ASSESSMENT OF MECHANICAL PROPERTIES OF THE HUMAN SKULL-CAP THROUGH BASIC BIOMECHANICAL TESTS AND QUANTITATIVE COMPUTED TOMOGRAPHY (QCT)

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Abstract

204 basic quasistatic load tests of 3 different test types (compression test, tensile test, shear test) were performed on fresh skull-bone specimens to determine the mechanical properties of the human skull-cap bone (Os parietale). For all tests a universal tensile test machine with measurement and documentation equipment was used at load velocities of 0,1 mm/s.

In addition to these tests Quantitative Computed Tomography (QCT) was applied to measure selectively the bone mineral density of the same parietal bone specimens. The aim was, to validate the QCT for the assessment of mineral bone density in the skull-bone in vivo and to define a predictive value for the individual mechanical properties. Geometric parameters, mechanical properties and the mineral content were determined to validate the QCT.

1 Introduction

Part of a current research project*) was a series of basic load tests on isolated bone specimens of the human skull-cap. This project dealt with a critical estimation and validation of Head Injury Criteria and the formulation of a Finite-Element-Method (FEM) model of the human head. Informations about the biomechanical behavior of the human skull-bone and a correlation between Quantitative Computed Tomography (QCT)-measurements and the biomechanical properties of the skull-bone was the main goal of these tests.

This research project was realized in a collaboration between the Technische Universität, Berlin (formulation of a FEM-model), and the Universität Heidelberg. This paper contains data of 204 quasistatic load tests (94 QCT-measurement sets) of the following 3 test types:

a) compression tests	n = 81	(64)
b) tensile tests	n = 50	(0)
c) shear tests	n = 73	(30)
Total number of tests :	n = 204	(94)

Devices were designed and manufactured for each load test to fix and load the specimens.

Diagrams of force and displacement were recorded from each test describing the mechanical characteristics of the skull-bone, especially of the spongiosa. These diagrams gave the basic data to be implemented in a FEM-model of the human skull. At the Institut für Fahrzeugtechnik of the Technische Universität, Berlin, work is still in progress developing and improving such a model.

Concerning the QCT-measurments several authors found a relationship between bone mineral density, the strength of this bone and the individual risk for fracture (Kleerehoper et al. 1985, Black et al. 1992). QCT has the ability to measure selectively the bone mineral density (Cody et al. 1989). Up to now standard QCT procedures have been limited to the vertebral column and the forearm. The aim of the study was to validate the QCT for the assessment of mineral bone density in the skull-bone in vivo and to evaluate a predictive value for the individual mechanical properties.

2 Material and Methods

2.1 Bone specimens

The bone specimens for the load tests were taken from fresh human cadavers. After the preparation of the skull, 2 parts (size: 20 x 50 mm) in symmetrical location to the sagittal plane (see figure 2.1) were taken out of the skull-cap using an oscillating saw.

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The specimens were prepared specially for each test type. The specimens´ final size for compression and shear tests was 10 x 10 mm and the size for the tensile tests was 20 x 20 mm. The individual geometrical parameters of the specimens were measured (total thickness (TT), thickness compacta interna (TCI) and externa (TCE) and thickness spongiosa (TS)). The density (D) of each specimen was determined from weight and water volume displace.

Up to the test performance the specimens have been stored under controlled conditions at a temperature of -20° Celsius. QCT was performed from 94 of these specimens before load test in order to correlate QCT-data with the quantitative results of the load tests.

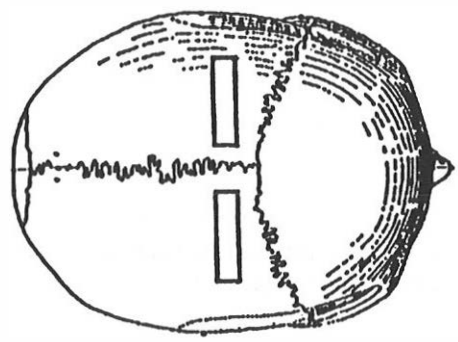


Figure 2.1: location of the specimens in the skull-bone

2.2 Test performance

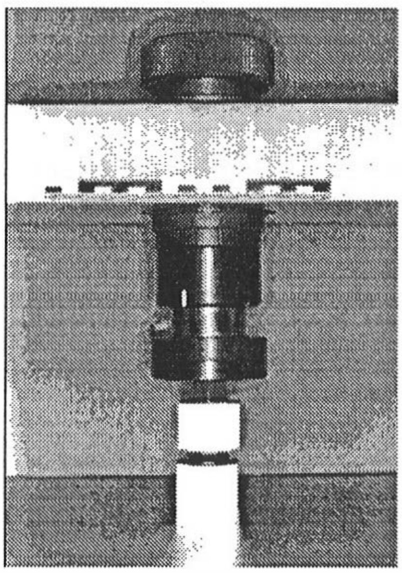
A calibrated universal tensile test machine of the manufacturer "Roell & Korthaus ", type RKM 50 was used for all load tests. The load velocity in all tests was 0,1 mm/sec. The force-displacement diagrams were recorded by an x-y-plotter.

2.2.1 Compression tests (n = 81)

Special specimen holders (see fig. 2.2 and 2.3) have been constructed and manufactured of Duralumin (horizontal and vertical length 40 x 40 mm). The corresponding planes of the holder pairs are convex (radius 70 < r < 100 mm) to fit both the convexity of the specimens and the holder planes.

Two load types of the compression tests were executed:

a) steady axial load up to 80% of the thickness of the specimen
b) steady axial load up to 55% of the adjusted switch-off load (2000 daN) of the test machine (after testing the probably collapse load) with deloading to 0 daN and reloading like a.) to gain the hysteresis of relaxation.



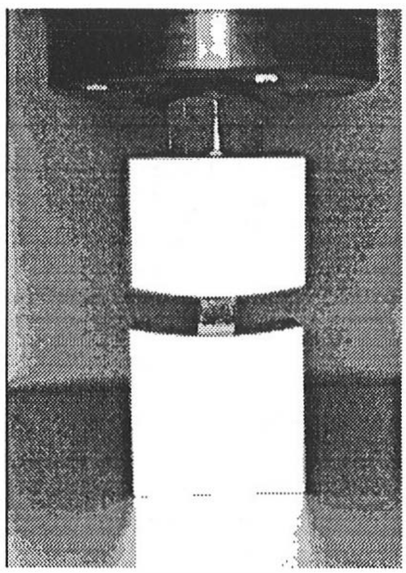


Figure 2.2; 2.3: set-up of the compression tests

2.2.2 Tensile tests (n = 50)

Due to the varying anatomy, i.e. geometry of the specimens, and due to the required high precision a special construction was necessary (see figure 2.4 and 2.5)."Pin holders" for the specimens have been designed and manufactured. The special feature is the distance between the drill holes, 6 drill holes (r = 1.6 mm) on each side and a difference of the corresponding part of 13 mm. The construction is available for others.

