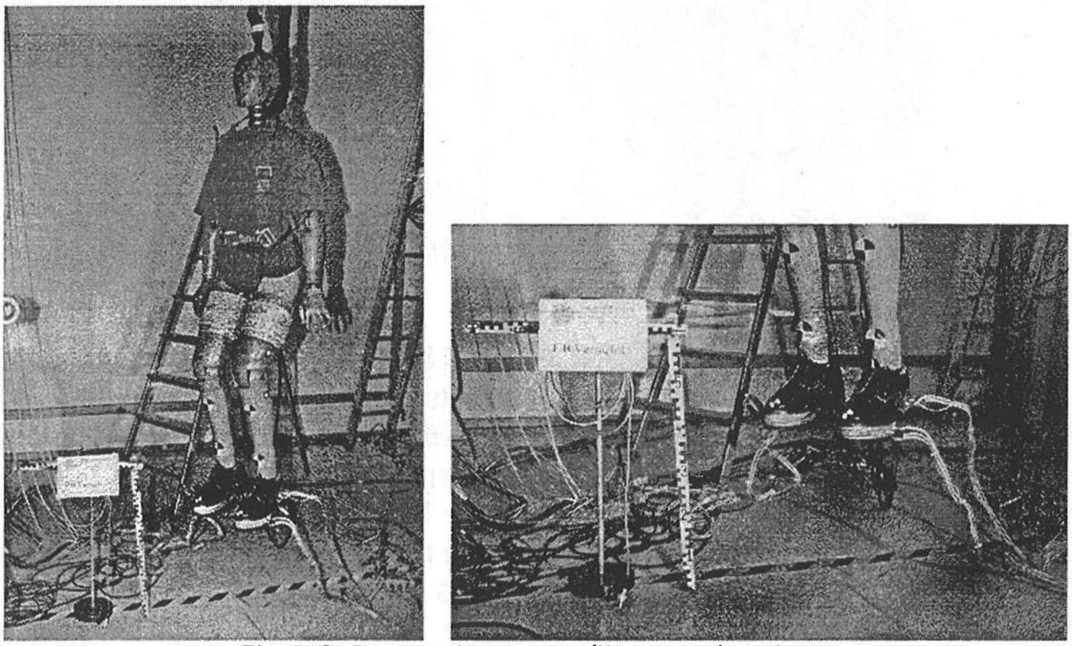

Fig. 7+8: Dummy drop tests with measuring shoes

Moments and forces were measured on the two lower extremities (lower and upper tibia (F_{ZLoTi}, M_{XLoTi}, M_{YLoTi}, F_{ZUpTi}, M_{XUpTi}, M_{YUpTi})) as well as the femur forces F_{Femur} and pelvis accelerations (a_{px}, a_{py}, a_{pz}) of the dummy.

The Tibia Index was calculated on the basis of the lower and upper tibia values.

Sole (F_{XSo}, F_{ZSo}, a_{ZSo}) and heel (F_{XHeel}, F_{ZHeel}, a_{ZHeel}) forces and accelerations were measured on the shoes (mass $m_{Shoe} \approx$ ca. 3,4 kg, depending on the amount of cable). The accelerations (a_{ZSo} and a_{ZHeel}) were taken in order to compensate for the interference from the mass of the measuring equipment integrated in the shoes. All the values for shoe forces given in this paper are corrected forces.

THE VOLUNTEER JUMP TESTS (Fig. 9) were performed at the Institute of Legal and Traffic Medicine of the University of Heidelberg. Jump heights were h_{Ju}=100, 220, 265, 370 and 475 mm with two jumps at each height. Volunteers were wearing the measuring shoes which were stuffed as required in order to ensure that the shoes stayed in place for different size feet.

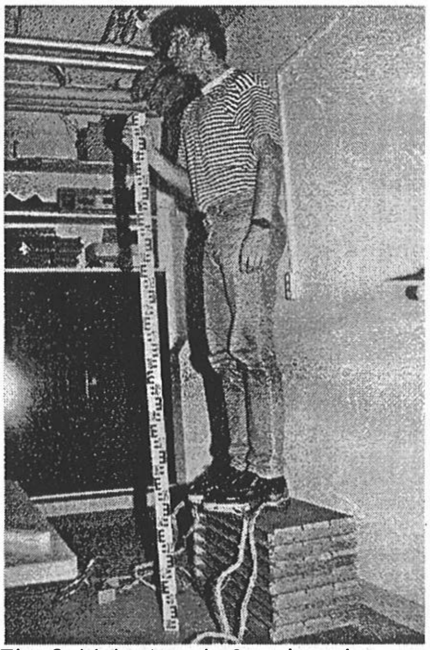

Fig. 9: Volunteer before jumping

Fig. 10: Volunteer at drop test

ADDITIONAL VOLUNTEER DROP TESTS were accomplished to compare the results with those of volunteer jump tests and dummy drop tests (Fig. 10). Jump tests had shown that the subjects absorbed the shock of landing to various degrees. For the drop tests, volunteers were therefore told to hold on to a wooden bar which was released manually through a trigger mechanism (belt buckle). Drop height was adjusted through a pulley. The subjects were involved in a conversation, so that their attention was diverted from the test and the fall happened unexpectedly.

RESULTS

A TOTAL OF 59 THORAX IMPACT TESTS were performed on volunteers (36 tests, 4f, 5m) and dummies (23 tests, Dummy H III). Two of the dummy tests werde conducted at much higher pendulum drop heights (h_{drop}=770 mm, $v_{imp}\approx$4 m/s) than the other tests to compare with those performed by Patrick in 1981([12]).

Fig. 11 and 12 show typical acceleration-time-histories of a volunteer and a dummy test at the same impact speeds.

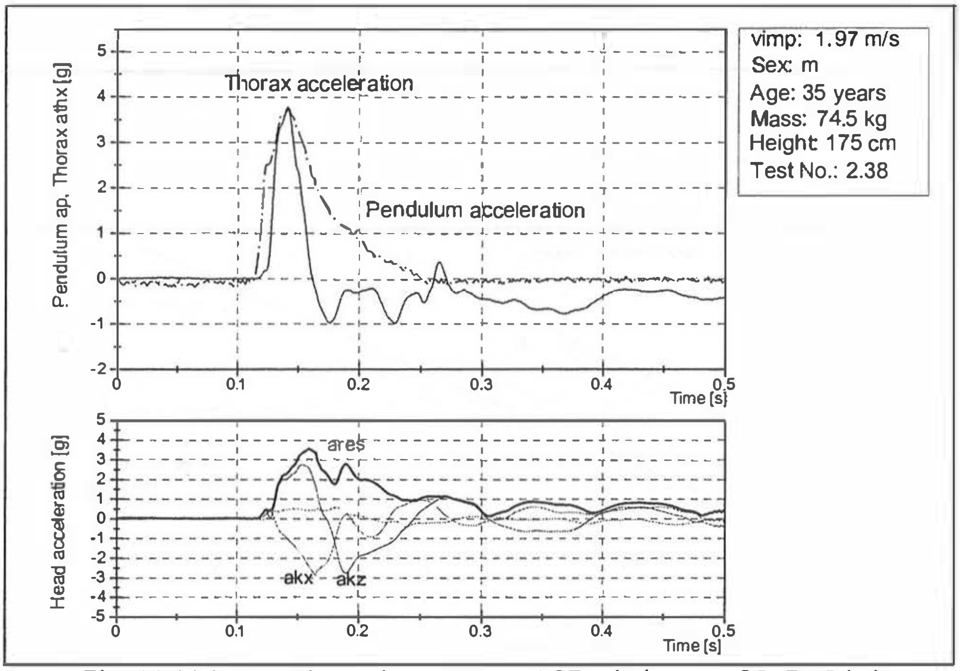

Fig. 11: Volunteer thorax impact, v_{imp}=1,97 m/s (m, age 35, 74,5 kg)

