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ORIGINAL ARTICLE

The trabecular architecture of the superior articular process of the lumbar spine (L2–S1)

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Abstract The role of the facet joint in low back pain has gained public attention lately. The objective of our study was to investigate whether there is any difference in the adaptation of the cancellous bone in the superior articular process depending on the specific stress condition in different levels of the spine. Therefore, the trabecular structure of the superior articular processes of L2 and S1 of 15 cadavers (aged 63–100 years) were studied using μCT (micro-computer tomography). Each sample was divided into five sections, each of which containing 20% of the slices. The following structure parameters were compared between L2 and S1 as well as within each process; bone-volume-fraction (BV/TV), trabecular number (Tb.N), trabecular thickness (Tb.Th), structure-model-index (SMI) and degree of anisotropy (DA). Statistically significant differences were observed between L2 and S1 for the BV/TV, SMI, Tb.Th and Tb.N in superior 2 sections. BV/TV, Tb.Th and Tb.N were higher in S1 than in L2. The SMI is lower, and even negative in S1 compared to L2, showing a more plate-like structure. Within the articular process all structure parameters show a similar distribution in L2 and S1. BV/TV, Tb.N and DA decreased from cranial to caudal while Tb.Th was highest in the most cranial and caudal sections, with the lowest value in the middle. The SMI, on the other hand, increased from cranial to caudal displaying more rod-like structures. These results can be explained by the different stress the processes of the different spinal levels are exposed to as well as the specific motion patterns of the facet joint. The processes of the os sacrum are exposed to a higher axial and ventral load due to their location and the lumbosacral flexion. In addition the upper sections of each process experience higher stress peaks than the lower ones. Therefore, this study shows the material distribution within the cancellous bone adapts to these specific stress conditions the facet joints are exposed to.

Keywords Lumbar spine · Facet joints · Trabecular architecture · Micro-computed tomography

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Introduction

It is well known that the facet joints play an important role in load transmission in the spine. Depending on the height of the intervertebral disc, they carry up to 16% of the axial load [1]. Additionally they are exposed to a ventral feed caused by back musculature and, at least in the lumbar spine, to lateral bending by limiting rotation [17, 18]. Putz exemplarily described a specific pointed arc structure of the trabeculae within upper articular processes of the lumbar spine [17]. However, to our knowledge, there has been no literature on the material distribution within the upper articular processes.

At the end of nineteenth century, Julius Wolff was one of the first to realize that there is a relationship between trabecular orientation and the stress bone exposed to. He formulated that bone is, therefore, capable of adapting to environmental factors [21]. About 100 years later Biggemann et al. [3] investigated the compressive strength of the lumbar vertebrae and found that the compressive strength can be described as a product of bone density and end-plate-area. Since trabecular bone density is nearly constant throughout the thoracolumbar spine, nature adapts to the craniocaudally increasing axial loads by increasing the end-plate-area. Whether the facet joints, which play an important part in the stability of the spine and its mobility as well, go through a similar adaptation is not clear. Small changes in load distribution may be enough to disturb the biomechanical balance and to induce or accelerate degenerative changes [11]. It is, therefore, important to learn more about the physiologic conditions to allow an early diagnosis or even prevent facet joint arthrosis. Degenerative processes are a socially and economically important problem, which will increase within the following decades due to the aging population.

The objective of our study was, therefore, to investigate whether there is a difference in trabecular orientation and material distribution within the superior articular processes of lumbar spine compared to the os sacrum. Furthermore our goal was to show if the material distribution changes from cranial to caudal within the processes corresponding to its stress environment. We chose micro-CT, a proven method for investigation of bone [8, 10, 12, 15], for evaluation. One of the advantages of this method is that the samples are not destroyed thus allowing further studies.

Materials and methods

Eighteen cadavers underwent dissection for this study (7 male and 11 female). The mean age of the subjects was 82.8 years. The cadavers were taken from the student dissecting course of Institute of Anatomy in Munich. All spines underwent standard computer tomography using Siemens CT-somatom-sensation 64. Three individuals (1 male and 2 female) with scoliosis and degenerative changes as well as specimens, which showed signs of former surgical interventions and destructive processes, were excluded. The superior articular processes of 10 individuals were totally intact. Due to the dissecting course, some of the superior articular processes of the other vertebra were either damaged or missing. Therefore, a total of 47 processes were investigated.