Parts of 20 x 20 mm were prepared from the main specimens in order to fit the specimens into the "pin holder". The spongiosa between compacta externa and interna was taken away (5 mm) on all 4 sides in a way that a square part of 10 x 10 mm with all three components remained. The square part was secured before by 4 parallel drill holes (r < half of the thickness of the spongiosa). Then the compacta interna and externa (around the square) were drilled 6 times. The drill holes were placed in the manner that one drill hole ends at the corresponding compacta.

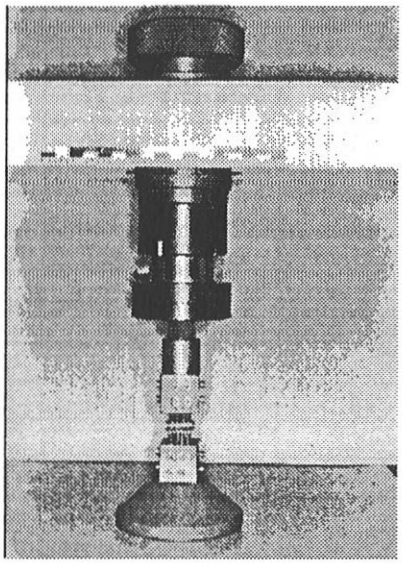
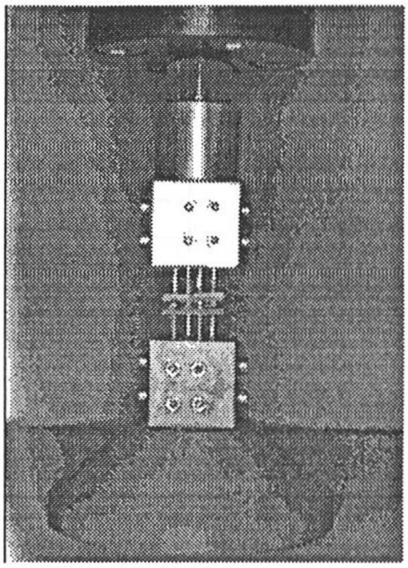


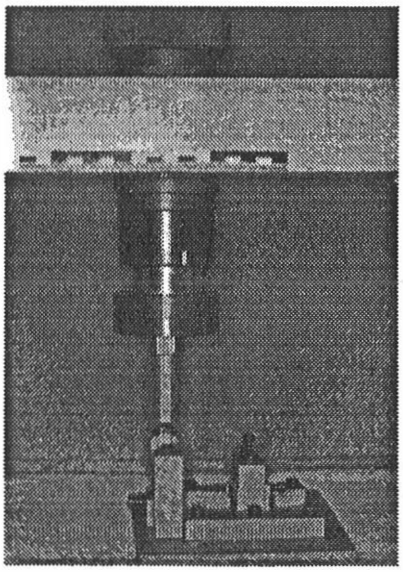
Figure 2.4, 2.5: set-up of the tensile test



2.2.3 Shear tests (n = 73)

The holders for the specimens have been constructed to stress the object vertically (see figure 2.6 and 2.7). The holder consists of 2 main parts, upper (vertically adjustable) and lower part (horizontally adjustable). The fitting of the specimens was done carefully (without preload). The specimens were exactly hold in position by a support.

Out of the main specimens square parts were prepared (10 x 10 mm). The lateral faces had to be parallel.



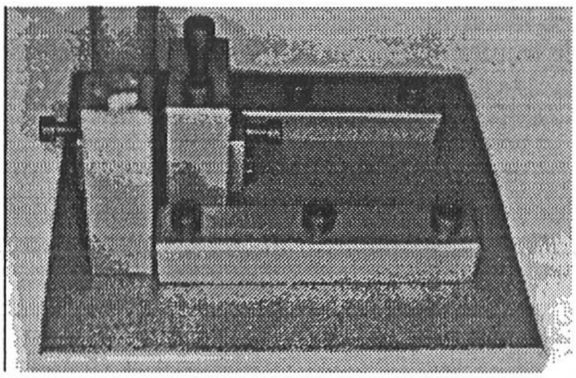


Figure 2.6, 2.7: set-up of the shear tests

3 Results and Discussion of the Quasistatic Load Tests

The below mentioned individual data and circumstances must be taken into account, to assess the results correctly:
Sex, age, health, localisation of separation and preparation of the specimens, individual characteristics of the specimens (e.g. mineralisation), individual characteristics of the structure (macroscopic geometry e.g. thickness of compacta interna / externa and spongiosa) and microscopic aspects like the structure of the trabecular system.
Whether there are influences or not has not yet been discussed during this project because of an expected normal statistic varying.
The following table shows the values of fracture - tension and the E - modulus (compression) of al load tests .

Test type	characteristic V.	dimension	n	MV	sd	min. V.	max.V.
Compression			81				
	Fracture - tension	daN/mm^2		13.01	3.22	5.41	20.44
	E - modulus	daN/mm^2		31.38	14.45	5.56	75.28
Tensile			50				
	Fracture - tension	daN/mm^2		0.49	0.22	0.10	1.16
Shear			73				
	Fracture - tension	daN/mm^2		1.5	0.69	0.42	3.39
			204				

Table 3.1: main values (load test data)

3.1 Compression tests

Table 1, annex, pp A1, A2 shows all documented values of the 81 compression tests.
4 typical force-displacement diagrams are given as examples: each 2 diagrams of figures 3.1a and 3.1b shows the load type a) and b).
It seems, that the geometry does not influence the test significantly. The individuality of the spongiosa (e.g. compacta bridges) needs further discussion.
Compression-fracture-tension: the mean value (MV) was found at 13 daN/mm^2 (5.4 - 20 daN/mm^2). This value is lower than the results of Evans and Lissner for the parietal bone (left: 18 daN/mm^2, right: 15 daN/mm^2), but significantly higher than those of Mc Elhaney et al. (left: 3.4 daN/mm^2, right: 3.5 daN/mm^2). This may be the result of topography and geometry of the test object.
E-modulus: the mean value was 31 daN/mm^2 (5.6 - 75 daN/mm^2). These results correlate with results of Barber et al. (parietal values 66 - 77 daN/mm^2). Only the MV was twice as high as we found (72 daN/mm^2). Mc Elhaney et al. found MV 5 - 6 times higher (left: 173 daN/mm^2, right: 180 daN/mm^2).

3.2 Tensile tests

Table 2, annex, pp A3 shows all documented values of the 50 tensile tests.
Two force-displacement diagrams are given as examples in figure 3.2 .

3.3 Shear tests

Table 3, annex, pp A4, A5 shows all documented values of the 73 shear tests.
Two force-displacement diagrams are given as examples: in figure 3.3 .