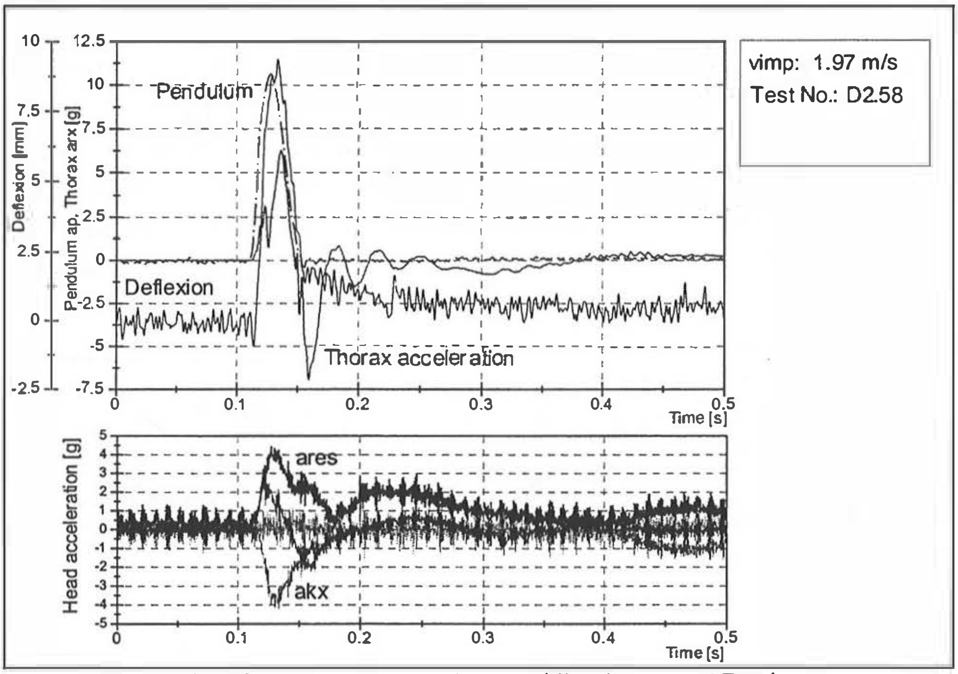

Fig. 12: Dummy thorax impact (tilted), v_{imp}=1,97 m/s

In Fig. 13, the pendulum force is plotted against impact velocity for both dummy and volunteer tests. The values were submitted to linear regression. The points marked with a small cross are the ones where the pendulum struck the thorax at a point below average.

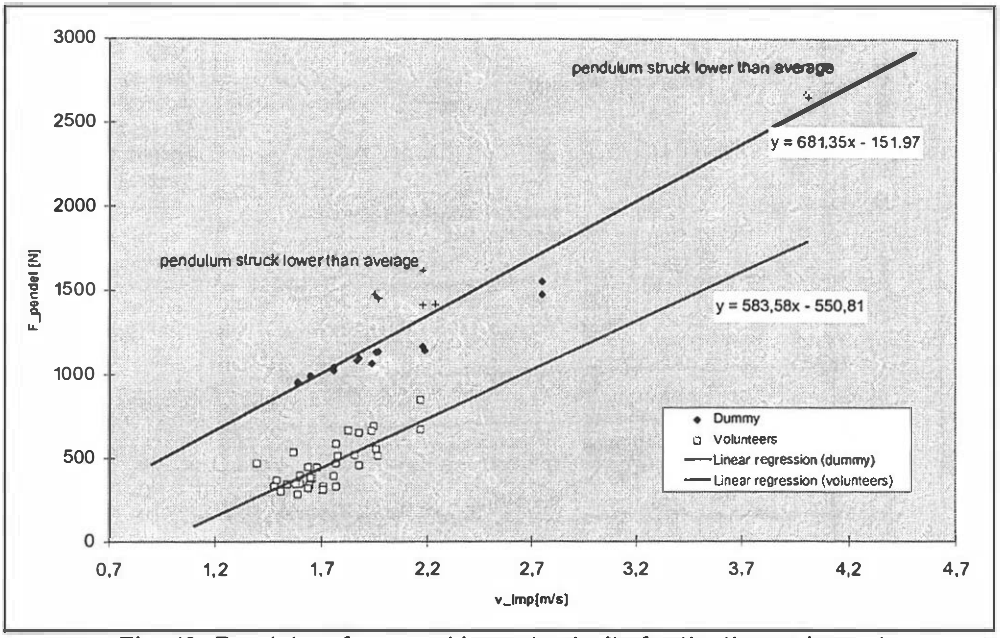

Fig. 13: Pendulum force and impact velocity for the thorax impact

The results for the volunteer tests are more widely scattered than for the dummy tests. The pendulum force recorded on the volunteers is significantly lower than on the dummies, although it was increased at roughly the same rate. This would seem to indicate a greater stiffness of the dummy.

The thorax acceleration curve is roughly linear for the dummy (Fig. 14), but here also the values are higher where the pendulum struck the target on the lower part of the sternum. Volunteer values are widely scattered and it is therefore not possible to apply linear regression, although a rising tendency can be observed.

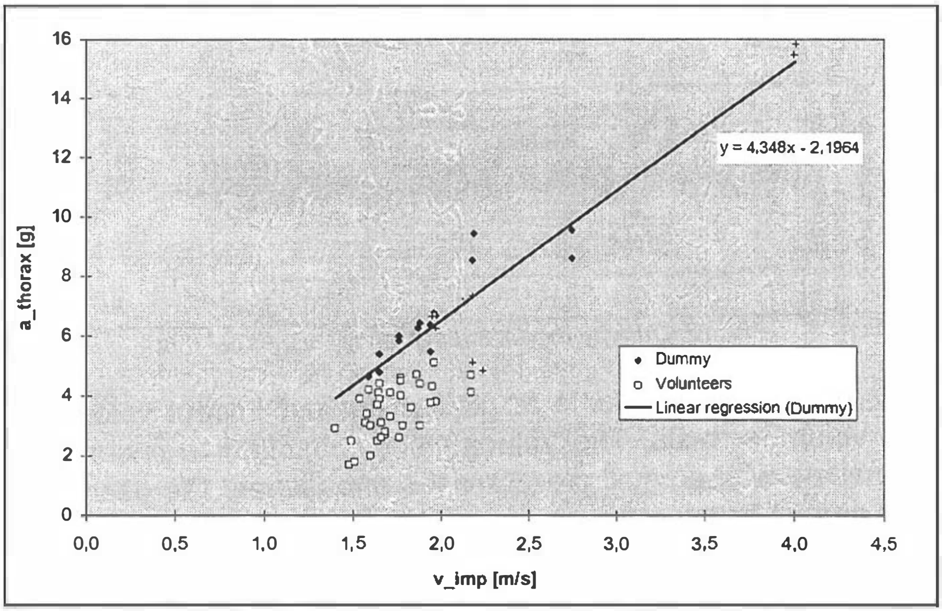

Fig. 14: Thorax acceleration as a function of impact velocity

Thorax deflexion as measured on the dummies is shown as a function of impact velocity in Fig. 15 and presents a linear course and little scattering.

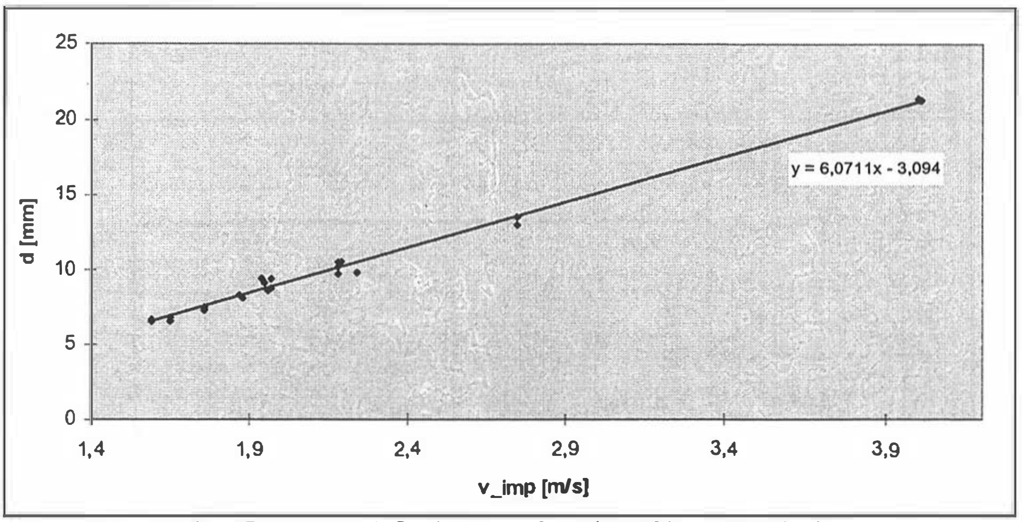

Fig. 15: Thorax deflexion as a function of impact velocity

A TOTAL OF 21 DUMMY DROP TESTS were performed at drop heights from h_{drop}=5 to 40 cm with either measuring shoes or normal shoes and varying leg positions. The results are summarized in Table 3 in the appendix.

