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Analysis of chosen strength factors of spine and spine-fixator set

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The paper presents chosen results of research on the lumbar-chest part of spine and the spine-fixator complex. Spines were gathered from cadavers. Both damaged and undamaged spines with and without fixator were investigated. Two types of fixator were used: a CD and a modified Zespol fixator (our idea) – marked as P. In the research, compression/distraction forces were applied. The analysis is based on the results of comparative calculation: load range, hysteresis loop area and neutral zone stiffness.

Key words: strength factors, spine fixator

1. Introduction

Everyday our life gets longer and the number of technical devices used in everyday life grows. This causes that every year the rate of spine damage is higher and higher [1]. Some damage in a treatment process needs fixation, also transpedicular fixation. Spine, as a part of skeleton causing that our body is able to stand in vertical position, is loaded with different types of stresses, in many cases complex ones [2], [3]. Unusual exploitation or chronic illnesses, often connected with advanced age, can lead to many types of spine injuries – fractures, spondylolisthesis, etc., [4].

In literature related to spine investigations, very often a range of applied forces or a range of motion is used. The range of forces, where the input is load, and the range of motion, where the input is motion, are the factors that make the analysis of spine strength possible [5], [6]. In paper [5], it was proposed to use as such factors, not only the range of motion or load (displacement: extension, bending angle, torsion), but also the range of elastic strain, plastic strain and value of Young's modulus, presented in Figure 1, as well as mechanical values commonly used for measuring nonlinear materials or constructions.

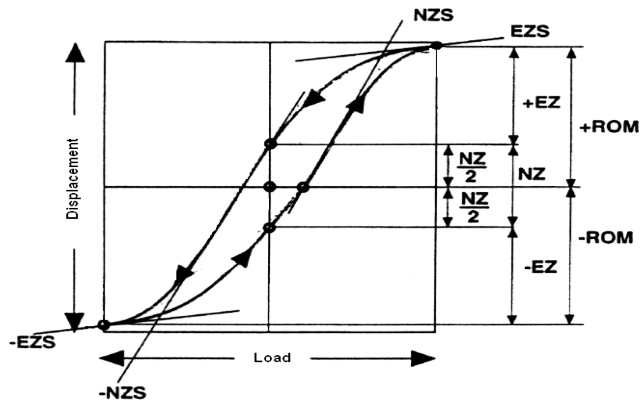

Fig. 1. Strength factors of spine, acc. to [10]:
NZ – neutral zone, EZ – elastic zone,
ROM – range of motion, NZS – neutral zone stiffness,
EZS – elastic zone stiffness

The aim of this work is to analyze the possibilities of estimating spine and spine-fixator strength, using the following factors: range of load, hysteresis loop area and constant of proportionality. A hysteresis loop as an energetic factor should better than standard parameters enable the spine behaviour to be marked. This fact was

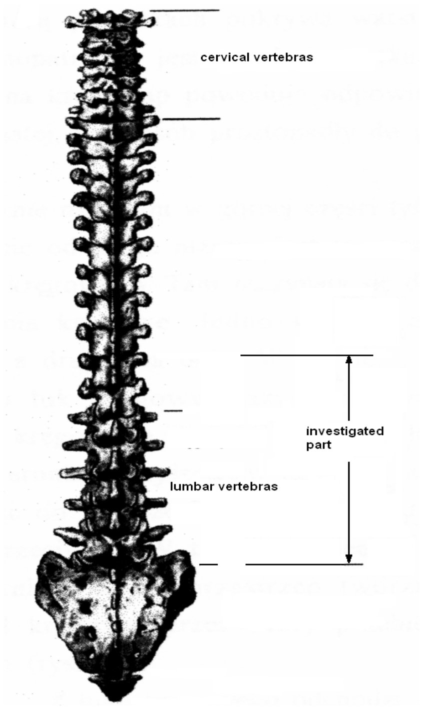

Fig. 2. Human spine, the part under investigation being marked

a)
b)