The lumbar spines with attached sacrum were extracted by professional preparators. The second lumbar vertebrae (L2) and the sacrum (S1) were isolated and the soft tissue was removed. Afterwards the superior processes were cut off by an oscillating saw and stored in formalin until further utilisation. The L2 was chosen since it shows all characteristic features of the lumbar vertebrae and is distant enough from os sacrum, thus exposed to different strain. The micro-tomographic images were obtained using a µCT 20 (Scanco Medical, Brüttisellen, Switzerland). The positioning of the samples inside the cylindrical holder (diameter of 17.4 mm) was orientated by anatomical landmarks, such as the articular surface and the free edges of the superior facet, to match the anatomical transversal plane. The scanned images were evaluated using a software supplied by the manufacturer. For evaluation a consistent threshold of 220 was used. Each sample was divided into five sections each measuring 20% of the height of the slices (Figs. 1, 2). The following structure parameters were determined: BV/TV, Tb.N, Tb.Th, SMI and DA. The SMI is an index of the three-dimensional structure of the trabeculae introduced by Hildebrandt [9]. Index 0 describes an ideal plate-like structure, index 3 an ideal rod-like structure and index below 0 a very dense sample with plate-like structure. The DA is a parameter of preference direction. If DA has a value of 1, no preference direction exists, i.e. the trabeculae are isotropic. If DA has a value > 1, a preference direction exists. All structure parameters were compared between L2 and S1 as well as within each process for each divided sections using a paired *t*-test. A *p*-value < 0.05 was considered statistically significant.

Results

As can be seen in the Fig. 3, BV/TV, Tb.Th and Tb.N were generally higher in S1 than in L2. There are statistically significant differences between L2 and S1 for the section one and two of BV/TV, SMI, Tb.Th and Tb.N. The SMI is lower, and even negative, in S1 compared to L2. DA was significantly higher in section five in S1 compared to L2.

Within the articular process structure parameters in both S1 and L2 show a similar distribution. BV/TV, Tb.N and DA generally decreased from cranial to caudal while Tb.Th decreased from the cranial to the middle section, then

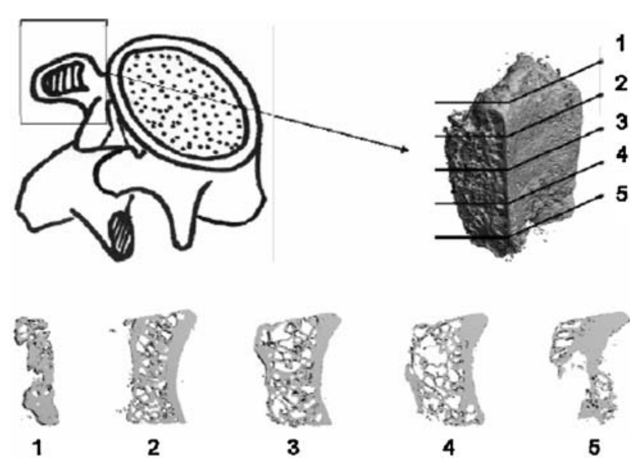

Fig. 1 µCT images of the middle of each section of L2 (*left*) showing the different trabecular orientation

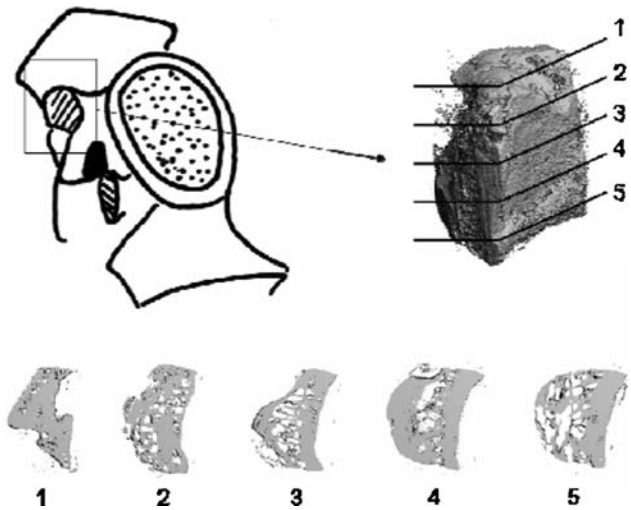

Fig. 2 µCT images of the middle of each section of S1 (*left*) showing the different trabecular orientation

increased again towards caudal. The SMI, on the other hand, is increasing from cranial to caudal. Statistically significant differences were seen mostly between the first two sections and the last three sections, and these differences were more prominent in S1 than in L2.