Fig. 16 & 17 show the shoe forces and lower tibia forces in z-direction for both legs (e.g. heel force right $F_{zHeelri}$) and drop height of h_{drop}=10 and 40 cm respectively.

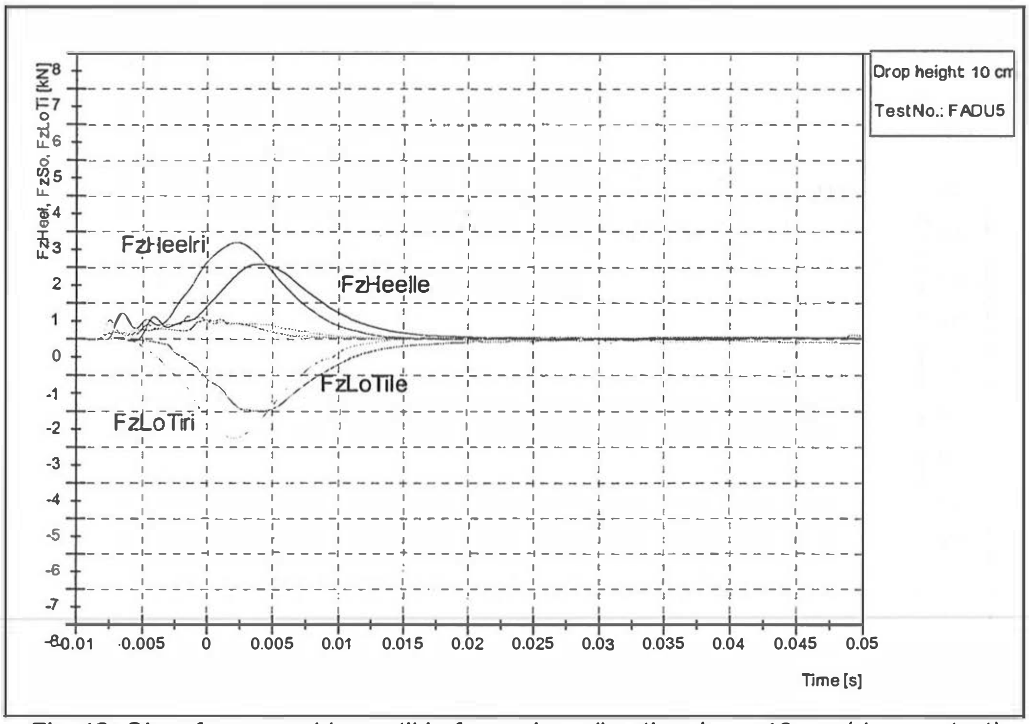

Fig. 16: Shoe forces and lower tibia forces in z-direction, h_{drop}=10 cm (dummy test)

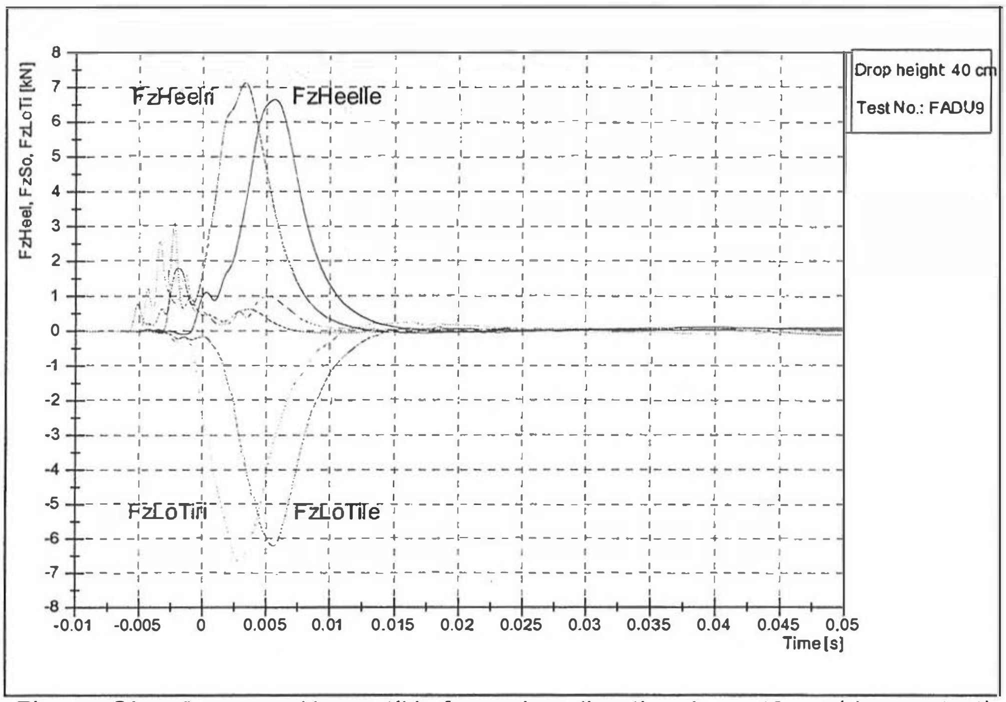

Fig. 17: Shoe forces and lower tibia forces in z-direction, h_{drop}=40 cm (dummy test)

As is evident from the accelerometer traces, heel force F_{zHeel} and lower tibia force F_{zLoTi} show good agreement.

Fig. 18 gives the Tibia Index for upper and lower tibia for 40 cm drop height.