No publication revealing results of either tensile tests or shear tests could be found; only tensile tests with a tangential traction load acting were described.

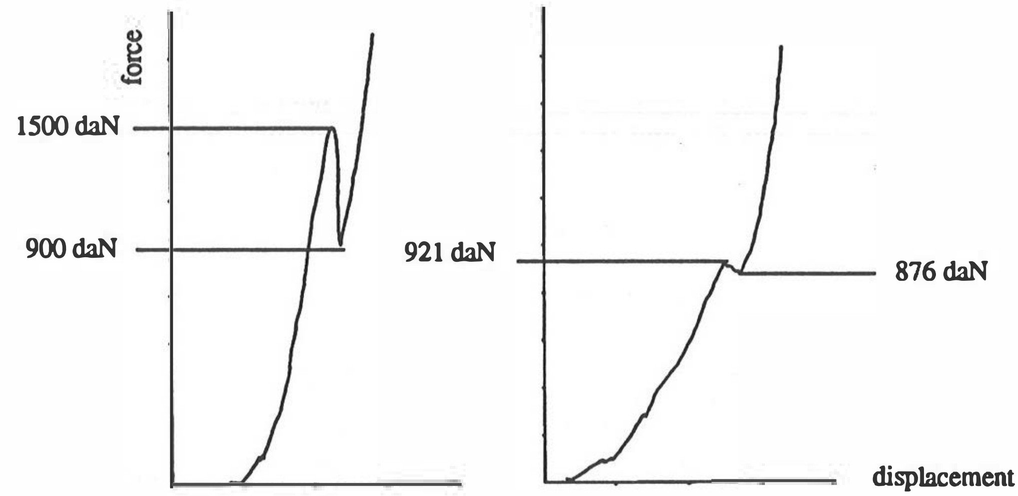


Figure 3.1a force-displacement diagram compression test, load type a)

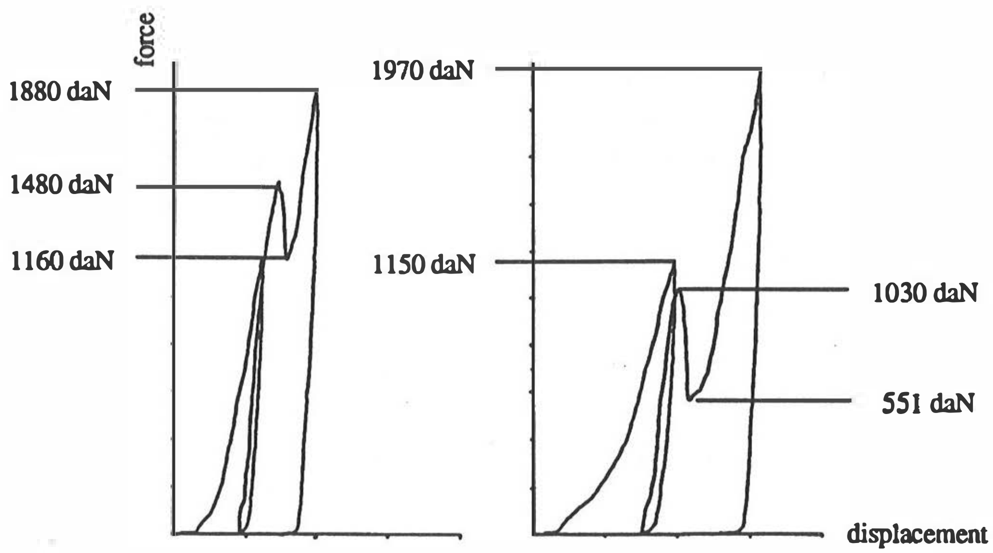


Figure 3.1b force-displacement diagram compression test, load type b)

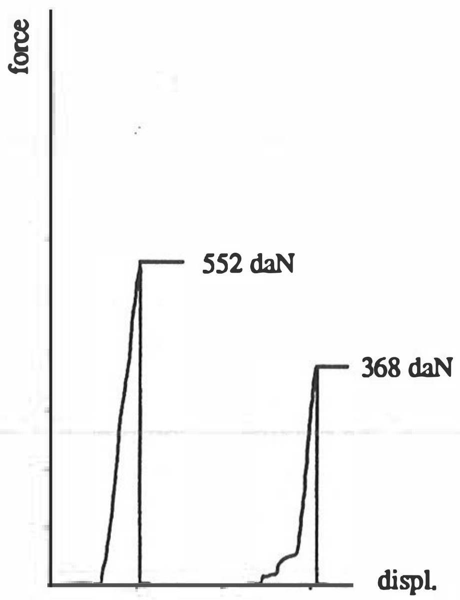


Figure 3.2: force-displacement diagram tensile test

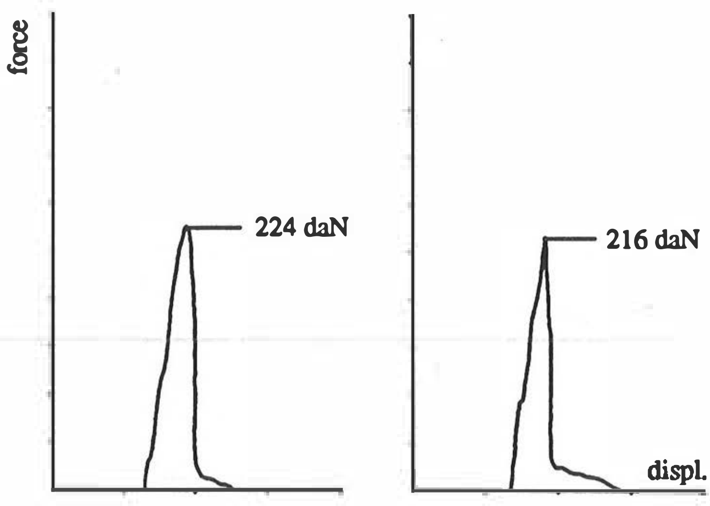


Figure 3.3: force-displacement diagram shear test

4 QCT-Measurement

Scans were taken of each specimen in the frontal and lateral plane. In our study we used a Siemens Somatom Plus CT and the Software Osteoprogramm with 120 kV, 165 mA and a zoom of 6.5 scan diameter of 40 cm and produced voxels of dimensions 0.787 x 0.787 x 1.0 mm. We selected manually regions of interest (ROI) corresponding to the inner and outer compacta and to the spongiosa. Regions of interest must be selected with care. The selections were performed manually with cursor on the computer screen. Mean value and standard deviation of each region of interest as well as the measured area were generated from the density data. The density data is given in Hounsfield units (HU).

