Biomechanical experimental data curation: an example for main lumbar spine ligaments characterization for a MBS spine model

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Abstract. This work overviews an extensive analysis in the context of mechanical characterization of human biomaterials, carried out over a broad set of published experimental data. Focused on main lumbar spine ligaments, several test procedures are exhaustively analyzed, in order to identify possible causes for divergences that have been found in some results. Moreover, guidelines are proposed for data filtering and selection. The main objective of the task was to retrieve trustworthy inputs to a hybrid Finite Element Analysis / Multibody System dynamic simulation model of the human intervertebral disc, which can be used on the prediction of nucleus prosthetics working performance.

Key words: biomechanics; data curation; experimental data; spine ligaments

1 Introduction

The knowledge on mechanical and geometrical properties of spine ligaments is a key requirement to understand and model, with a minimum of fidelity, the normal operation of the column [1]. One of the most relevant characteristics of ligaments mechanical behavior is their force/elongation nonlinearity. Actually, ligaments are expected to allow small movements around their neutral position, without significant actuating or produced force and, simultaneously, to provide stability to the column, by a progressive increase in stiffness as motion amplitude increases and physiological limits are approached. This behavior was typified by Panjabi *et al*, 1992 [2], who formulated the concepts of 'neutral' and 'elastic' working zones.

A considerable number of published experimental studies on the subject can be found, but usually following different procedures, ranging from testing each ligament *per si* or the entire 'functional spinal unit' (FSU). On the other hand, the majority of the tests are performed *in vitro*, while *in vivo* tests are restricted to ligaments laying near the skin surface, as the supraspinous and the interspinous [3], [4], [5], [6], [7], [8]. Besides, the majority of these works present force-displacement and/or stress-strain curves that are linear extrapolations – based on very few points or just on the final rupture conditions [7], [9], [10], [11], [12]. As consequence, the crucial part of the viscoelastic behavior is vanished.

In normal daily activities, ligaments' working condition fall in the zones where the most noticeable stress-strain ratio changes occur. Therefore, it is indispensable to rely upon experimental data, but also on a careful analysis of the experimental test protocols that are followed, in order to assure some reliability to the model.

Here, some of the most relevant experimental works on mechanical characterization of the lumbar spinal ligaments are analyzed, in order to detect incoherencies, point out possible explanations to these discrepancies, compare and find common aspects among some authors' results and emphasize the most relevant factors to take into consideration during curation processes. These are the main guidelines for collecting information on biomaterials mechanical properties, to be introduced in an hybrid Finite Element Analysis/ Multibody System (FEA/MBS) dynamic simulation model of the intervertebral disc, which is used for *in silico* performance prediction of *nucleus pulposus* prosthetic implants.

2 Analysis of experimental works and criteria for data selection

Each ligament is mechanically characterized by the combination of three factors: force, elongation and stiffness, where the stiffness corresponds to the slope of the force-displacement/ stress-strain curve as shown in Fig.1 [13].

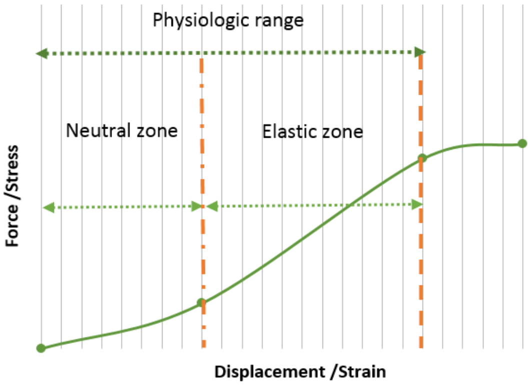


Fig. 1 Typical load-displacement curve of a ligament. Adapted from [1].

In a curation process of published data, a huge spread of results for the properties of the same ligament can be found (Fig. 2) [9], [14], [15]. This variability may be due to factors such as: dissimilarity in the age of specimens' donors, differences in test protocols, degeneration of specimens, storing, conditioning handling, or simply by test errors. These are just some of the possible factors, since the mechanical characteristics of a ligament are dependent on several variables, such as age, sex, weight, height, physical fitness and genetic influence [16].

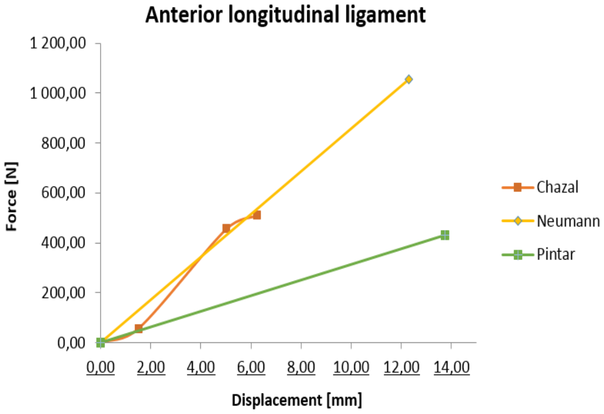


Fig. 2 Anterior longitudinal ligament force-displacement curves [9], [14], [15].

