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Title: Mechanical loading influences the lumbar intervertebral disc : A cross-sectional study in 308 athletes and 71 controls

Year: 2021

Version: Accepted version (Final draft)

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Please cite the original version:

Owen, P. J., Hangai, M., Kaneoka, K., Rantalainen, T., & Belavy, D. L. (2021). Mechanical loading influences the lumbar intervertebral disc : A cross-sectional study in 308 athletes and 71 controls. *Journal of Orthopaedic Research*, 39(5), 989-997. <https://doi.org/10.1002/jor.24809>

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Mechanical loading influences the lumbar intervertebral disc. A cross-sectional study in 308 athletes and 71 controls

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Short title: Sport-specific IVD adaptation

Author contributions: Study design: MH, KK. Study conduct: MH, KK. Data collection: MH, KK. Data analysis: PO, TR, DB. Data interpretation: PO, MH, KK,

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/jor.24809.

TR, DB. Drafting manuscript: PO, DB. Revising manuscript content: PO, MH, KK, TR, DB. Approving final version of manuscript: PO, MH, KK, TR, DB.

Conflict of interest: All authors declare they have no conflicts of interest.

Acknowledgements: This study was supported by a Grant-in-Aid for Scientific Research (B) from the Japan Society for the Promotion of Science (grant number: 19300220). Gerontology Research Center is a joint effort between the University of Jyväskylä and the University of Tampere.

ABSTRACT

There is evidence in animal populations that loading and exercise can positively impact the intervertebral disc (IVD). However, there is a paucity of information in humans. We examined the lumbar IVDs in 308 young athletes across six sporting groups (baseball, swimming, basketball, kendo, soccer and running; mean age 19yrs) and 71 non-athletic controls. IVD status was quantified via the ratio of IVD to vertebral body height (IVD hypertrophy) and ratio of signal intensity in the nucleus to that in the annulus signal (IVD nucleus hydration) on sagittal T2-weighted MRI. P-values were adjusted via the false discovery rate method to mitigate false positives. In examining the whole collective, compared to referents, there was evidence of IVD hypertrophy in basketball ($P \leq 0.029$), swimming ($P \leq 0.010$), soccer ($P = 0.036$) and baseball ($P = 0.011$) with greater IVD nucleus hydration in soccer ($P = 0.007$). After matching participants based on back-pain status and body height, basketball players showed evidence of IVD hypertrophy ($P \leq 0.043$) and soccer players greater IVD nucleus hydration ($P = 0.001$) than referents. Greater career duration and training volume correlated with less (i.e. worse) IVD nucleus hydration, but explained less than 1% of the variance in this parameter. In this young collective, increasing age was associated with increased IVD height. The findings suggest that basketball and soccer may be associated with beneficial adaptations in the IVDs in young athletes. In line with evidence on other tissues, such as muscle and bone, the current study adds to evidence that specific loading types may beneficially modulate lumbar IVD properties.

Key words: Sports; Spine; Magnetic resonance imaging; Exercise; Back Pain; Low Back Pain; Intervertebral Disc

INTRODUCTION

Tissues, such as bone, that play a role in transmitting mechanical load, adapt to the load applied to them ¹. Similarly, the exercise training principle of specificity postulates that physiological adaptations will only occur when the tissue of interest is targeted and stressed ². For example, progressive resistance exercise training can increase the size of muscle (i.e. hypertrophy) ³, whereas impact-loading exercise training has been shown to increase bone mineral density ⁴.

However, there is limited evidence in humans of which exercise training modalities target and stress the intervertebral disc (IVD). Studies of IVD tissue and cells in vitro

have shown that loading can result in anabolic responses ^{5,6}, specifically cyclical loads of 0.2-0.8 megapascal, at 0.1-1.0Hz for up to eight hours/day was considered in one review of the field to lead to an anabolic response of the IVD ⁵. Animal studies reported beneficial modulation of the IVD with exercise: three months of exercises in adult dogs improved IVD uptake of glucose, oxygen and glycogen ⁷ and eight weeks of treadmill- exercise in rats increased IVD matrix production ⁸ and cell numbers in the IVD stem cell niche and the outer annulus ⁹. A further study of 11 weeks treadmill exercises in rats found increased IVD glycosaminoglycan concentration ¹⁰. Moreover, treadmill exercises of injured and sham IVDs in rats stimulated cell proliferation in both groups ¹¹. These animal data support a positive impact of locomotive exercise on the IVD of quadrupedal animals.

Studies in human athletic populations have shown that certain types of exercise or loading can be detrimental for the IVD. For example, greater lumbar IVD degeneration was observed in gymnasts compared to non-athlete controls ¹², as well as in weight lifters and soccer players compared to shooters ¹³. Moreover, exercise training load appears to be associated with lumbar IVD degeneration, with elite swimmers shown to have a greater prevalence of degeneration compared to recreational swimmer referents ¹⁴. However, data on a beneficial impact of exercise in humans on the IVD is less conclusive.