Test type / QCT	characteristic V.	dimension	n	MV	sd	min. V.	max.V.
Compression			64				
with QCT	QCI	HU		1588	± 158.19	1139	1898
	QCE	HU		1723	± 163.99	1297	2168
	QS	HU		672	± 283.67	100.6	1446
	SQV			3.19	± 1.59	1	6
Shear			30				
with QCT	QCI	HU		1572	± 162.55	1139	1827
	QCE	HU		1727	± 132.38	1337	2001
	QS	HU		710	± 272	210	1446
	SMV			3.28	± 1.68	1	6

Table 4.1: main values (QCT data)

To compare QCT measurements, the mineral content, content of organic substance and water content (values in %) in these specimens were determined by combustion (Hunger et Leopold 1978) after mechanical tests.
Additionally, on the base of the CT-radiograph, we discerned for the whole specimens 6 patterns (semiquantitative values (SQV)) of cancellous bone correlating with trabecular macromorphology and density appearances:

SQV 1	dense homogeneous	SQV 4	soft-homogeneous
SQV 2	dense, only few clearings	SQV 5	soft, only few clearings
SQV 3	many clearings	SQV 6	soft, many clearings

4.1 Statistical methods

Statistical analyses were performed using analysis of variance (significance was accepted at the 0.05 probability level) and Spearman Correlation analysis.
Continous data is presented as mean value and standard deviation.
The probability to predict mechanical properties (compression-fracture-tension (CFT) and shear-fracture-tension (SFT)) as function of geometrical data, QCT-data and age - either as function of the age alone - was calculated using standard logistic regression models. Those regression models were weighted by the goodness of fit models. For this procedure the continual values CFT and SFT have to be transformed in ordinal values.
The analysis of goodness of fit gives the ratio of correctly predicted observations (PRED). This means a number of correctly predicted observations, i.e. the maximum compression tension, divided by the total number of observations. This analysis also gives the mean probability difference (PDIF). This means the absolute difference between the estimated probabilities for the predicted mechanical properties (table 4.2).
For the statistical analysis only the mean values of measurements were used, since there was a strong correlation between the measurements in frontal and lateral plane (QCT-data) concerning outer compacta (QCE): $r = 0.57$, $p < 0.0001$, inner compacta (QCI): $r = 0.64$, $p < 0.0001$, spongiosa (QS): $r = 0.7$, $p < 0.0001$.

4.2 Results and discussion - QCT measurement

4.2.1 Correlation between QCT-data and biological data

Many authors found that the CT-numbers (or HU) represent only an average of the attenuation coefficients of all the materials to be found in the bone, including mineral content, collagen, organic substance, water and fat. Therefore an error could be introduced by the variable fat content which can vary regionally in the obtained specimens from the same individuum. Some authors revealed an error up to 20% for vertebral bodies (Cann 1988, Fischer et al. 1993). Therefore, we determined whether there is a correlation between the density, the real mineral content determined by combustion and the obtained HU.

A strong correlation was found between the QCT-data of the inner part of the compacta resp. spongiosa and bone mineral content ($r = 0.34$, $p < 0.01$, resp. $r = 0.69$, $p < 0.01$), content of water ($r = -0.29$, $p < 0.01$, resp. $r = -0.34$, $p < 0.01$) and organic substance ($r = -0.33$, $p < 0.01$, resp. $r = -0.49$, $p < 0.01$) and the spongiosa as well as for the density ($r = 0.41$, $p < 0.01$, resp. $r = 0.67$, $p < 0.01$).

The semiquantitative estimation of the macromorphological patterns of the spongiosa (SQV 1-6) revealed a strong correlation to the HU of the spongiosa determined by QCT ($r = -0.67$, $p< 0.0001$). The SQV also shows a correlation to the mineral content ($r = -0.52$, $p < 0.001$), the content of organic substance ($r = 0.5$, $p < 0.01$) and the density ($r = -0.44$, $p < 0.001$).

4.2.2 Correlation between QCT-data and mechanical properties

Compression tests

The correlation analysis shows a strong correlation between the QCT- data from QCI and the compression-fracture-tension (CFT): $r = 0.34$, $p < 0.01$.

Shear tests

The correlation analysis shows a strong correlation between shear-fracture-tension (SFT) and density ($r = 0.41$, $p< 0.05$), content of organic substance ($r = 0.39$, $p < 0.05$) and the mineral substance ($r = 0.6$, $p < 0.005$) as well as the QCT-data for spongiosa ($r = 0.60$, $p < 0.005$) and the SQV ($r = -0.64$, $p < 0.0001$).

4.2.3 Prediction model

Compression tests

For logistic regression analysis, the dependent variable (continual values of the CFT) was divided in three groups as follows:

group 1:	CFT < 10 daN/mm^2
group 2:	10 < CFT< 15 daN/mm^2
group 3:	CFT > 15 daN/mm^2

The independent variables were a combination of parameters and were named:

Model I:
age, geometrical data (TS, TCE, TCI,TT), the semiquantitative value (SQV) and the QCT values (QCI, QCE, QS);

Model II:
age, geometrical data (TS, TCI, TCE, TT) and the QCT values (QCI, QCE, QS);

Model III:
age only .

The highest reliability to predict CFT gives the model I with 76,5 % correctly predicted observations, followed by the model II with 70.3 % correctly predicted observations. If CFT has to be predicted by the age alone (model III), only 51.5 % observations are correctly predicted (table 4.2).

The frequency distribution of the 3 CFT groups according to the predicted values are shown in table 4.3 .

Shear test:
For logistic regression analysis, the dependent variable (continual values of the SFT) was divided in three groups as follows:

group 1:	SFT < 1 daN/mm^2
group 2:	1 < SFT< 2 daN/mm^2
group 3:	SFT > 2 daN/mm^2

The independent variables were:

Model I:
age, geometrical data (TS, TT), the semiquantitative value (SQV) and the QCT values (QS);

Model II:
age, geometrical data (TS, TT) and the QCT values of spongiosa (QS);

Model III:
age only .

The highest reliability to predict SFT gives the model I with 73.3 % correctly predicted observations, followed by the model II with 66.6 % correctly predicted observations.
If SFT has to be predicted by age alone (model III), only 50 % observations are correctly predicted (see table 4.2).
The frequency distribution of the 3 SFT groups according to the predicted values are shown in table 4.3.