2.1 Dumas et. al, 1987

Tensile tests were carried out on 25 specimens with an average age of 66 years old, collected from 14 human lumbar columns between levels T11 and L5, not later than 24 hours after death. A method of progressive dissection was used, i.e. starting with the motion segment (MS), the set without the disc was tested. Afterwards, each ligament was removed and the remaining of the MS was tested again, which lead to force-elongation curves for each one of the situations. During the tests the ligaments were covered with a commercial jelly, in order to maintain hydration. For preconditioning, the specimens were previously subjected to several loading cycles. The results are shown in Fig.3.

Despite of a rigorous methodology for conservation of the ligaments and of having extensively characterized the samples, recording weight, sex, age and time interval since the death, some procedures could compromise the performance of the ligaments. For instance, the progressive dissection of the ligaments coupled to the preconditioning, may induce permanent deformations, probably due to the presence of micro ruptures in the fibers. Another disadvantage of the methodology is that, only supraspinous ligament was tested individually.

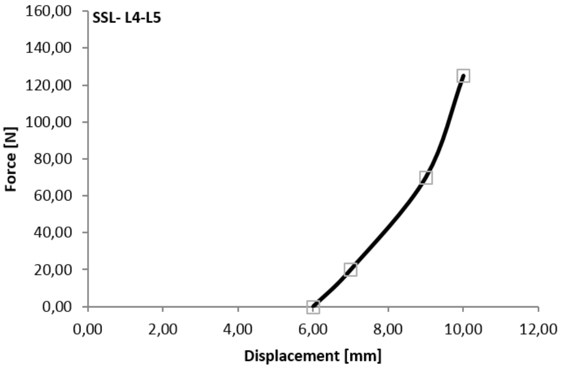


Fig. 3 Typical force-elongation curve obtained for one specimen (supraspinous ligament), according to [6].

2.2 Pintar et. al, 1992

In situ tests for determination of the biomechanical properties of the lumbar ligament were performed using 132 bone-ligament-bone type samples taken from 38 cadavers. The average age of the tested specimens is 63 years old, and the tests were performed up to 48 hours after death. The geometric studies were performed using a cryomicrotome technique. The force-elongation curves were obtained from normalized force-time and displacement-time curves. In order to reduce the number of curves, values were averaged for each tested ligament, according to their level in the column. Results are shown in Fig.4, whereas Table 1 summarizes the tested parameters.

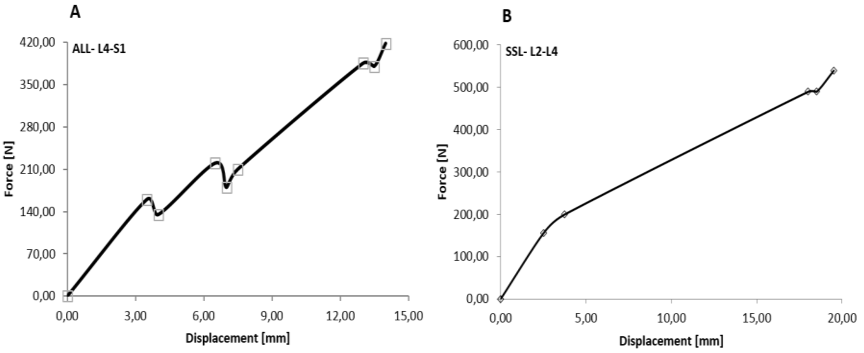


Fig. 4 Average biomechanical force-deformation curves, adapted from [9], **derived for: A-Anterior longitudinal ligament**; **B-Supraspinous ligament.**

This paper presents a significant number of test samples, with different approaches, when compared with most of available studies, namely in what concerns to the relation established between each of the tested parameters and the column level.

Table 1. Biomechanical parameters of human lumbar ligaments.