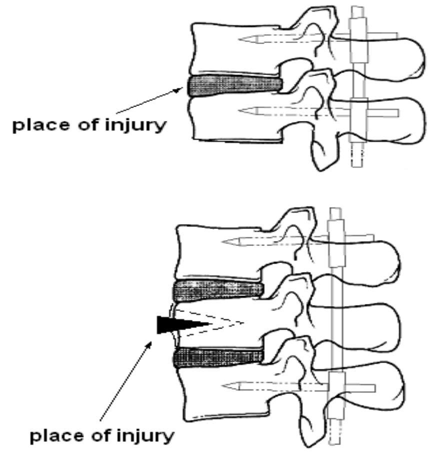

Fig. 3. 2-segment (a) and 3-segment (b) fixation

proved in many publications about strength and durability of materials [7], [8], especially when object response is nonlinear. The area of hysteresis loop represents dissipation energy in a set under investigation. It appears that in cases of small value of dissipation energy, this factor is very responsive. The constant of proportionality used in this paper is equal to the inverse of Young's modulus – marked with a letter – because of a possible comparison for relative values of all factors. The present work was based on the results of research of spines obtained from corpses, spine-fixator complex CD and fixator of our construction P under compression-distraction stress.

2. Materials and methods

In the investigation, 5 spines were used, which were obtained from cadavers, part from Th_{11} through the lumbar spine to the lower back part (Figure 2). Strength in 3-segment and 2-segment stabilization (FSU – Functional Spine Unit) was analyzed. FSU fixation consisted in placing fixator screws in two nearest ones, while in 3-segmental fixation, the distance between screws was two vertebrae, as presented in Figure 3. There are no results for the third spine because it had been naturally damaged before the investigation started. The mean age of persons under investigation was 43.5 years and ranged from 40 to 50 years. The muscles were removed from every specimen. Ligaments and discs were left untouched. Radiological tests were conducted on every specimen, to exclude spine illnesses and densitometry test was performed to mark bone density (BMD). Spines from persons who were killed in accidents were not collected, because there was a probability of their being damaged. Then specimens were frozen at –22 °C in double foil bags. 24 h before the investigation spines were defrosted to +4 °C and one our before the investigation – they were defrosted completely. Throughout the whole research period specimens were moistened with physiological salt. Treating specimens in such a way did not change their durability factors [9], [10].

In Figure 3, places where spine was damaged are marked. In the case of FSU fixation, disc was damaged by making a hole perpendicular to spine axis. In the case of 3-segmental fixation, the middle vertebra was damaged by cutting out a wedge width-long. Ligaments were left untouched. In the analysis, two kinds of fixator were used: a CD-rod system [11] and a P-system which is relative to ZESPOL type [12], modified by connecting two holes in one longitudinal hole. Screws were modified by turning their outer diameter to 6 mm, while keeping the root diameter of 4.5 mm. In the investigation, use was made of an Instron 8501 machine with holding apparatus, whose model was proposed under two Polish patents 114484 and 114485. A view of the working place and example object are presented in Figure 4, whereas in Figures 5 and 6, only the holding apparatus is presented.

Fig. 4. Working place, with fixed spine visible

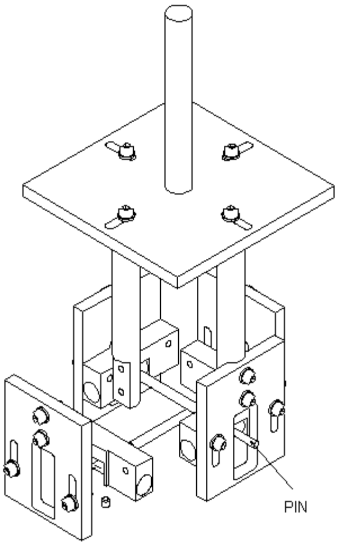

Fig. 5. Upper part of the holding apparatus

Investigation method (registered, patent submission no. 364315):

1. One of the vertebrae was fixed to the bottom part of the holding apparatus, which makes stable arrangement of the spine in proper axis possible.

2. Crossed pins were embedded in the other working vertebra.

3. Pins were fixed to the upper part of the holding apparatus; such a configuration ensures equality of the applied load.

4. Compression–distraction forces were applied to achieve a –4 mm/+3 mm displacement.

The advantage of this fixing system is that vertebra is fastened by many locally focused forces, which prevents the vertebrae fragments from crushing. Also, using this system it is not only the end vertebrae, linked to the elements via the applied forces, that can be investigated. Besides, there is no need to cut a spine into segments. A segment, to which loads are applied, can be used in two different fixations. This fact enables research to be conducted on segments consisting of 2 and 3 vertebrae on the same spine fragment.