Test	Model	PDIF	PRED
Compression	model I	10,2 %	76,5 %
	model II	9,9 %	70,3 %
	model III	10,5 %	51,5 %
Shear	model I	8,1 %	73,3 %
	model II	12,2 %	66,6 %
	model III	11,8 %	50,0 %

PDIF: Mean probability difference
PRED: Ratio of correctly predicted observations

Table 4.2: analysis of goodness of fit

frequency distribution									
	compression tests					shear tests			
	frequency Compr.	group 1	group 2	group 3	total	group 1	group 2	group 3	total
model I		7	6	0		5	1	0	
model II	group 1	6	7	0	13	3	3	0	6
model III		3	9	1		0	6	0	
model I		3	29	2		0	12	3	
model II	group 2	3	29	2	34	2	12	1	15
model III		3	26	5		0	15	0	
model I		0	4	13		0	4	5	
model II	group 3	0	7	10	17	0	4	5	9
model III		0	13	4		0	9	0	
model 1		10	39	15		5	17	8	
model II	total	9	43	12	64	5	19	6	30
model III		6	48	10		0	30	0	

Table 4.3: frequency distribution of the 3 groups - compression tests and shear tests

5 Summary and Conclusions

More basic data concerning the mechanical and functional properties of the human head should be available for the development of new models and for the optimization of existing head impact models (e.g. mathematical models, especially FEM-models, validation of human body-surrogates (dummies) including the measurement as well as approvement of head injury criteria).
Basic data of the mechanical properties of the skull-bone with an exact discription of the test design are very seldom in the literature. No results at all could be found from tensile and shear load tests of the spongiosa. For this reason methods and results of a part of numerous quasistatic basic tests are discribed and presented in this study.
Those results are related to 204 load test, which are divided into 81 compression tests, 50 tensile tests and 73 shear tests on separated fresh skull-bone specimens. All tests were performed on a universal tensile test machine at a load velocity of 0,1 mm/s.
The mean values of the fracture tension were found for compression load at 13 daN/mm^2, for tensile load at 0,49 daN/mm^2 and for shear load at 1,5 daN/mm^2.
Typical force-displacement-diagrams are shown in chapter 3. All results of the measurements are given in the annex. The original data and diagrams are implemented partially in a FEM-model of the head being developed at the Technische Universität Berlin, Institut für Fahrzeugtechnik (* see introduction).
Furthermore QCT-measurements were performed on the specimens of the compression and shear tests: for the validation of a mathematical model by reconstruction of real accidents, it is necessary to know the individual fracture load limits. From patients with survived head injuries, only age and sex are known parameters to predict the mechanical properties of the involved bone. The determination of the mechanical properties of the human skull-cap bone in patients is possible only by non-invasive clinical methods. Using QCT there is a chance to determine bone density a) non-invasively, b) separate for the cortical and cancellous bone and c) directly at the side of clinical involvement or impact.
The combination of parameters determined by QCT was found as a high predictive parameter for compression fracture tension (CFT) and shear fracture tension (SFT) with 76.5 / 73.3 % correctly predicted values, whereas by parameter age alone only 51.5 / 50 % of the values are correctly predicted.
Using QCT in such a sense, it seems to be possible to develop a method, to predict the mechanical properties of the skull-bone in vivo in patients with head injuries direct at the side of impact and to estimate the individual loading values.
Furtheron, because there is a high correlation between the measured Hounsfield units and the real mineral content determined by combustion and the density, it could be possible to compare mechanical data from survived accidents, letal accidents and in vitro tests, which could be usefull to validate a FEM-model.
The clarification of differences of comparable quasistatic and dynamic tests is an aspect to perform dynamic tests on similar specimens with similar impact design to quasistatic tests.

Annex :

Tables 1 - 3, pages A1 - A5 of the annex show the data of all **204** quasistatic load tests.

table 1 ,	pages A1, A2	data compression tests
table 2 ,	page A3	data tensile tests
table 3 ,	pages A4, A5	data shear tests