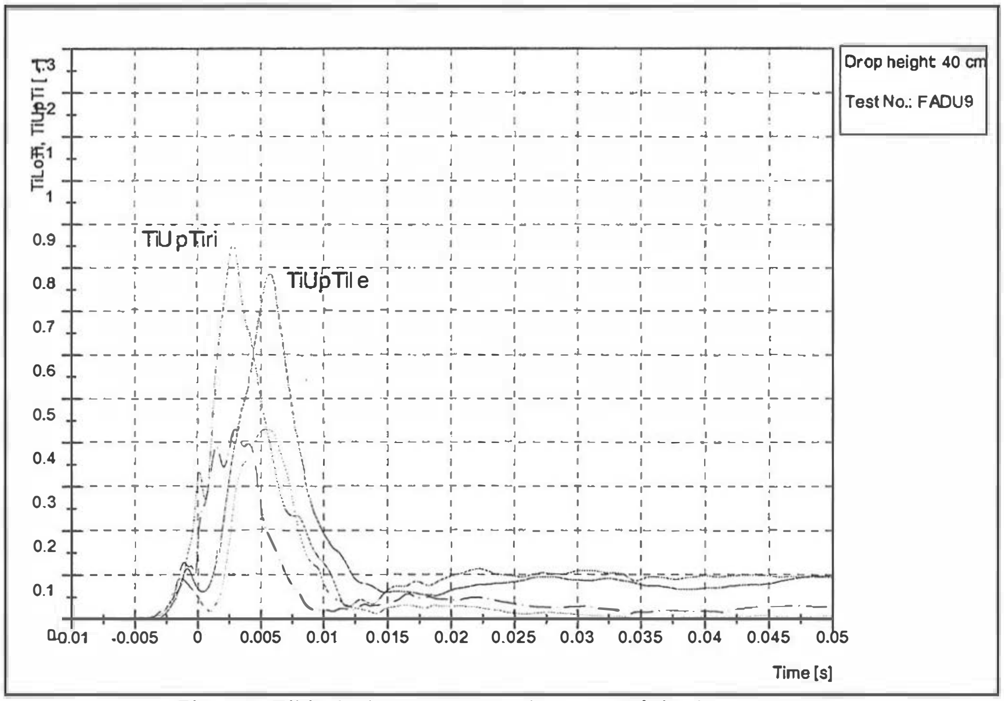

Fig. 18: Tibia Index Upper and Lower Tibia, h_{drop}=40 cm

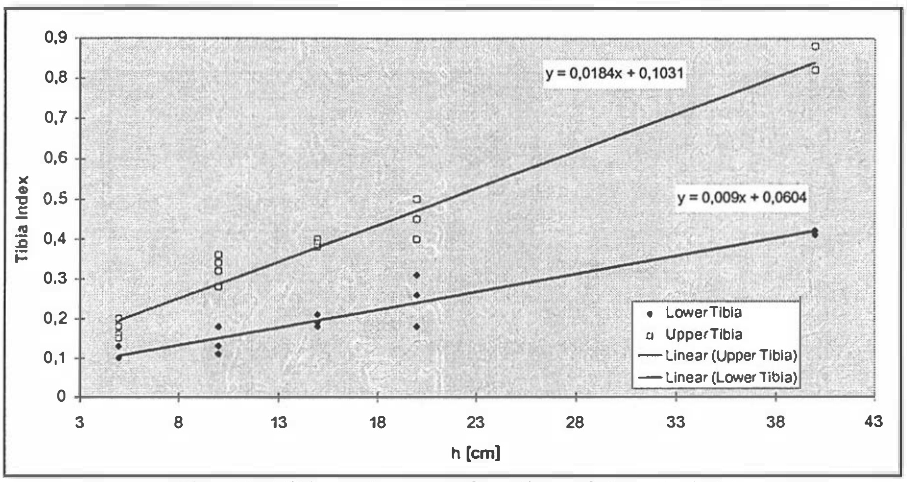

Fig. 19: Tibia Index as a function of drop height

Fig. 19 contains the Tibia Index right and left for both upper and lower tibia as a function of drop height. The values for the lower tibia are from TI=0.1 (drop height 5 cm) to TI=0.4 (drop height 40 cm) and thus lower than for the upper tibia (TI=0,15 to TI=0,88). The Tibia Index was calculated for the first 25 ms of impact.

Fig. 20 shows the correlation of heel and tibia force in z-direction and drop height for the right and the left leg. Values range from 1.5 kN for the lowest drop height of 5 cm to 6.5 kN for 40 cm. Heel and tibia measurements show good agreement.

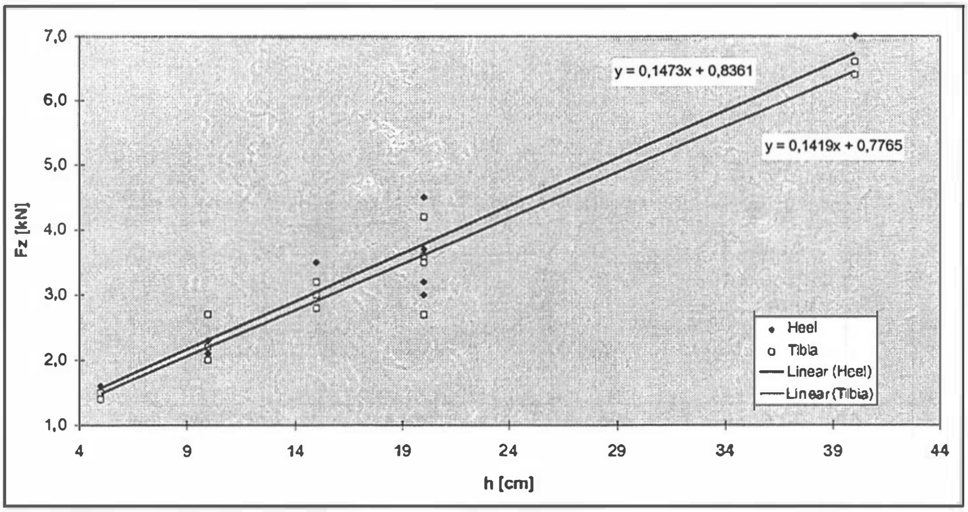

Fig. 20: Heel and tibia force in z-direction as a function of drop height

EIGHT VOLUNTEERS (2 f, 6 m; subjects 1, 6, 8-13, cf. Table 2) were tested in 80 jump tests for a height of $10 \leq h_{Ju} \leq 47{,}5$ cm (Appendix Tables 8-13).

Fig. 21 & 22 show shoe forces in z-direction for a subject approximating the 50^{th}-percentile male anthropometry from the lowest and highest jump heights.

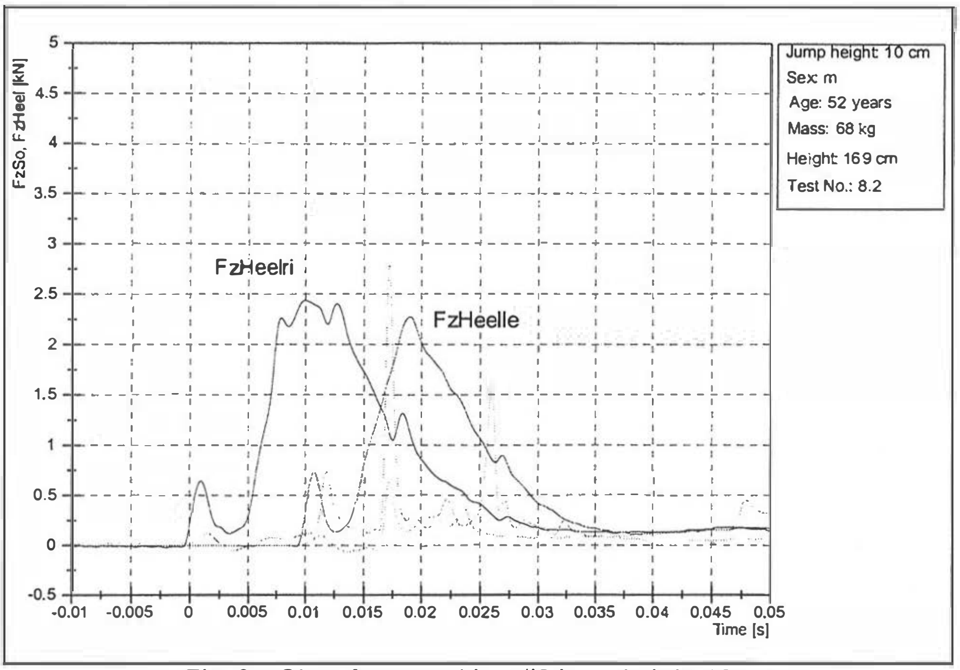

Fig. 21: Shoe forces subject #8 jump height 10 cm

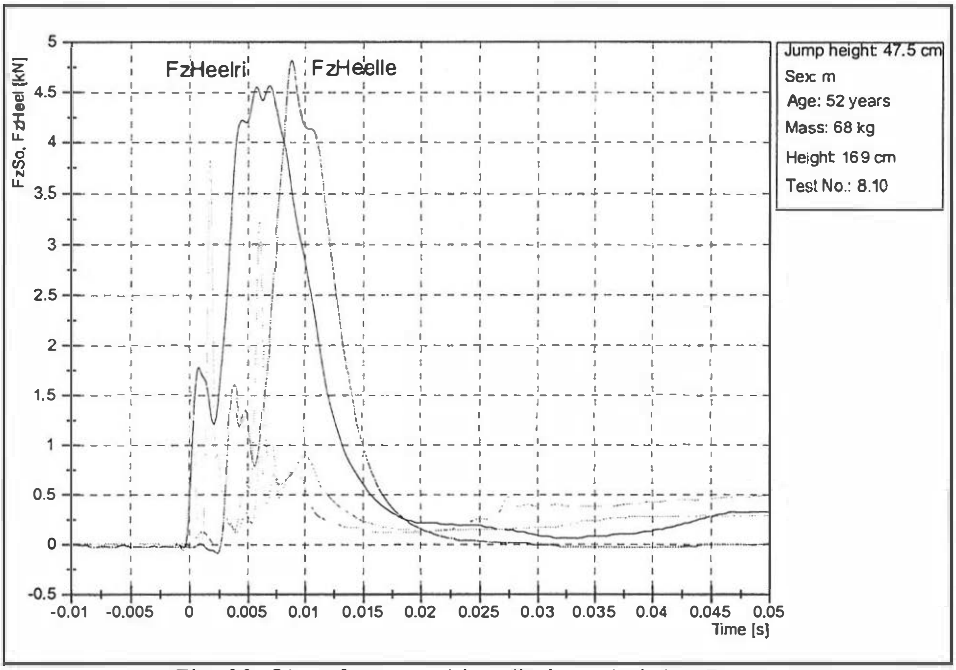

Fig. 22: Shoe forces subject #8 jump height 47,5 cm

Fig. 23 presents shoe load as a function of jump height. The subject is 169 cm tall, weighs 68 kg and has a foot length of 24.5 cm. Values of between 1.6 and 2.5 kN (heel force) are already reached for jump heights of 10 cm. For the highest jumps from 47.5 cm, loads rose up to 4.7 kN with force increasing with jump heights. With increased height, subjects tended to absorb the shock of landing inadvertently by bending their knees.