Emerging evidence supports the notion that certain types of exercise training may be beneficial to lumbar IVD characteristics ¹⁵. For example, high-volume cycling ¹⁶ and long-distance running and jogging ¹⁵ were shown to be associated with better lumbar IVD hydration and glycosaminoglycan levels (i.e. greater IVD T2-times ¹⁷) compared to non-athletic controls. Additionally, long-distance runners had a greater IVD height relative to vertebral body height, which suggests IVD hypertrophy in response to prolonged exposure to long-distance running ¹⁵. These findings were replicated in middle-aged adults ¹⁸, which suggests beneficial adaptations from specific types of loading may combat age-related deterioration of IVDs. Furthermore, recent evidence ¹⁹ showed that people who perform vigorous physical activity are have, on average, greater T2-times and apparent diffusion co-efficients in the lumbar IVDs, implying greater hydration and glycosaminoglycan levels. Whilst these data provide initial evidence of a potentially beneficial effect of specific kinds of exercise on the IVD, the breadth of the evidence is limited. Similarly, the sample size of these prior studies was typically small, which may limit generalisability.

We aimed to examine the adaptation of the IVD in a range of sporting types, in addition to non-athlete controls in a large sample size. We hypothesised that participation in sports involving upright load-bearing activities, such as running, would be associated with more beneficial IVD characteristics than non-athletic referents.

MATERIALS AND METHODS

This study was approved by the Ethical Committee of the Graduate School of Comprehensive Human Sciences, University of Tsukuba (notification number: 100)

and the Deakin University Human Research Ethics Committee (reference number: 2017-257). All participants provided their informed written consent prior to participation. This research complied with the Australia Code for the Responsible Conduct of Research (2018).

Participants

We selected a range of sports that we expected would apply different habitual physical loading to their lumbar spine. Well-trained (i.e. participation for greater than five years) male and female athletes across six sporting codes (baseball, swimming, basketball, kendo, soccer and running) who spent a minimum of 5 years in their sport were included in the study²⁰. Non-athletic controls included those who had not participated in competitive sport more than three times per week throughout their lifetime. Participants were excluded if they had previously undergone spine surgery. Lifetime low back pain status (yes/no), height and weight, career duration and training load (days per week, hours per day) were assessed via subjective questionnaire.

Magnetic resonance imaging, image processing and analysis

To quantify IVDs, a T2-weighted, density-weighted, fast spin-echo sagittal sequence (thickness, 6.0 mm; interslice distance, 0 mm; repetition time, 4000 ms; echo time, 125 ms; field of view, 300 x 300 mm, 256 x 256 pixels) was used on a 0.2-T Imager scanner (AIRIS Mate, Hitachi Medical AG, Tokyo, Japan). Data were exported for offline processing. A single midline slice was used in further processing. ImageJ 1.52a (<http://rsb.info.nih.gov/ij/>) was used to perform all quantitative MRI measures with the examiner blinded to group allocation (a random number, obtained from www.random.org, was assigned to each image). After segmenting the IVD, a custom written ImageJ plugin ("ROI Analyzer"; <https://github.com/tjrantal/RoiAnalyzer> and <https://sites.google.com/site/daniellbelavy/home/roianalyser>) was used to rotate the region of interest (ROI) to the horizontal and measure height and signal intensity of the IVD as a whole, as well as in five subregions from anterior to posterior (Figure 1). Subregions were calculated by the custom written plugin to be of equal width from the most anterior and most posterior point of the rotated ROI. Height was calculated as the average number of pixels in each vertical pixel column of the rotated ROI (for the whole IVD and also within each subregion). To obtain the height of the vertebral body from L1 to L5, similar measurements were performed. The ratio of IVD height to the height of the superior vertebral body was then calculated (as a measure of IVD hypertrophy, normalised to the height of the vertebral body; as performed in prior work¹⁵). To assess the relative hydration of the nucleus and account for variation between scans on T2-weighted imaging, we used an approach established in prior work²¹ and calculated the ratio of signal intensity in the nuclear region to the mean of anterior and posterior annulus (as a measure of the relative hydration of the nucleus). The angle of the region of interest fitted to the IVD relative to the horizontal was calculated for each IVD. All levels from L1/2 to L5/S1 were measured. An average of all lumbar levels was also calculated. Lumbar lordosis was calculated as the angle between the L1/2 and L5/S1 IVDs. Primary analysis focussed on (a) the ratio of IVD

height to vertebral body height and (b) the ratio of signal intensity between the nucleus and annulus.