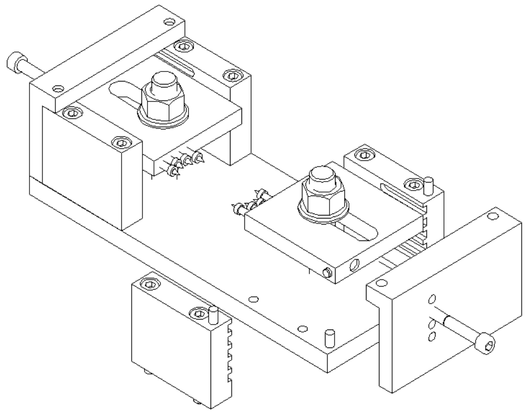

Fig. 6. Bottom part of the holding apparatus

The research proceeded in three full sinusoidal cycles. The third of them, being representative, was analyzed [5]. The displacement was established, and the frequency was set at 0.01 Hz.

3. Research results

As a result, functions of forces and displacement were registered. Then, we constructed graphs arranged in load–displacement sets.

An example of hysteresis loop obtained in the investigation is presented in Figure 7. Some chosen factors were marked: range of load (min-max), area of hysteresis loop and neutral zone stiffness.

An example set of results for the fourth spine: third hysteresis loops is presented in Figure 8. Four cases can be distinguished: damaged spine with CD fixator, damaged spine with P fixator, damaged spine without fixator, and undamaged spine. In Table 1, sets of calculation results are arranged together for all the spines investigated as maximal (max) and minimal (min) values of load and range of load (min-max). Presented are also values of the area of hysteresis loop (area), proportionality factor *a*, and relative values

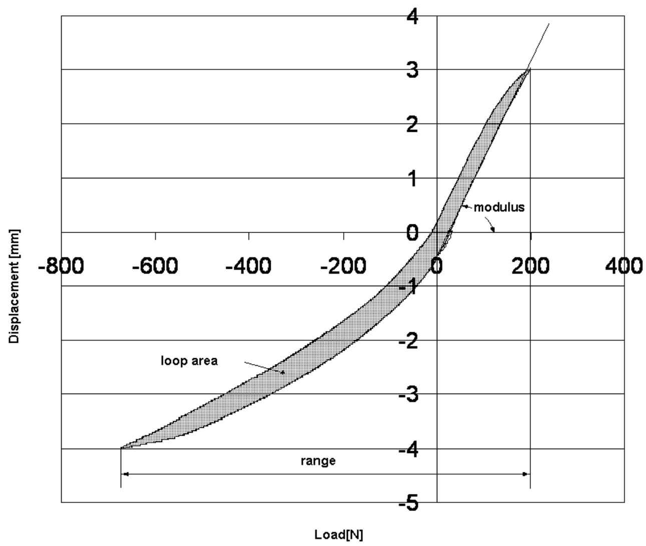

Fig. 7. Example hysteresis loop
(spine 4, undamaged, 2-segment fixation)

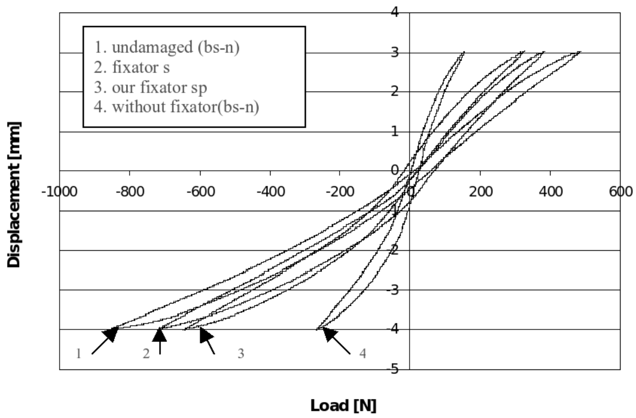

Fig. 8. Example hysteresis loops
(spine 1, 3-segment fixation)