Fig. 24 & 25 show heel and sole load as a function of drop height for the tallest subject (weight 93 kg, height 192 cm, foot length 28 cm).

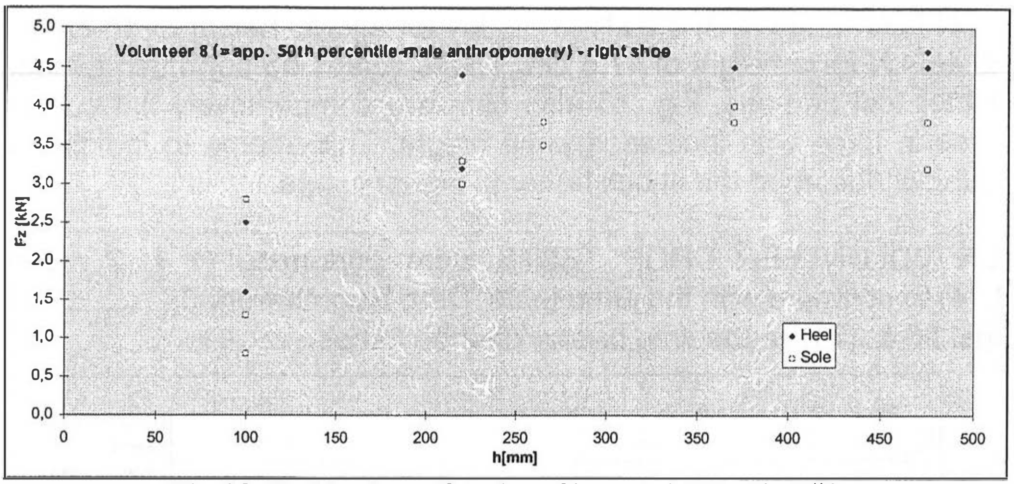

Fig. 23: Foot load as a function of jump height subject #8

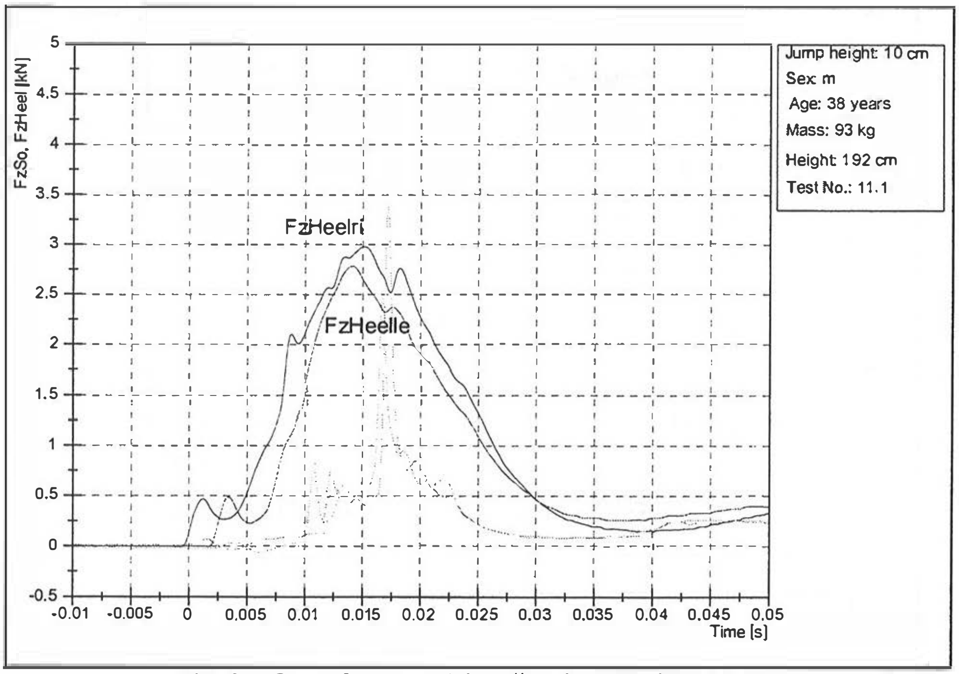

Fig. 24: Shoe forces subject #11 jump height 10 cm

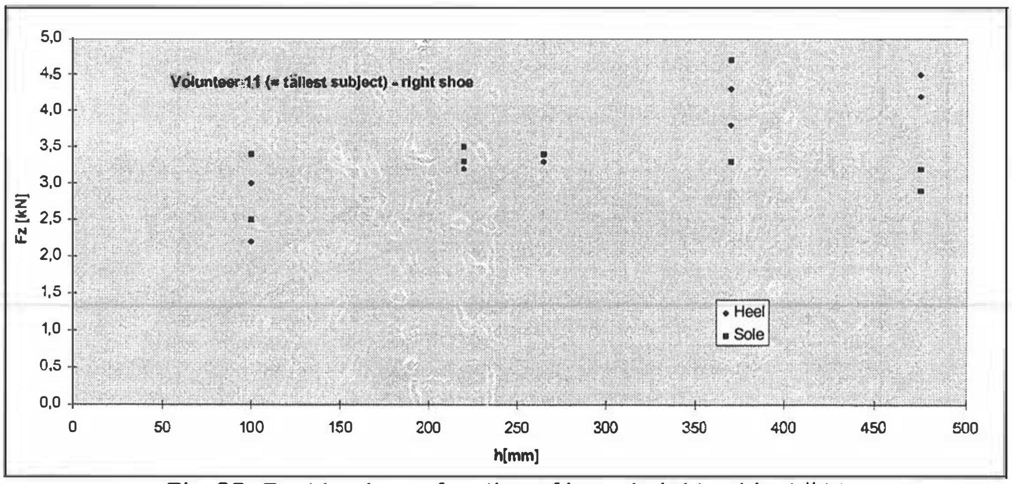

Fig. 25: Foot load as a function of jump height subject #11

Heel loads range from 2.2 kN to 3.0 kN for a jump height of 10 cm and from 4.2 to 4.6 kN for a height of 47.5 cm. These values do not much exceed those for lighter test persons. Fig. 25 also shows a comparatively flat curve for the increase in force with increased jump height. This seems to indicate that the test subject absorbed the shock better in higher jumps.

TEN VOLUNTEER DROP TESTS were performed (1 f, 2 m; subjects 9,13,14) to compare with the jump tests. Drop heights were $5 \leq h_{drop} \leq 10$ cm.

Figs. 26 & 27 give the time history of shoe forces.