Parameter	***Ligament***	***T12-L1***	***L1-L2***	***L2-L3***	***L3-L4***	***L4-L5***	***L5-S1***
Stifness (N mm^{-1})	ALL	32.9	32.4	20.8	39.5	40.5	13.2
	PLL	10.0	17.1	36.6	10.6	25.8	21.8
	LF	24.2	23.0	25.1	34.5	27.2	20.2
	ISL	12.1	10.0	9.6	18.1	8.7	16.3
	SSL	15.1	23.0	24.8	34.8	18.0	17.8
Stress at failure (MPa)	ALL	9.1	13.4	16.1	12.8	15.8	8.2
	PLL	7.2	11.5	28.4	12.2	20.6	19.7
	LF	13.2	2.5	1.3	2.9	2.9	4.1
	ISL	4.2	5.9	1.8	1.8	2.9	5.5
	SSL	4.0	15.5	9.9	2.6	12.7	14.0
Strain at failure (%)	ALL	31.9	44.0	49.0	32.8	44.7	28.1
	PLL	16.2	15.7	11.3	15.8	12.7	15.0
	LF	61.5	78.6	28.8	70.6	102.0	83.1
	ISL	59.4	119.7	51.5	96.5	87.4	52.9
	SSL	75.0	83.4	70.6	109.4	106.3	115.1

However, other studies, such as [14] and [17], sustain that there is no significant difference in the mechanical properties of the ligaments along the column's level.

Besides, although the authors ensure a "match" between age, geometrical and mechanical properties of the ligaments, the way results are presented avoids to clearly establish this relationship. Since, two distinct groups of samples were involved in this study, one to determinate geometrical characteristics of the ligaments and another to determinate de mechanical properties.

Moreover, as force-elongation curves were obtained by normalization of time dependent curves, their usual sigmoid shape was vanished, which means that an important part of the physiological behavior of the ligaments was lost. Finally, the reconstruction of stress-strain curves, based on the tabulated data, lead to linear graphs since only the values for the for the rupture point are provided.

These results may be suitable as an initial approach for simpler models, where ligaments can be modeled as linear springs, but not to complex models.

3 Experimental data, suitable for modeling purposes

3.1 Chazal et. al, 1985

This work reports the results of tensile tests performed on 43 human samples, taken from 18 spines, 34 obtained from 12 fresh cadavers and tested within 24 hours after death, and the remaining 9 selected from living humans and withdrawn through of surgical procedures. The average age of donors is 53 years. The samples were of the bone-ligament-bone type, to avoid damage to the ligaments by the clamping system of the test rig, and were tested immediately or within a few hours after dissection. In the latter case, the ligaments were immersed in a solution of water, alcohol and glycerin, to retain hydration [14], [18]. Specimens taken from living donors were tested within one hour after excision and, meanwhile, placed in Ringer's solution [7], [14], [18].

Since ligaments are composed of long and short fibers, and mechanical properties are directly dependent on their anatomical integrity, they were tested intact. Moreover, for the same reason, supra and interspinous ligaments were tested together in order to prevent possible damage, as they share part of the fibers' structure.

Test results, in spite of not providing the force-elongation curves record three points (A, B and C) that allow their extrapolation (Table 2). Although it is not the ideal solution, it provides a reasonable approximation, as shown in Fig.5-A for the highlighted sample in Table 2 (dashed box). Results show consistency between different samples for the same type of ligament (Fig.5-B), which is an indication of the accuracy and reliability of the performed tests.

In this study, besides the results of the tensile tests, geometric characteristics and other details of the samples are provided, such as age, gender of the donor and column level of the sample, allowing to establish relations among all these data. Thus, it becomes easier to analyze and compare results, as well as to gather possible causes for discrepancies. Although the average age of donors is higher than desirable, this is a problem common to most studies on spinal ligaments.

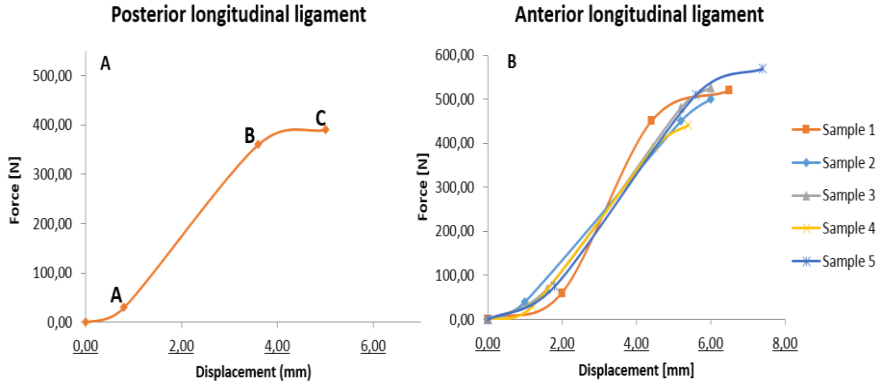
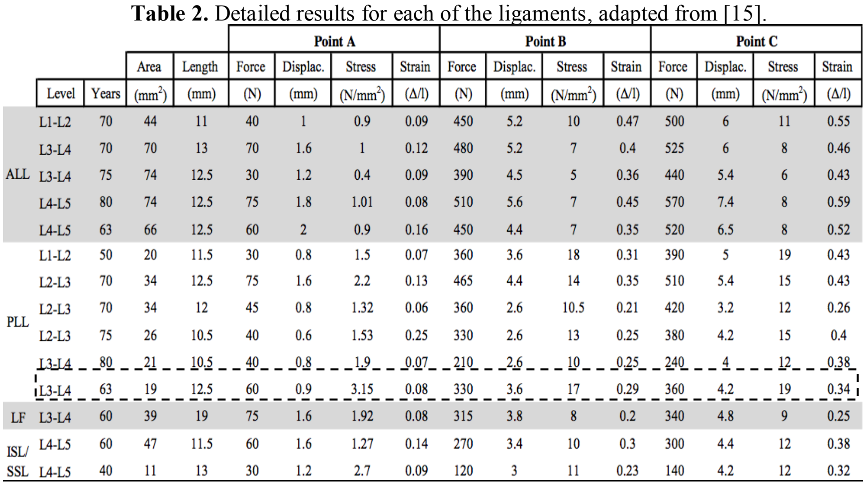