Table 1. Compression–distraction (–4, +3 mm) results

Fixation													
2– segment							3–segment						
Spine		1	2	3	4	5	Spine		1	2	3	4	5
bs–n	min	–728.7	–695.54	–286.79	–871.44	–738.37	bs–n	min	–858.15	–575.11		–310.67	–630.42
	max	418.5	480.82	234.84	248.96	348.25		max	487.08	207.79		293.4	386.45
	range	1147.2	1176.36	521.63	1120.4	1086.62		range	1345.23	782.9		604.07	1016.87
	range. rel.	1	1	1	1	1		range. rel.	1	1		1	1
bs–u	min	–602.99	–781.36	–255.94	–674.28	–654.78	bs–u	min	–266.46	–93.32		–270.28	–191.59
	max	280.78	229.6	201.73	199.63	202.39		max	158.1	87.31		163.99	52.95
	range	883.77	1010.96	457.67	873.91	857.17		range	424.56	180.63		434.27	244.54
	range. rel.	0.77	0.86	0.88	0.78	0.79		range. rel.	0.32	0.23		0.72	0.24
s	min	–692.56	–795.68	–240.13	–712.63	–716.82	s	min	–721.15	–453.92		–415.86	–531.51
	max	380.16	382.42	233.35	251.01	304.53		max	384.67	404.23		263.52	326.03
	range	1072.72	1178.1	473.48	963.64	1021.35		range	1105.82	858.15		679.38	857.54
	range. rel.	0.94	1	0.91	0.86	0.94		range. rel.	0.82	1.1		1.12	0.84
sp	min	–590.15	–806.97	–280.78	–746.74	–707.73	sp	min	–645.9	–563.82		–479.27	–623.47
	max	349.31	379.39	227.35	251.01	296.16		max	326.72	282.27		257.95	312.86
	range	939.46	1186.36	508.13	997.75	1003.89		range	972.62	846.09		737.22	936.33
	range. rel.	0.82	1.01	0.97	0.89	0.92		range. rel.	0.72	1.08		1.22	0.92

Description:

bs–n – undamaged spine
bs–u – injured spine without fixator
s – injured spine with CD fixator
sp – injured spine with P fixator
min, max – minimal, maximal value of load
range, rel. range – range of load and its relative value related to undamaged spine

related to undamaged spine (range rel., *a* rel., and area rel.). For the third spine, for 3-segment fixation no results are presented because the spine had been naturally damaged before the research started.

In Tables 1–3, there are no results for the third spine, for 3-segment fixation. It was damaged by osteoporosis. A 2-segment fixation was conducted on Th11 and Th12 vertebrae, after which the stabili-

Table 2. A set of results representing the hysteresis loop area

Fixation														
2-segment							3-segment							
Spine		1	2	3	4	5	Spine		1	2	3	4	5
bs–n	area	436.31	526.21	134.18	498.66	388.89	bs–n	area	436.84	493.23		321.44	402.65
	area rel.	1	1	1	1	1		area rel.	1	1		1	1
bs–u	area	287.94	354.75	92.51	378.34	269.49	bs–u	area	167.29	58.73		211.65	198.81
	area rel.	0.66	0.67	0.69	0.76	0.69		area rel.	0.38	0.12		0.66	0.49
s	area	407.16	426.72	122.42	441.04	390.05	s	area	467.16	522.41		264.68	452.61
	area rel.	0.93	0.81	0.91	0.88	1		area rel.	1.07	1.06		0.82	1.12
sp	area	427.39	432.19	104.69	425.52	331.42	sp	area	384.69	552.93		380.77	526.47
	area rel.	0.98	0.82	0.78	0.85	0.85		area rel.	0.88	1.12		1.18	1.31
Same as in Table 1: area, area rel. – area of hysteresis loop related to undamaged spine													

Table 3. A set of results representing the proportionality factor *a*

Fixation													
2–segment							3–segment						
Spine		1	2	3	4	5	Spine		1	2	3	4	5
bs–n	*a*	0.009	0.009	0.008	0.013	0.010	bs–n	*a*	0.007	0.018		0.014	0.009
	a rel.	1	1	1	1	1		*a* rel.	1	1		1	1
bs–u	*a*	0.018	0.013	0.009	0.018	0.021	bs–u	*a*	0.03	0.10		0.024	0.07
	a rel.	1.93	1.49	1.15	1.35	2.11		*a* rel.	4.11	5.67		1.74	7.71
s	*a*	0.0097	0.009	0.008	0.013	0.013	s	*a*	0.010	0.011		0.014	0.099
	a rel.	1.04	1.00	1.03	1.00	1.29		*a* rel.	1.39	0.62		1.03	1.08
sp	*a*	0.011	0.008	0.008	0.014	0.013	sp	*a*	0.011	0.015		0.014	0.013
	a rel.	1.20	0.90	0.98	1.03	1.26		*a* rel.	1.50	0.81		1.01	1.33
Same as in table 1: *a*, *a* rel. – regression line modulus and its relative value related to undamaged spine													

zation was of no use for to further investigation on 3-segment fixation.