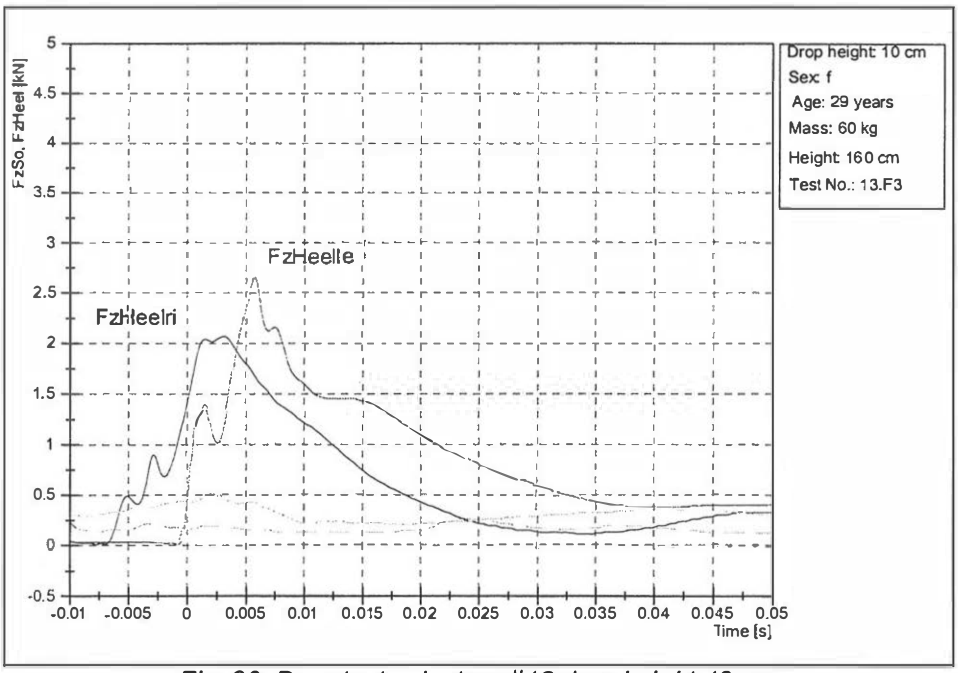

Fig. 26: Drop test volunteer #13 drop height 10 cm

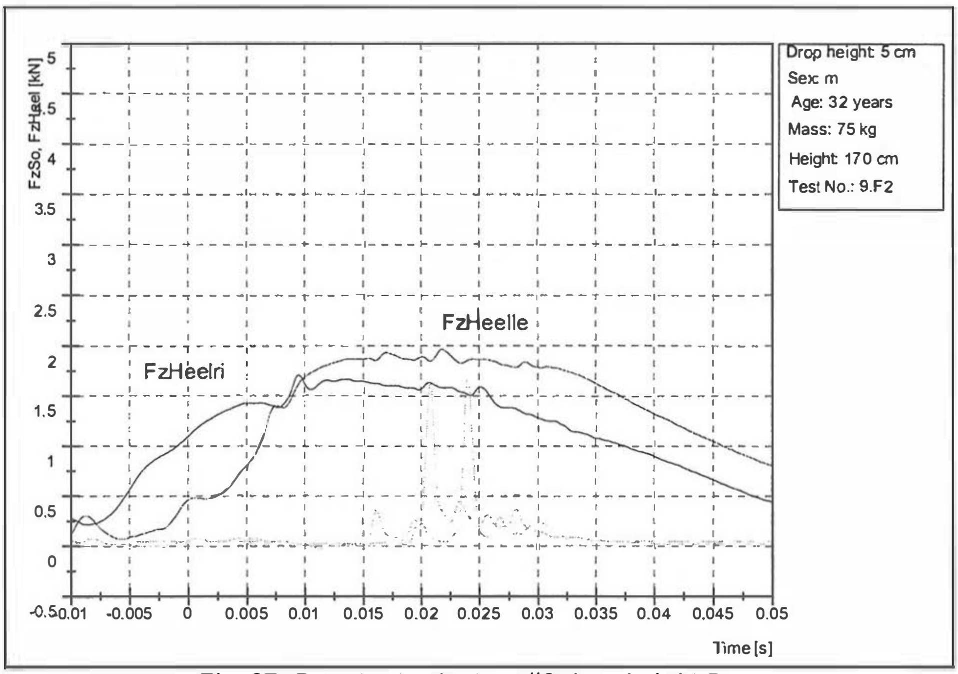

Fig. 27: Drop test volunteer #9 drop height 5 cm

Both male subjects stopped the experiment after the second test at a height of h_{drop}=5 cm. The outstretched posture (subjects were holding on to the release mechanism) and the comparatively hard measuring shoes combined to give them a strong blow which was transmitted through the spine to the base of the skull and momentarily caused slight discomfort. The lower extremities were not affected.

The graphs show quite clearly that the subjects could not absorb the impact energy through the sole and through bending of the knees as in the jump tests, which is why they first hit the ground hard with the heel. The force-time-histories also show that the interval of increased loading is much longer than for the jump tests.

The female test subject suffered no serious discomfort. She absorbed the shock of landing with a reflex bending of the knees, maybe because she is a well trained sportswoman.

DISCUSSION

The loading of various body regions was meant to exceed the Euro-NCAP 'green' rating. This aim was not achieved for all of them, because test subjects reached their individual tolerance levels. Neither was an identical instrumentation of dummies and volunteers feasible. Therefore comparisons were drawn mostly between impact loads for dummies and volunteers and dummy protection criteria will be judged indirectly on the basis of volunteer tests.

THORAX IMPACT TESTS show good linearity for acceleration and deformation as a function of impact load. This indicates a good repeatability of the dummy tests. Volunteer loads were scattered up to 50% due to the different reactions and constitutions. The dummy thorax impact tests imitating Patrick's volunteer tests resulted in an acceleration of 16 g at the thorax centre of gravity. Thorax deformation of d_{Th} = 21,4 mm closely approximated the 'green' Euro-NCAP rating (d_{Th} = 22 mm).

Patrick, however, measured a volunteer thorax deformation of 46 mm on the basis of high speed films, which points to the high stiffness of the Hybrid III thorax. A calculation of the Viscous Criterion for the dummy test yielded a value of VC=0.14 m/s which is not critical compared to the green rating threshold value of VC=0.5 m/s.

TIBIA INDEX AND TCFC (Tibia Compression Force Criterion) were tested by drop tests with the HIII dummy and in volunteer jump tests. Both criteria were taken and evaluated for dummy upper and lower tibias, whereas the volunteer measuring shoe loads were used in comparison.

There was good agreement between corrected shoe forces and dummy lower tibia forces in z-direction. There were no striking differences between dummy tests with measuring shoes or normal shoes in either tibia force F_z or TI. Slight variations are probably due to differences in touching the ground, as the dummy could be positioned more exactly without measuring shoes. Neither do force-time-histories vary to any considerable extent.

The green rating threshold of TI= 0.4 is reached for a drop height of h_{drop}=20 cm in dummy drop tests and a TCFC of 2 kN, equally suggested as threshold value, already at h_{drop}=10 cm.

Volunteer jump tests yielded similar results concerning compression force. Volunteers tolerated a shoe force of 4 kN without permanent damage, although some slight pain on the sole of the foot occurred twice with a delay of 24h, probably due to the stiff sole of the measuring shoes.

This seems to indicate that the Euro-NCAP green rating of TCFC= 2kN is too low and should be raised to TCFC = 4 kN.

The tibia forces recorded on the dummy were evidently higher than for the volunteers for bigger drop heights. The Instrumented Leg is much stiffer and less flexible than the human lower extremities and thus only roughly comparable.

For a drop height of h_{drop}=40 cm and bended knees, the upper Tibia Index recorded on the dummy was TI=0.8. As volunteers tolerated jumps from an even bigger height without injury, a threshold value of TI=0.4 for the Instrumented Leg seems to be too high. The use of an enhanced measuring tool for the lower extremities is therefore strongly recommended.

Dummy validation tests using 3-5 HIII dummies employed and calibrated in various laboratories might be very useful. A variation of measuring values of up to 20-25% could be expected. This might have a huge influence on the fixing and assessment of rating criteria, as dummy deviation might exceed the rating brackets.

ACKNOWLEDGEMENTS

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Special thanks to all our volunteer colleagues.