Discussion

The objective of the study was to show to what extent the cancellous bone of the superior articular process is adapted to the stress it is exposed to. The results of this study show that the trabecular structure in S1 is denser, thicker and has higher number of trabeculae than the L2 in the upper section. According to Putz [17], the upper articular processes of the lumbar spine limit rotation due to their alignment in sagittal plane. Thus they are mainly exposed to bending in the transversal plane. The resulting stress is especially high at dynamic movements like walking and running. He postulated with the help of a photoelastic model that the trabeculae of the processes should run in a specific pointed arch structure to cope with the bending stress. However, he could only substantiate this theory exemplarily. At the lumbosacral region, on the other hand, there is a larger angle between L5 and sacrum. Consequently the ventral feed in this region is especially high [18] as described by Kummer

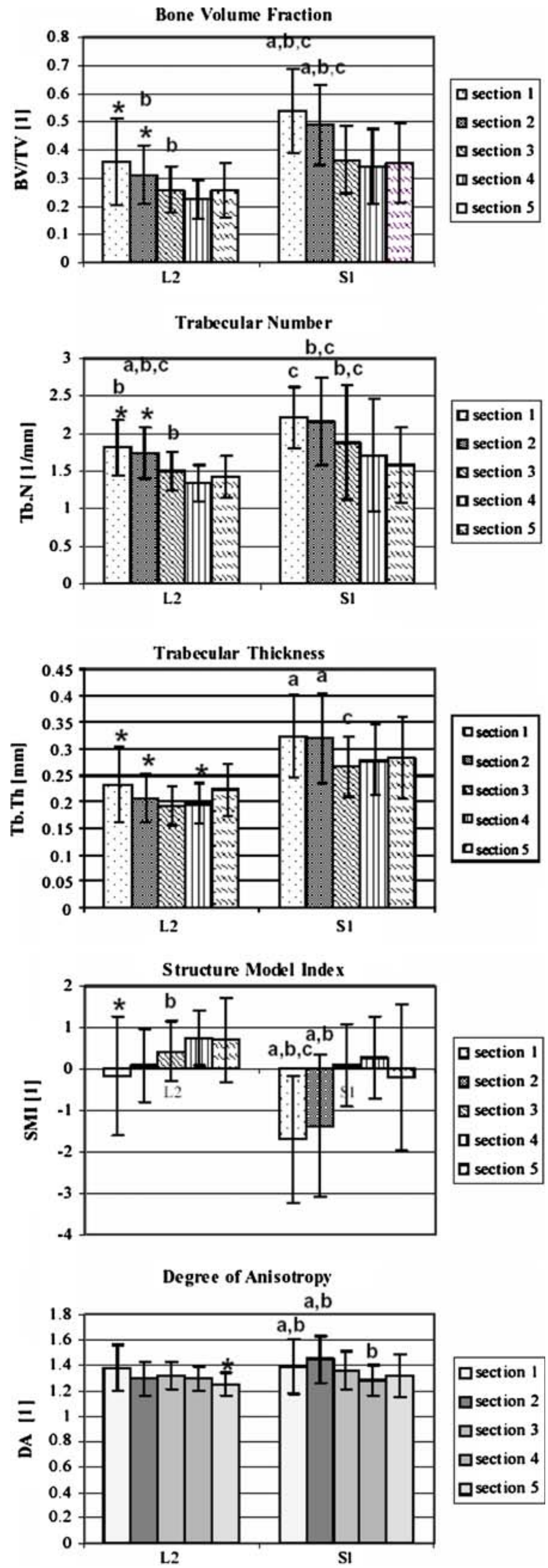

Fig. 3 Distribution of the structure parameters within the segments one to five (from *top* to *bottom*) of the superior articular process of L2 and S1. *$p < 0.05$ compared to S1 in each section; [a]$p < 0.05$ compared to section 3; [b]$p < 0.05$ compared to section 4; [c]$p < 0.05$ compared to section 5

[13] among others. Accordingly the trabeculae should be orientated depending on the stress, mainly perpendicular to the articular surface. Certainly the pictures of our study support this thesis (Figs. 1, 2), but our hypothesis that these differences in trabecular orientation between L2 and S1 would be corroborated by differences in the DA, was only proven in the lowest section. In S1, however, the differences within each articular process, namely between the superior two and the sections three and four, were statistically significant. The trabeculae were orientated more anisotropically with a specific directionality in the superior two sections. This may suggest a higher stress gradient or a different mode of stress within S1.