4. Analysis of research results

In the analysis, research results were set for range (Figure 9 a1 and a2), area (b1 and b2) and modulus (c1 and c2) in the form of charts of relative values related to undamaged spine, mark 1 corresponding to 2-segment fixation, 2 corresponding to 3-segment fixation.

The legend describing the first graph, pointing out the results obtained for other spines, corresponds also to the rest of the graphs, except d1 and d2. Description of the *x*-axis is explained in Table 1. Columns in charts a1–c2 show mean values, in sequence for all the spines under investigation. In Figure 9 d1 and d2, only mean values are presented.

Analysing the results presented, it appears that making damage, simulating natural injury, lowers the values of the particular factors: for FSU stabilization mean value is about 82% of their starting value, for 3-segment fixation it is about 40%. Using the fixators under investigation in most cases results in the return to starting conditions:

- For 2-segment fixation, for each fixator, mean values of the factors analyzed are less than 1, but more than 0.92.
- For 3-segment fixation, mean values of change of load range are close to 1. The values of loop areas were slightly higher for CD fixator. Proportionality factors were higher for P fixator.

In the case of far fixation analysis of Figure 9 a1, b1 and c1, it appears that dispersion of relative values of the range of load changes and that of the areas of hysteresis loops are comparable and much smaller than dispersion of *a* factor. For 3-segment fixation the least dispersion is observed for hysteresis loops (Figure 9 b2). This is confirmed by the values of standard deviation set in Table 2.