LITERATURE

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Appendix

Table 1: Thorax impact Dummy

Test No.	Pendulum				Head		Neck			Thorax				VC
Dummy	drop height	velocity	acc.	Force	acc.	acc.	Force	Force	Moment	back	c.g.	c.g.	Defl.	VC
HIII 50%	h_{Pd}	v_{imp}	a_{Pd}	F_{Pd}	a_{Cx}	a_{Cz}	F_{Nx}	F_{Nz}	M_{Hy}	a_{Bx}	a_{Thx}	a_{Thz}	d_{Th}	
	[mm]	[m/s]	[g]	[N]	[g]	[g]	[N]	[N]	[Nm]	[g]	[g]	[g]	[mm]	[m/s]
D2.42	132	1,59	7,07	955,8	-2,6	1,7	97	67,83 / -69,80	10,9	-4,6	-2,6	0,9	6,7	0,017
D2.43	132	1,59	6,95	946,2	-2,5	1,6	101	68,69 / -71,21	10,8	-4,7	-2,7	0,9	6,5	0,015
D2.44	143	1,65	7,32	994,3	-2,6	1,6	106	70,10 / -71,14	11,4	-5,4	-2,9	1,0	6,5	0,015
D2.45	143	1,65	7,17	984,3	-2,6	1,6	104	71,21 / -69,06	11,4	-4,8	-2,8	0,9	6,8	0,012
D2.46	163	1,76	7,51	1023,4	-3,0	1,8	109	77,07 / -72,55	12,4	-5,8	-3,1	1,0	7,3	0,015
D2.47	163	1,76	7,58	1044,2	-2,9	1,8	111	73,8 / -73,35	12,4	-6,0	-3,1	1,0	7,5	0,019
D2.48	184	1,88	7,97	1095,2	-3,1	1,8	122	78,59 / -79,15	13,4	-6,4	-3,3	1,1	8,1	0,022
D2.49	184	1,87	7,94	1083,3	-3,0	1,8	120	80,6 / -80,02	13,3	-6,3	-3,2	1,0	8,3	0,022
D2.50	200	1,96	8,29	1132,2	-3,1	1,9	128	83,05 / -75,6	14,2	-6,8	-3,3	1,1	8,6	0,021
D2.51	200	1,97	8,32	1135,5	-3,2	1,9	126	81,62 / -81,57	14,3	-6,7	-3,4	1,0	8,8	0,025
D2.52	400	2,75	11,32	1550,3	-4,5	2,6	184	114,02 / -98,82	20,2	-9,5	-5,1	1,5	13,5	0,054
D2.53	400	2,75	10,79	1474,5	-4,0	2,6	161	121,61 / -103,99	18,5	-8,6	-4,8	1,5	13,0	0,048
D2.54	200	1,94	7,8	1065,3	-3,0	1,5	115	67,19 / -58,02	13,8	-6,4	-3,0	0,8	9,4	0,031
D2.55	200	1,94	7,74	1064,8	-3,0	1,5	121	67,27 / -66,83	14,3	-5,5	-3,1	0,6	9,4	0,038
D2.56	250	2,19	8,4	1142,2	-3,4	2,2	135	98,32 / -92,69	14,5	-9,4	-3,7	1,1	10,5	0,031
D2.57	250	2,18	8,57	1165,1	-3,4	2,0	136	90,93 / -86,48	15,1	-8,5	-3,8	1,1	10,2	0,026
D2.58	200	1,97	10,63	1449,8	-4,2	3,1	162	116,64 / -81,71	16,3	-6,3	-4,8	1,3	9,4	0,041
D2.59	200	1,95	10,68	1477,4	-4,4	3,2	159	114,95 / -79,71	16,5	-6,7	-4,8	1,3	9,1	0,033
D2.60	250	2,18	11,79	1614,4	-4,7	3,3	169	125,89 / -89,78	18,5	-7,3	-5,5	1,5	10,5	0,039
D2.62	250	2,18	10,26	1414,2	-3,7	1,4	146	64,01 / -54,09	16,3	-5,1	-3,6	0,8	9,7	0,029
D2.63	250	2,24	10,31	1416,4	-3,8	2,6	146	70,95 / -41,21	16,5	-4,8	-3,6	0,8	9,8	0,032
D2.65	770	4,00	19,49	2666,5	-6,9	5,1	281	211,87 / -131,19	31,2	-15,5	-10,2	2,2	21,4	0,14
D2.66	770	4,01	19,07	2649,7	-7,0	4,2	283	187,53 / -122,49	32,0	-15,8	-9,5	1,7	21,3	0,148

Table 2: Thorax impact volunteers

No.	Anthropometric data							Pendulum				Head		Thorax
	Sex	Age	Weight	Height	Th. circumf.	Th. depth	Th.- breadth	Drop height	velocity	acc.	Force	acc.	acc.	Back
			m_B	l_K	$circ_{Th}$	h_{Th}	b_{Th}	h_{Pd}	v_{imp}	a_{Pd}	F_{Pd}	a_{Cx}	a_{Cz}	a_{Bx}
		[J]	[kg]	[cm]	[cm]	[cm]	[cm]	[mm]	[m/s]	[g]	[N]	[g]	[g]	[g]
1.1	m	59	72	173	98	22,6	34,5	102	1,49	2,7	366,7	n.g.	n.g.	2,5
1.2	m	59	72	173	98	22,6	34,5	128	1,40	3,4	469,8	n.g.	n.g.	2,9
1.3	m	59	72	173	98	22,6	34,5	128	1,57	3,9	535,6	n.g.	n.g.	3,1
2.4	m	35	74,5	177,5	95,5	23,2	31,8	126	1,48	2,5	330,3	n.g.	n.g.	1,7
2.5	m	35	74,5	177,5	95,5	23,2	31,8	121	1,51	2,2	301,7	n.g.	n.g.	1,8
2.6	m	35	74,5	177,5	95,5	23,2	31,8	141	1,60	2,9	397,5	n.g.	n.g.	2
2.7	m	35	74,5	177,5	95,5	23,2	31,8	143	1,64	3,3	447,6	n.g.	n.g.	2,5
3.8	m	29	80	178	101	24,5	32,2	143	1,68	3,2	447,6	n.g.	n.g.	2,7
3.9	m	29	80	178	101	24,5	32,2	143	1,68	3,3	444,4	n.g.	n.g.	2,8
3.10	m	29	80	178	101	24,5	32,2	163	1,78	3,7	514,8	n.g.	n.g.	3
4.11	w	23	59,5	164,5	84	19,3	26	132	1,54	2,6	343,5	n.g.	n.g.	3,9
4.12	w	23	59,5	164,5	84	19,3	26	142	1,65	2,5	337,6	n.g.	n.g.	4,1
4.13	w	23	59,5	164,5	84	19,3	26	143	1,65	2,7	381,2	n.g.	n.g.	4,4
5.14	w	25	70	173	91	19,8	28,5	132	1,60	2,5	346,7	n.g.	n.g.	3
5.15	w	25	70	173	91	19,8	28,5	143	1,66	2,9	396,1	n.g.	n.g.	2,6
5.16	w	25	70	173	91	19,8	28,5	143	1,66	2,8	378,9	n.g.	n.g.	3,1
6.26	w	36	57	165	83	19,2	27,3	132	1,58	2,5	345,9	2,2	2,5	3,4
6.27	w	36	57	165	83	19,2	27,3	144	1,65	2,8	383,9	2,4	3,1	3,9
6.28	w	36	57	165	83	19,2	27,3	153	1,71	2,4	332,7	2,0	2,4	3,3
7.29	w	22	54,5	164,5	83	17,9	26,9	132	1,59	2,1	284,8	3,1	2,6	4,2
7.30	w	22	54,5	164,5	83	17,9	26,9	143	1,64	2,4	321,5	3,7	3,1	3,7
7.31	w	22	54,5	164,5	83	17,9	26,9	153	1,71	2,3	312,4	3,3	2,8	4,1
7.32	w	22	54,5	164,5	83	17,9	26,9	163	1,77	2,3	329,8	3,3	2,5	4,6
8.33	m	52	68	169	94	23,4	30,4	163	1,77	3,4	470,8	3,8	3,2	4
8.34	m	52	68	169	94	23,4	30,4	184	1,86	3,8	517,6	2,8	2,7	4,7
8.35	m	52	68	169	94	23,4	30,4	200	1,96	4,0	554,4	3,2	3,3	5,1
2.36	m	35	74,5	177,5	95,5	23,2	31,8	163	1,76	2,9	393,0	2,7	2,3	2,6
2.37	m	35	74,5	177,5	95,5	23,2	31,8	184	1,88	3,4	457,5	2,9	2,7	3
2.38	m	35	74,5	177,5	95,5	23,2	31,8	200	1,97	3,7	514,6	2,9	2,8	3,8
1.39	m	59	72	173	98	22,6	34,5	163	1,77	4,3	586,5	1,9	1,7	4,5
1.40	m	59	72	173	98	22,6	34,5	184	1,88	4,7	652,4	1,9	1,5	4,4
1.41	m	59	72	173	98	22,6	34,5	200	1,95	5,1	691,7	2,3	1,8	4,3
9.67	m	32	75	170	101	25	33	180	1,83	4,8	666,1	2,9	2,5	3,6
9.68	m	32	75	170	101	25	33	200	1,94	4,8	662,9	2,6	2,7	3,75
9.69	m	32	75	170	101	25	33	250	2,17	6,2	847,3	2,6	2,7	4,11
9.70	m	32	75	170	101	25	33	250	2,17	4,9	671,4	2,8	3,1	4,68