Fig. 5 A- Force-displacement curve for PLL (points A, B and C);
B- Force-displacement curves for ALL (data retrieved from table2).

Table 2. Detailed results for each of the ligaments, adapted from [15].



					Point A				Point B				Point C			
	Level	Years	Area (mm^2)	Length (mm)	Force (N)	Displac. (mm)	Stress (N/mm^2)	Strain (Δ/l)	Force (N)	Displac. (mm)	Stress (N/mm^2)	Strain (Δ/l)	Force (N)	Displac. (mm)	Stress (N/mm^2)	Strain (Δ/l)
ALL	L1-L2	70	44	11	40	1	0.9	0.09	450	5.2	10	0.47	500	6	11	0.55
	L3-L4	70	70	13	70	1.6	1	0.12	480	5.2	7	0.4	525	6	8	0.46
	L3-L4	75	74	12.5	30	1.2	0.4	0.09	390	4.5	5	0.36	440	5.4	6	0.43
	L4-L5	80	74	12.5	75	1.8	1.01	0.08	510	5.6	7	0.45	570	7.4	8	0.59
	L4-L5	63	66	12.5	60	2	0.9	0.16	450	4.4	7	0.35	520	6.5	8	0.52
PLL	L1-L2	50	20	11.5	30	0.8	1.5	0.07	360	3.6	18	0.31	390	5	19	0.43
	L2-L3	70	34	12.5	75	1.6	2.2	0.13	465	4.4	14	0.35	510	5.4	15	0.43
	L2-L3	70	34	12	45	0.8	1.32	0.06	360	2.6	10.5	0.21	420	3.2	12	0.26
	L2-L3	75	26	10.5	40	0.6	1.53	0.25	330	2.6	13	0.25	380	4.2	15	0.4
	L3-L4	80	21	10.5	40	0.8	1.9	0.07	210	2.6	10	0.25	240	4	12	0.38
	L3-L4	63	19	12.5	60	0.9	3.15	0.08	330	3.6	17	0.29	360	4.2	19	0.34
LF	L3-L4	60	39	19	75	1.6	1.92	0.08	315	3.8	8	0.2	340	4.8	9	0.25
ISL/ SSL	L4-L5	60	47	11.5	60	1.6	1.27	0.14	270	3.4	10	0.3	300	4.4	12	0.38
	L4-L5	40	11	13	30	1.2	2.7	0.09	120	3	11	0.23	140	4.2	12	0.32

5 Conclusions

When collecting experimental data from literature, a thorough and careful analysis is indispensable to ensure that the chosen data suit the model purposes.

As a matter of fact, there is a reasonable number of published papers on experimental tests, retrieving mechanical properties of biomaterials. However, when examined closely, it turns out that some studies have information gaps, failures in procedures, or data inconsistencies that make much arguable their use in a model that is expected to reproduce the in vivo behavior of a given bio-structure. Thus, when selecting this kind of data, there is a certain number of factors that must always be considered, such as, age, possible pathologies of the donors, handling and storage procedures of the samples (for instance, hydration status), and testing protocols.

Besides, when the objective is to use those experimental (real) data in computational models, namely in the case of the spinal ligaments, it is desirable to seek and choose results obtained from samples of the same or adjacent levels. Specifically, in the case of the lumbar spine, samples of the lowest levels (L3-L4, L4-L5) should be selected whenever possible, due to their working conditions of higher loads and greater mobility [19].

The major drawbacks of most of the studies are related to the high average age of the source specimens, but also to the fact that several works do not supply force-elongation curves, which is essential for the understanding, analysis and characterization of ligaments' behavior.

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