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			Data Compression Tests (incl. data QCT)						(n=81)										
T. Nr.	Age	Sex	TT	TCE	TCI	TS	D	CFT	PEM	WCC	WCS	OCC	OCS	MCC	MCS	SQV	QCI	QS	QCE
	(year)		(mm)	(mm)	(mm)	(mm)	g/cm3)	(daN/mm2)		%	%	%	%	%	%		(HU)	(HU)	(HU)
P 001	18	f	6,97	1,57	1,88	3,52	1,57	10,42	19,76	13,27		30,94		55,79		3,00	1628	346	1801
P 002	86	m	3,75	1,10	1,50	1,15	1,54		15,51							6,00	1275	338	1858
P 003	54	m	6,02	1,50	1,63	2,89	1,58	14,18	28,02	12,91		32,62		54,47		3,00	1721	445	1449
P 004	20	m	6,00	1,45	1,50	3,05	1,75	13,65	21,58	14,34		31,65		54,01		2,00	1622	752	1593
P 005	23	f	6,25	1,96	1,45	2,84	1,53	14,84	30,97	14,07		33,42		52,51		5,00	1558	101	1938
P 006	30	m	6,15	1,83	1,65	2,67	1,76	20,44	50,61	13,10		31,24		55,66		2,00	1550	760	1578
P 007	54	f	6,08	1,80	1,20	3,08	1,70	14,32	28,09	13,26		31,25		55,49		1,50		1047	1900
P 008	57	f	5,52	2,05	1,23	2,24	1,40	13,46	17,96	12,36	16,43	31,48	36,39	56,16	47,18	5,00	1530	464	1642
P 009	70	f	7,68	1,35	1,00	5,33	1,39		20,22	13,92	26,95	35,41	39,60	50,67	33,45	4,00	1459	342	1605
P 010	26	f	6,23	2,38	1,97	1,88	1,70	18,97	45,35	12,55	23,04	29,42	32,44	58,03	44,52	3,00	1800	731	1773
P 011	61	m	4,65	1,23	0,93	2,49	1,52	16,38	26,47	12,04	20,84	31,90	39,85	56,06	39,31	6,00	1195	318	1813
P 012	76	f	6,77	1,47	1,27	4,03	1,67	13,91	31,41	11,65	13,17	31,02	35,89	57,33	50,94	3,00	1569	780	1766
P 013	26	f	7,88	2,65	1,77	3,46	1,83	17,28	75,28	11,81	13,31	31,17	35,52	57,02	51,07	1,00	1789	1194	2168
P 014	78	f	7,52	1,07	0,57	5,88	1,75	11,01	22,64	12,55	14,21	28,90	33,29	58,55	52,50	2,00	1495	970	1640
P 015	57	m	3,95	1,03	0,60	2,32	1,63	7,91	30,11	12,08	11,70	31,23	41,63	56,69	46,67	5,50	928	155	1510
P 016	26	m	6,47	1,90	1,40	3,17	2,12	11,99	37,62	15,14	21,65	30,32	35,37	54,54	42,98	2,50	1771	873	1920
P 017	47	f	6,00	2,42	2,12	1,46	1,90	16,06	60,72	9,76	9,43	28,17	29,66	62,17	60,91	3,00	1731	1446	2001
P 018	41	m	5,32	1,90	1,13	2,29	1,70	15,97	39,45	11,81	13,75	30,59	38,67	57,60	47,58	2,50	1561	757	1688
P 019	25	m	9,07	1,43	0,85	6,79	1,42	11,81	29,54	14,16	33,96	34,49	35,48	51,35	30,56	6,00	1210	164	1609
P 020	24	m	4,62	2,05	1,78	0,85	1,98	18,07	42,89	13,04	13,79	32,87	34,06	54,09	52,15	3,00	1501	808	1681
P 021	56	m	4,52	1,67	1,03	1,82	1,54	17,85	51,45	12,14	13,42	33,82	41,30	54,04	45,28	5,50	1542	424	1815
P 022	85	f	8,77	1,02	0,72	7,03	1,33	6,03	14,48	16,51	23,97	35,50	45,89	47,99	30,14	6,00	1197	358	1297
P 023	52	m	6,42	2,00	1,20	3,22	1,59	13,94	34,81	12,89	12,69	32,65	49,09	54,46	38,22	5,00	1290	385	1783
P 024	66	m	6,07	2,98	1,53	2,56	1,80	16,07	41,63	11,61	16,27	30,68	34,76	57,71	48,97	3,00	1695	773	1733
P 025	39	m	6,18	1,78	1,78	2,62	1,69	13,77	33,06	11,73	17,54	30,60	37,32	57,67	45,14	2,00	1640	846	1392
P 026	37	m	5,95	1,82	1,30	2,83	1,61	12,16	32,26	12,94	21,78	32,12	42,14	54,94	36,08	5,00	1694	566	1332
P 027	66	m	6,02	2,07	1,18	2,77	1,76	11,82	13,55	12,20	13,45	31,45	37,97	56,65	48,58	6,00	1611	685	1810
P 028	68	m	5,48	2,18	2,05	1,25	1,88	16,01	29,12	12,02	12,16	29,54	33,83	58,44	54,01	3,00	1638	796	1678
P 029	32	m	7,25	1,95	1,72	3,58	1,52	14,35	32,62	12,14	15,71	32,02	44,01	55,84	40,28	5,50	1538	254	1610
P 030	34	f	7,45	1,57	1,65	4,23	1,68	13,45	33,58	12,33	21,85	30,47	32,87	57,20	45,28	1,50	1599	690	1884
P 031	21	m	6,47	1,43	1,52	3,52	1,54	18,11	58,11	12,88	19,21	31,37	41,23	55,75	39,56	5,00	1560	200	604
P 032	53	m	7,20	2,97	2,15	2,08	1,75	12,69	39,30	10,59	11,54	30,18	38,00	59,23	50,46	5,00	1711	1139	1931
P 033	42	f	8,95	2,49	1,93	4,53	1,81	13,22	22,60	11,39	13,88	29,91	30,12	58,70	56,00	1,00	1548	1112	1560
P 034	60	f	5,83	1,08	0,97	3,78	1,68	9,79	17,49	12,91	18,02	31,98	35,75	55,11	46,23	5,00	1499	699	1606
P 035	27	m	6,15	1,68	1,77	2,70	1,73	10,14	24,95	13,45	20,68	29,97	33,47	56,58	45,85	2,00	1471	672	862
P 036	61	f	6,07	1,87	0,92	2,28	1,54	9,13	22,01	14,07	26,73	27,16	28,97	58,77	44,30	5,00	1546	693	1683
P 037	50	m	8,08	2,32	1,77	3,99	1,81	13,00	38,83	10,56	11,44	31,33	40,13	58,11	48,43	1,50	1638	1005	1484
P 038	70	f	4,95	1,25	1,18	2,52	1,75	14,10	35,31	11,18	14,55	31,13	34,25	57,69	51,20	2,50	1404	756	739
P 039	30	m	7,23	1,73	1,85	3,65	1,72	16,40	43,97	11,65	19,22	31,71	34,24	56,64	46,54	3,00	1715	425	1577
P 040	62	m	7,43	2,00	1,43	4,00	1,75	9,99	25,21	11,97	15,67	29,86	35,60	58,14	48,73	2,00	1642	934	1837
P 041	48	m	6,33	1,70	1,83	2,80	1,70	14,72	55,22	11,08	17,01	31,27	40,29	57,88	42,80	6,00	1803	364	1862
P 042	67	m	4,10	1,55	1,37	1,18	1,30	12,79	54,79	11,64	12,70	34,07	32,91	54,23	54,39	2,00	1429	924	833
P 043	33	m	6,82	1,84	1,79	3,19	1,61	16,06	60,38	12,91	24,89	30,56	32,30	56,53	42,81	2,00	1844	453	1758