Comparing L2 and S1, the BV/TV of S1 is statistically significantly higher than that of L2 in the superior two sections. Within the processes, the BV/TV of both L2 and S1 decreases from cranial to caudal. The Tb.N showed a similar trend as BV/TV. The Tb.Th is higher in S1 than in L2 and shows two peaks; one in section one and the other in section five, with the lowest value in section three. The biomechanical qualities of bone do not primarily depend on the bone's density but on the trabecular architecture [5]. Nevertheless, the distribution of BV/TV and Tb.N refers to the specific stress the bone is exposed to. This stress seems to be higher in the cranial sections than in the middle and caudal ones. This can be explained by the specific sliding movement within a motion segment during flexion and extension. The articular surfaces are either lowered into the joint or pulled out of the joint within the region of the joint capsule. During lateral flexion, the process is pulled out of the joint at one side and lowered into it at the other [4]. Therefore the actual contact area of the articular surfaces decreases and the articular cavity gapes [16]. This way the cranial sections are more stressed than the caudal ones. This is true for both levels L2 and S1, and corresponds with the observation of Tischer et al. [20], that the majority of cartilage injuries can be found in the upper areas.

As mentioned above, the biomechanical qualities of bone strongly depend on the form of the trabeculae. One measurement of the trabecular form is the SMI, which was established by Hildebrandt and Rüegsegger in 1997 [9]. Generally the plate-like structure is said to be more stable than the rod-like one [2]. In our study, the SMI is lower in S1 than in L2, showing statistically significant differences in section one. In L2 it is mostly positive, between zero and one, increasing from cranial to caudal. So there is a tendency towards a rod-like structure in the caudal sections. In S1 even the SMI of the upper sections is negative which means that the structure in this region is extremely dense and concave plate-like. This corresponds to the measurements of BV/TV, Tb.N and Tb.Th and supports the theory that the main stress being effective on the superior articular process is localized in the cranial segments. Also the trabecular structure tends to be more plate-like as the donor's age increases [6, 9]. According to Grote, this change is especially noticeable in the lumbar spine compared with the cervical spine [7]. This does not seem to be the case for the superior articular processes (results not shown). Several reasons for this lack of structure transformation are conceivable. Either it can be seen as a sign that neither the kind of stress nor its intensity changes over the decades. Or due to loss of disc height and the subsequent change of the curvature, the superior articular processes of the elderly bear even more weight than younger ones [1]. It could also be due to the small sample number of a relatively advanced-age population in our study.

One of the limitations of this study is the limited sample number. However, the fact that the samples are from a dissection course makes it very difficult to obtain a large number of intact processes. Also because the examined vertebrae are from the dissecting course, the donors' average age does not correspond to the average age of the general population. This surely has some effects on the trabecular architecture [19]. However, since these changes are a specific adaptation on stress as well, the obtained samples are suitable for our study. Another problem is the rather small sample holder which required adjustment in some of the samples dimension. However, only the cortical bone was adjusted in this process and should not have influenced the trabecular structure or division into five sections. The fact that the samples were stored in formalin should not have effected the μCT measurements [14].

Conclusion

Our investigation shows that there are differences between the facet joints of L2 and S1 in examined parameters. Denser, thicker, plate-like structure with trabeculae was observed more in S1 than in L2, especially in the superior two sections. Within the process the structure parameters BV/TV, Tb.N and Tb.Th decrease from superior to inferior while the values of SMI increase. This shows an adaptation of the trabecular architecture to the higher axial strain of S1 on the one hand and to the typical motion pattern in L2 and S1 on the other hand.

Facet arthrosis develops when physiologic adaptation mechanisms are overtaxed and is found ubiquitously in the aging spine. And first signs of arthrosis can be found in the third decade [7]. In order to better understand degenerative processes and consequentially to develop a prophylaxis and therapy further investigation is important.

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