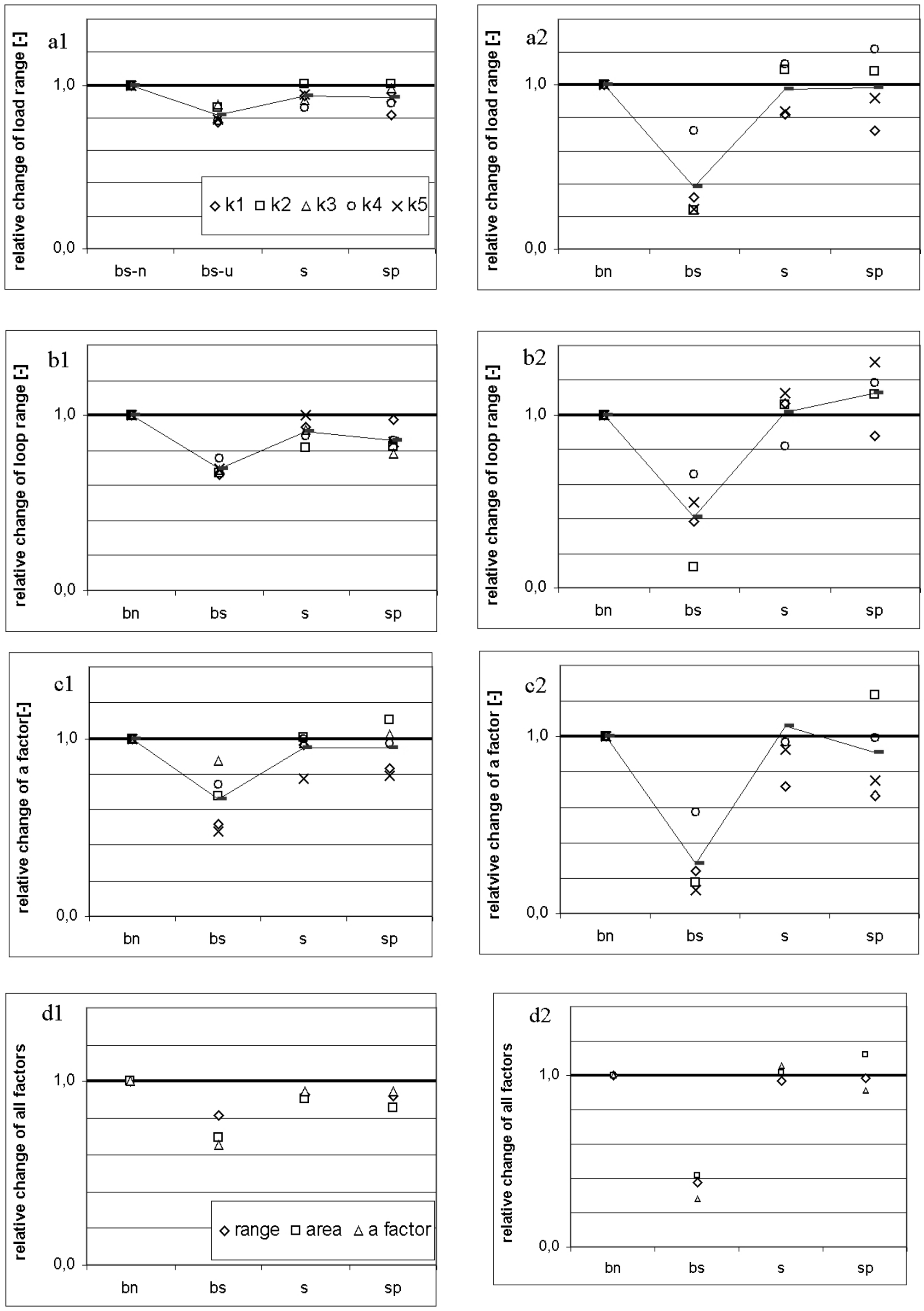

Fig. 9. Related values of range, hysteresis loop area and proportionality factor

Table 4. Standard deviation for the factors being analysed

Stabilization type	2-segment fixation				3-segment fixation			
Fixator	bs–u	CD	P	Mean	bs–u	CD	P	Mean
Range	0.044	0.046	0.066	0.052	0.231	0.161	0.213	0.202
Loop area	0.033	0.062	0.066	0.054	0.226	0.133	0.179	0.179
a factor	0.144	0.084	0.117	0.115	0.201	0.388	0.253	0.281

In Table 2, results of calculation of standard deviation are collected for the measured factors for different configurations of spines. The dispersion of values is generally bigger for 3-segment fixation. For FSU fixation, standard deviation of *a* factor is greater than that of the load range and loop areas: three or four times for damaged spine, up to 50% for CD fixation, and about two times for P fixator. For 3-segment fixation, the results are confirmed by the calculations made for spine-fixator sets. From the analysis of mean values of standard deviations it follows that generally the best results are obtained in loop calculations.

The estimated values, as presented in Figure 9 d1 and d2, are much alike mean values of hysteresis loop areas, see Figure 9 b1 and b2. This could indicate that the values obtained for hysteresis loops are the best factors to describe spine behaviour after damage and fixation.

5. Discussion

Factors commonly used in publications, which allow the spine behaviour to be evaluated, in most cases do not satisfactorily describe the hysteresis loop shape. Except NZS and EZS mentioned at the beginning, to compare behaviour in in vitro and in vivo tests use is made of the max and min values of loads and median [13]. Extreme values of loads or movements [14], mean values or median do not include enough non-linear stiffness changes. Because the important problem is such that spine with stabilizator is too stiff, finding a factor that better describes spine behaviour is essential. That value is the area of hysteresis loop. In addition, the results of our investigation show that factor is the most reliable one, the standard deviation of its value being the smallest, compared to common factors. The hysteresis loops measure dissipation energy, and are used with success in other domains of mechanics as comparative value.

This paper is an introduction to analysis which allows finding optimal fixator shape and material by using FEM model. Optimal fixation means the one which behaves almost like undamaged spine. The hysteresis loop area analyzed will be used to compare results from FEM modelling and experimental investigation.

6. Conclusion

Analysing the results obtained proves that each factor under consideration can describe spine and spine-fixator behaviour. However, as hysteresis loop depends on variability of either displacement or load, this factor seems to be most efficient. This is confirmed by the analysis conducted, including dispersion and similarity of tendencies. Is to say that in initial analysis, range of load, range of motion, area of hysteresis loop and NZS can be useful, but deeper analysis should rely on calculation of load–displacement hysteresis loops.

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