T. Nr.	Age	Sex	TT	TCE	TCI	TS	D	CFT	PEM	WCC	WCS	OCC	OCS	MCC	MCS	SQV	QCI	QS	QCE
	(year)		(mm)	(mm)	(mm)	(mm)	g/cm3)	(daN/mm2)		%	%	%	%	%	%		(HU)	(HU)	(HU)
P 044	27	m	3,88	1,30	1,33	1,25	1,73	18,02	46,60	12,22	16,68	30,16	34,17	57,62	49,15	5,00	1537	620	1649
P 045	61	m	8,12	2,33	1,77	4,02	1,68	12,09	25,08	11,83	14,79	31,09	36,20	57,08	49,01	5,00	1596	481	1621
P 046	29	f	5,02	1,27	1,33	2,42	1,72	15,82	30,30	12,58	18,84	30,18	31,08	57,24	50,08	2,00	1572	588	1812
P 047	28	m	6,33	1,37	1,41	3,55	1,66	14,81	21,35	12,02	13,74	31,45	40,01	56,53	46,25	5,00	1679	415	1622
P 048	37	f	7,85	2,27	2,90	2,68	1,83	14,87	50,64	12,21	15,66	30,32	32,79	57,47	51,55	2,00	1747		1841
P 049	31	m	6,57	1,02	1,05	4,50	1,69	9,27	13,98	11,55	16,11	30,92	35,64	57,53	48,25	1,00	1689	846	1591
P 050	72	f	5,12	1,07	0,62	3,43	1,44	11,91	35,23	12,22	17,48	33,39	39,64	54,39	42,88	6,00	1139	210	1597
P 051	65	m	6,72	1,65	1,67	3,40	1,61	7,26	9,17	10,87	11,55	32,36	41,05	56,77	47,40	5,00	1621	435	1849
P 052	32	m	4,75	1,18	1,23	2,34	1,52	12,79	39,62	14,36	26,27	30,68	37,28	54,96	36,45	5,00	1562	243	1807
P 053	22	m	7,28	1,37	1,58	4,33	1,66	16,31	42,27	12,25	16,26	32,15	36,85	55,60	46,89	6,00	1570		1506
P 054	52	f	6,83	1,93	1,48	3,42	1,67	12,85	18,94	11,61	16,20	31,06	33,74	57,33	50,06	2,00	1642	765	1771
P 055	74	f	4,68	1,08	0,53	3,07	1,50	12,47	12,89	12,03	17,59	32,70	36,67	55,27	45,74	2,00	760	554	1746
P 056	60	m	9,23	1,37	1,62	6,24	1,59	8,78	15,79	11,17	15,03	31,24	38,06	57,59	46,91	2,00	1498	712	1725
P 057	80	f	4,80	0,67	0,57	3,56	1,52	10,95	22,14	14,45	17,09	35,17	40,12	50,38	42,79	4,00	1415	684	1337
P 058	25	f	9,55	3,02	2,62	3,91	1,70	8,15	18,77	12,13	18,10	31,32	33,72	56,55	48,18	2,00	1594	631	1613
P 059	50	f	7,17	1,58	0,70	4,89	1,72	11,69	17,40	12,11	18,94	33,08	32,40	54,81	48,66	2,50	1494	641	1784
P 060	81	f	6,22	1,30	0,95	3,97	1,58	8,58	23,48	8,74	11,06	33,87	39,59	57,39	49,35	1,00	1333	817	1527
P 061	42	f	5,68	1,90	1,98	1,80	1,88	15,07	39,95	10,89	14,15	29,70	31,76	59,41	54,09	1,50	1687	979	1935
P 062	62	m	4,93	1,38	0,73	2,82	1,73	13,05	28,35	12,77	19,38	30,94	37,51	56,29	43,11	6,00	1244	385	1806
P 063	64	f	8,00	0,92	0,82	6,26	1,57	5,97	7,29	14,95	23,84	31,94	32,09	53,11	44,07	2,00	1358	755	1378
P 064	30	m	5,23	1,97	1,50	1,76	1,86	16,54	21,08	11,81	15,92	31,12	35,85	57,07	48,23	2,00	1773	706	1663
P 065	26	f	4,87	1,77	1,67	1,43	1,81	18,00	41,69	11,36	15,96	29,05	31,91	59,59	52,13	3,00	1827	1166	1837
P 066	53	f	5,88	1,77	2,05	2,06	1,75	10,93	15,29	11,45	14,61	29,77	30,85	58,78	54,54	3,00	1496	853	1727
P 067	45	f	5,63	1,42	1,30	2,91	1,66	13,29	16,92	12,97	18,14	31,18	34,39	55,85	47,47	3,00	1613	613	1820
P 068	61	m	7,97	1,17	0,98	5,82	1,53	5,41	5,59	10,59	12,35	30,89	45,31	58,52	42,34	6,00	1461	404	1868
P 069	68	m	7,08	1,63	1,05	4,40	1,52	8,24	18,16	11,68	11,94	31,17	43,03	57,15	45,03	5,00	1695	521	1714
P 070	40	m	5,05	1,21	1,18	2,66	1,70	12,96	42,01	12,40	17,06	31,01	36,80	56,59	46,14	2,00	1759	504	1859
P 071	41	m	7,05	2,27	1,28	3,70	1,65	10,60	72,97	11,72	12,30	31,22	41,26	57,06	46,44	6,00	1546	118	1674
P 072	36	m	6,02	1,77	1,68	2,57	1,83	15,22	36,24	11,38	15,31	29,69	32,44	58,93	52,25	1,00	1715	933	1745
P 073	48	f	7,03	2,45	1,92	2,66	1,71	13,44	37,41	11,75	14,55	29,72	32,79	58,53	52,66	3,00	1606	957	1804
P 074	42	m	4,30	1,57	1,62	1,11	1,86	11,48	22,94	11,97	17,01	30,14	34,90	57,89	48,09	1,50	1677	1266	1548
P 075	55	f	7,62	2,53	2,18	2,91	1,71	13,86	25,42	11,12	12,58	30,10	32,10	58,78	55,32	2,00	1665	1097	1841
P 076	28	f	7,45	1,99	2,73	2,73	1,70	14,77	32,74	11,99	16,28	30,34	31,88	57,67	51,84	3,00	1468	337	1820
P 077	66	m	5,43	1,70	1,23	2,50	1,71	12,29	30,76	11,07	14,22	30,85	38,12	58,08	47,66	2,00	1699	926	1812
P 078	49	m	4,97	1,62	1,12	2,23	1,67	15,22	38,20	11,62	14,36	31,42	37,78	56,96	47,86	2,00	1760	526	1869
P 079	30	m	6,38	1,75	1,33	3,30	1,67	9,51	39,37	11,65	16,54	32,02	39,19	56,34	44,27	3,00	1898	915	1897
P 080	82	f	7,23	1,70	1,13	4,40	1,72	8,67	14,92	13,91	17,03	30,21	30,72	55,88	52,25	2,50	1425	705	1759
P 081	40	m	7,73	1,57	0,70	5,46	1,59	10,03	21,63	12,28	13,37	33,19	43,09	54,53	43,54	2,00	1615	339	1974

	Data Tensile Test		(n=50)		
T. NR.	Sex	Age	Area	Fmax	Tension
		(year)	(mm2)	(N)	(N/mm2)
T 001	f	78	49	552	11,17
T 002	m	64	64	416	6,50
T 003	f	73	74	316	4,27
T 004	f	57	64	364	5,69
T 005	m	43	72	400	5,56
T 006	f	85	33	80	2,46
T 007	m	61	49	268	5,47
T 008	f	37	98	260	2,65
T 009	m	31	40	460	11,63
T 010	m	60	47	136	2,88
T 011	f	82	53	448	8,53
T 012	f	64	53	319	6,04
T 013	f	55	74	368	4,99
T 014	f	28	77	500	6,54
T 015	m	26	44	104	2,36
T 016	m	20	80	380	4,75
T 017	f	63	45	80	1,78
T 018	m	22	36	124	3,44
T 019	m	22	65	408	6,30
T 020	f	39	95	288	3,03
T 021	m	52	92,15	400	4,39
T 022	m	44	64	276	4,27
T 023	m	43	64	300	4,66
T 024	f	53	81	236	2,91
T 025	m	37	70	96	1,36
T 026	m	58	63	204	3,24
T 027	m	40	69,3	330	4,76
T 028	m	74	67,5	560	8,30
T 029	m	65	48	290	5,95
T 030	m	21	75	80	1,13
T 031	f	79	80,1	80	1,00
T 032	f	30	64	160	2,50
T 033	m	25	62,4	490	7,85
T 034	m	24	80,1	470	5,87
T 035	m	29	71,2	330	4,63
T 036	m	57	77,43	340	4,39
T 037	m	37	67,5	440	6,52
T 038	f	42	76,5	450	5,88
T 039	m	71	90	360	4,00
T 040	m	58	72	340	4,72
T 041	m	52	72	430	5,97
T 042	f	47	87	400	4,60
T 043	f	47	71,25	380	5,33
T 044	m	33	68	300	4,41
T 045	f	48	78,4	560	7,10
T 046	m	39	94	250	2,66
T 047	m	50	85,5	410	4,80
T 048	f	50	72	470	6,53
T 049	f	57	86,48	300	3,47
T 050	f	52	86,45	350	4,05