Table 3: Dummy drop tests

Test No.	Drop height [cm]	Force [kN] right Heel	right Sole	right Lower Tibia	left Heel	left Sole	left Lower Tibia	Tibia Index TI lower right	lower left	upper right	upper left	Comments
13	5	1,6	-	1,5	1,6	0,2	1,5	0,13	0,10	0,18	0,20	Dummy legs
14	5	1,5	-	1,4	1,5	0,3	1,4	0,13	0,10	0,16	0,15	bent
12	10	2,3	0,8	2,2	2,3	0,6	2,2	0,13	0,11	0,28	0,34	
11	10	2,7	0,7	2,7	2,1	0,5	2,0	0,18	0,11	0,36	0,32	
10	15	3,2	1,5	3,0	3,0	1,1	2,8	0,19	0,19	0,40	0,39	
9	15	3,5	0,3	3,2	3,0	0,3	2,8	0,21	0,18	0,40	0,38	
8	20	4,5	-	4,2	3,7	2,5	3,5	0,31	0,26	0,50	0,45	
7	20	3,2	1,0	3,6	3,0	3,0	2,7	0,26	0,18	0,40	0,40	
15	40	7,0	3,0	6,6	6,6	2,5	6,4	0,42	0,41	0,88	0,82	
1	20	4,6	1,8	5,4	6,0	2,7	7,0	0,35	0,43	0,65	1,00	Dummy legs
2	20	5,3	1,2	5,0	5,4	2,0	5,1	0,38	0,30	0,73	0,68	roughly straight
3	30	8,5	2,1	9,7	8,5	4,6	9,6	0,63	0,67	1,30	1,20	
4	30	7,6	2,0	8,2	7,3	2,3	8,0	0,56	0,56	1,06	1,06	
5	40	9,0	2,3	10,0	8,6	3,3	10,5	0,82	0,70	1,42	1,23	
6	40	11,0	2,0	11,5	9,5	3,0	10,0	0,8	0,70	1,64	1,38	
16	20			3,9			3,6	0,22	0,21	0,50	0,54	Dummy with
17	20			3,0			3,4	0,2	0,25	0,38	0,45	normal shoe
18	30			4,7			5,2	0,31	0,36	0,63	0,66	
19	30			5,4			4,6	0,36	0,33	0,65	0,60	(cf. Test No. 7-15)
20	20			6,1			5,6	0,41	0,41	0,80	0,79	Dummy position
21	20			6,0			6,2	0,41	0,42	0,77	0,85	cf. Test No. 1-6

Volunteer jump tests

Table 4: Volunteer 10

Volun. No.	Drop height [mm]	Fz [kN] Heel right	Heel left	Sole right	Sole left
10	100				
	100				
m_B=62 kg	220	2,0	1,3	2,0	2,3
l_B=180 cm	220	2,2	2,5	2,2	2,4
l_F=27,5 cm	265	3,0	2,8	3,4	2,8
	265	2,6	2,7	2,7	2,9
	370	3,0	2,7	1,5	2,4
	370	2,3	2,8	3,7	2,7
	475	3,2	3,4	4,9	3,5
	475	3,1	3,5	4,4	3,8

Table 5: Volunteer 9

Volun. No.	Drop height [mm]	Fz [kN] Heel right	Heel left	Sole right	Sole left
9	100				
	100				
m_B=75 kg	220				
l_B=170 cm	220				
l_F=25 cm	265	2,6	3,1	1,7	2,0
	265	3,4	3,5	1,9	1,5
	370				
	370				
	475	3,6	4,3	3,7	4,0
	475	3,5	4,5	1,7	3,3

Table 6: Volunteer 8

Volun. No.	Drop height [mm]	Fz [kN] Heel right	Heel left	Sole right	Sole left
8	100	1,3	1,8	0,8	1,4
	100	2,5	2,3	2,8	1,6
	100	1,6	1,3	1,3	1,7
m_B=68 kg	220	3,2	3,0	3,3	1,8
l_B=169 cm	220	4,4	3,8	3,0	2,2
l_F=24,5 cm	265	3,5	3,4	3,8	2,3
	265	3,5	2,9	3,5	3,8
	370	4,5	4,0	4,0	3,2
	370	4,0	3,7	3,8	2,3
	475	4,5	4,8	3,2	3,8
	475	4,7	4,1	3,8	3,1

Table 7: Volunteer 11

Volun. No.	Drop height [mm]	Fz [kN] Heel right	Heel left	Sole right	Sole left
11	100	3,0	2,8	3,4	2,5
	100	2,2	1,8	2,5	2,7
m_B=93kg	220	3,3	3,6	3,3	1,4
l_B=192cm	220	3,2	3,5	3,5	1,7
l_F=28cm	265	3,4	3,2	3,4	4,3
	265	3,3	3,0	3,4	4,3
	370	3,8	3,2	3,3	3,6
	370	4,3	3,6	4,7	4,9
	475	4,2	4,5	2,9	3,4
	475	4,5	4,8	3,2	3,8

Tabelle 8: Volunteer 12

		Fz [kN]			
Volun. No.	Drop height [mm]	Heel		Sole	
		right	left	right	left
12	100	2,5	2,1	1,9	2,0
	100	2,9	2,8	2,5	2,0
m_B=64 kg	220	3,8	3,6	2,3	1,9
l_B=172 cm	220	3,9	3,5	2,9	3,0
l_F=24,5 cm	265	3,5	3,3	1,6	1,9
	265	3,8	3,3	2,1	1,9
	370	3,7	3,3	2,2	2,3
	370	3,9	3,0	0,8	0,8
	475	4,2	3,5	4,2	3,8
	475	4,2	3,2	3,5	5,1

Tabelle 9: Volunteer 6

		Fz [kN]			
Volun. No.	Drop height [mm]	Heel		Sole	
		right	left	right	left
6	100	0,6	1,0	1,5	1,2
	100	1,4	1,1	1,2	-
m_B=57 kg	220	1,2	1,5	1,6	1,3
l_B=165 cm	220	1,3	1,9	1,1	1,9
l_F=25 cm	265	2,6	1,3	2,4	1,6
	265	2,6	1,4	2,4	1,6
	370	2,1	1,5	2,5	2,8
	370	2,6	2,4	2,2	2,3
	475	2,4	2,7	1,9	2,0
	475	3,3	2,3	2,0	1,6

Tabelle 10: Volunteer 1

		Fz [kN]			
Volun. No.	Drop height [mm]	Heel		Sole	
		right	left	right	left
1	100	2,1	1,4	1,3	0,8
	100	1,7	1,5	2,8	1,0
m_B=70 kg	220	3,8	2,5	1,3	3,1
l_B=173 cm	220	3,3	2,4	2,5	2,4
l_F=26,5 cm	265	2,6	2,4	3,0	3,1
	265	2,8	2,5	1,4	2,9
	370	3,7	1,9	2,7	1,1
	370	3,2	2,8	3,4	2,7
	475	4,5	2,0	1,5	3,3
	475	4,1	3,4	2,7	2,5

Tabelle 11: Volunteer 13

		Fz [kN]			
Volun. No.	Drop height [mm]	Heel		Sole	
		right	left	right	left
13	100	2,0	1,3	1,3	0,8
	100	1,8	1,2	2,5	2,4
m_B=60 kg	220	2,7	1,8	1,9	2,5
l_B=160 cm	220	2,5	2,4	3,2	1,1
l_F=23,3 cm	265	2,4	3,1	3,1	1,7
	265	3,1	3,0	2,9	1,6
	370	3,2	3,6	3,0	2,0
	370	3,0	3,6	3,6	2,3
	475	4,1	4,6	2,8	1,7
	475	4,2	3,5	3,0	3,5