Abbreviation Index

C	compression
CS	cervical spine
CFT	compression-fracture-tension [daN/mm^2]
CT	Computed Tomography
f	female
F_{max}	maximal force [daN]
FEM	finit element method
Group 1	group f / m 1: (18 < age < 45)
Group 2	group f / m 2: (46 < age < 60)
Group 3	group f / m 3: (61 < age)
HU	Hounsfield Units
m	male
MTT	maximum tensile-tension [daN/mm^2]
MCC	mineral content of compacta [%]
MCS	mineral content of spongiosa [%]
MV	mean value
OCC	organic content of compacta [%]
OCS	organic content of spongiosa [%]
p	probability level
PDIF	mean probability difference
PEM	pressure-elasticity-modulus [daN/mm^2]
PRED	correctly predicted observations
QCE	QCT-value compacta externa
QCI	QCT-value compacta interna
QCT	Quantitative Computed Tomography
QS	QCT-value spongiosa
r	radius of specimen [mm]
ROI	region of interest
S	shear
sd	standard deviation
ST	shear-tension
SFT	shear fracture-tension
SQV	semiquantitative value (spongiosa)
T	tensile
TNR	testnumber
TCE	thickness compacta externa [mm]
TCI	thickness compacta interna [mm]
TS	thickness spongiosa [mm]
TT	total thickness [mm]
WCC	water content of compacta [%]
WCS	water content of spongiosa [%]

			Data Sheer Tests (Incl. data QCT)			(n=73)			
T. Nr.	Sex	Age	Spec. Area	Spec. Thickness	TS	Max. Force	MTT	QS	Remarks
			(mm2)	(mm)	(mm)	(daN)	(daN/mm2)	(HU)	
S 001	m	61	109	5,8	4	84	0,77	318	
S 002	f	73	103	7	5	194	1,88		
S 003	f	47	99	4,7	1,6	336	3,39	1446	Compacta fractured
S 004	m	56	100	5,1	2,3	120	1,20	424	
S 005	m	66	105	6,1	4,4	92	0,88	685	
S 006	m	68	100	5,5	2	248	2,48	796	
S 008	f	60	95	6,2	4,2	164	1,73	699	
S 009	m	27	100	5,6	3,2	162	1,62	672	
S 010	f	61	122	6	3,5	56	0,46	693	
S 011	f	70	100	6	2,9	230	2,30	757	
S 012	m	66	95	5	2,1	257	2,44		
S 013	f	60	96	6	2,4	112	1,17		
S 014	m	33	100	6	3,5	120	1,20		
S 015	m	67	101	4,1	3	262	2,60	924	Compacta fractured
S 016	m	32	94	6,7	4	152	1,61		
S 017	m	24	97	5,5	2,7	100	1,03		
S 018	m	27	111	4,9	2,1	132	1,19	621	
S 019	f	29	102	6,5	4,4	244	2,39	589	
S 020	m	53	105	5	2,3	112	1,07		
S 021	m	31	86	6,5	4,5	148	1,71	846	
S 022	f	72	102	5,9	3,5	88	0,86	210	
S 023	m	32	99	4,5	1,6	148	1,49	244	
S 024	m	36	104	5,1	3,3	124	1,19		
S 025	m	48	99	4,5	3,1	84	0,84		
S 026	f	52	98	6,3	3	130	1,33	765	
S 027	f	52	110	6,5	2,5	136	1,23		
S 028	m	60	102	4,5	3,6	142	1,39	712	
S 029	f	80	96	5	4,2	124	1,29	648	
S 030	m	25	96	5	2,3	144	1,50		
S 031	f	81	92	7	5,5	164	1,78	817	
S 032	f	81	90	7	6	110	1,22		Compacta fractured
S 033	f	65	110	8,3	2,4	358	3,25		
S 034	f	32	110	5,3	3,9	132	1,20		
S 035	m	57	106	5,7	3,2	86	0,78		
S 036	m	58	119	5,5	4,2	220	1,85		
S 037	m	62	117	5,5	4	88	0,75	385	
S 038	m	30	112	6	3	217,6	1,80	706	
S 039	f	26	92	4,8	1,8	124	1,34	1166	
S 040	f	53	99	6,5	3,2	144	1,45	853	
S 041	m	64	112	5,5	3	136	1,21		
S 042	f	45	106	7	5	218	2,06	613	
S 043	m	28	105	4,6	3,2	134	1,28		

T. Nr.	Sex	Age	Spec. Area	Spec. Thickness	TS	Max. Force	MTT	QS	Remarks
			(mm2)	(mm)	(mm)	(daN)	(daN/mm2)	(HU)	
S 044	m	28	91	6,2	4	56	0,61		
S 045	m	68	96	5,2	2,5	56	0,68	521	
S 046	m	40	111	6	4	163,2	1,47	505	
S 047	m	53	105	6	3	184	1,74		
S 048	m	36	104	6	2	228	2,19	933	
S 049	m	42	99	4,8	2,3	208	2,10	1266	
S 050	m	50	94	6	4,7	97,6	1,04		
S 051	m	29	97	6,4	2,4	148	1,53		
S 052	m	20	94	6,1	2,5	81,6	0,87		
S 053	m	73	100	4,5	2,2	160	1,60		Compacta fractured
S 054	m	41	90	4	2	80	0,89		
S 055	m	66	84	5,8	2	280	3,34	926	
S 056	m	49	85	4,9	2,3	126	1,49	526	
S 057	f	57	83	7,1	5,3	50	0,60		
S 058	m	24	82	7,5	3,5	60	0,73		
S 059	m	24	92	7,2	3,9	204	2,21		
S 060	m	55	97	6,1	2,1	84	0,87		
S 061	m	28	109	6	2,3	192	1,76		
S 062	m	47	95	8	4,2	62,4	0,65		
S 063	f	62	95	5,5	4,5	40	0,42		
S 064	f	89	101	7	5	172	1,70		
S 081	f	50	95	6,2	3	168	1,93		
S 101	f	57	96	5,1	2,8	264	2,75		
S 102	f	51	102	5	3,2	96	0,94		
S 103	m	59	91	4,8	3,8	222	2,44		
S 104	m	24	93	7,5	2,5	75,2	0,81		
S 105	m	29	99	7,2	2,5	224	2,26		
S 106	m	29	97	7,1	2,1	193,6	2,04		
S 107	m	50	108	6	4	68,8	0,64		
S 108	m	29	110	5,3	2,2	120	1,09		
S 109	f	65	99	8	1,7	216	2,18		