Statistical analyses

All analyses were conducted using STATA statistical software version 15 (College Station TX, USA). Measures were compared between athletic groups and controls by one-way analysis of covariance with participant height as a covariate or chi-square test. Additionally, due to differences between participant groups for body height, IVD parameters were assessed between-group using one-way analysis of variance of participants matched based on low back pain status (yes/no) and height within 2 cm (n=22 per group). The latter approach accounted for the effect of body size variance on spinal parameters, in particular body height, which has been shown to vary among athletic groups²². Similar supplemental analysis of all athletic groups pooled versus control was also performed. The strength and direction of associations between IVD parameters and anthropometric data and training load variables were assessed by Pearson correlation coefficient and partial Pearson correlation coefficient adjusting for age, height and sex. Analyses used IVD outcomes (a) averaged across all lumbar vertebral levels, and (b) at each individual lumbar vertebral level. To mitigate the risk of type I errors, all P-values were adjusted by the false discovery rate method²³. An alpha-level of 0.05 was adopted for all statistical tests.

RESULTS

The total sample analyses consisted of 308 athletes and 71 controls, with matched-analyses included 22 athletes per group (total athletes: n=132) and 22 controls (Table 1). Mean (range) age of the total sample was 20 (18-24) years. All sporting groups had greater height than control (all: $P<0.01$). The running and swimming groups also had a 12% ($P=0.004$) and 8.5% ($P=0.013$) greater prevalence of back pain compared to controls, respectively.

IVD and spine properties in the total sample

In the total sample, average and individual lumbar IVD tended to have greater height in the baseball (7.0-10%, all: $P\leq 0.009$), basketball (8.4-17%, all: $P\leq 0.013$), soccer (5.8-9.0%, all: $P\leq 0.020$) and swimming (7.0-9.0%, all: $P\leq 0.014$) groups, compared to controls. Similarly, average lumbar IVD width was greater compared to controls for the baseball (5.9%, $P=0.008$) and basketball (6.6%, $P=0.003$) groups (Table 1). Lumbar lordosis was less (lumbar spine flatter) in the swimming group only.

For the primary outcomes of focus (Table 2; Figure 2), average lumbar IVD height to vertebral body height ratio was 7.6% greater than controls in both the basketball ($P=0.001$) and swimming ($P=0.001$) groups (Table 2). Similarly, greater individual IVD height to vertebral body height ratio was observed compared to controls for basketball (6.3-14%, all: $P\leq 0.029$) and swimming (7.6-15%, all: $P\leq 0.010$). Individual IVD height to vertebral body height ratio was also greater at L2-L3 for soccer (8.7%, $P=0.036$) and L3-L4 for baseball (7.6%, $P=0.011$), compared to controls. Nucleus-

annulus signal intensity ratio in the soccer group was 13% ($P=0.007$) greater at the L2-L3 IVD compared to controls.

IVD and spine properties in the matched sample

When considering the matched sample, the only remaining significant differences were that the basketball group had greater average (9.0%, $P=0.024$), L2-L3 (11%, $P=0.024$), L3-L4 (13%, $P=0.004$) and L4-L5 (7.8%, $P=0.043$) IVD height (Table 1). Matched sample analyses revealed the basketball group had greater average lumbar (10%, $P=0.035$), L3-L4 (15%, $P=0.007$) and L4-L5 (11%, $P=0.043$) IVD height to vertebral body height ratio compared to controls (Table 3; Figure 2). Moreover, L2-L3 IVD nucleus-annulus signal intensity ratio was 21% ($P=0.001$) greater in the soccer group compared to controls (Table 3).

All athletes pooled

Supplemental Table S-1 presents the analyses of athletic groups pooled versus controls. Whilst a number of significant differences were present when comparing all athletes versus control, after analysing the matched pairs collective, few significant differences remained, with only a higher nucleus-annulus signal intensity ratio at L3/4 in athletes.

Relationship between training variables and the spine

After controlling for age, body height and sex (Table 4), training variables did not correlate with IVD height to vertebral body height ratio, but did correlate significantly, and negatively, with nucleus-annulus signal intensity ratio correlated significantly. These associations were however, weak explaining less than 1% of the variance in these parameters (i.e. $r<0.1$).

DISCUSSION

The main findings from this study were that basketball, swimming, baseball and soccer were associated with beneficial IVD parameters compared to controls. Specifically, soccer was associated with better IVD nucleus hydration (i.e. greater nucleus-annulus signal intensity ratio), whereas basketball, swimming, baseball and soccer groups all demonstrated greater IVD hypertrophy (i.e. greater IVD height to vertebral body height ratio). However, once variations in participant height were considered (i.e. matched sample analyses), only basketball and soccer were associated with beneficial IVD health. Greater career duration and training load were associated with worse IVD nucleus hydration (i.e. lower nucleus-annulus signal intensity ratio), but the magnitude of this association was weak.

Following matched sample analyses, basketball and soccer were the only remaining groups exhibiting beneficial IVD parameters (i.e. greater IVD hypertrophy or hydration) compared to controls. Whilst we are unaware of any previous studies that have examined the association between basketball and beneficial IVD characteristics, we previously hypothesized²⁴ that sports involving ballistic and high-impact

(jumping) loading patterns would be detrimental to IVD health, in accordance with higher rates of IVD degeneration seen in volleyball players²⁵. This may imply that basketball could be detrimental to the IVD. Notably, the findings of the current study suggest that this prior hypothesis was incorrect and that basketball is associated with beneficial IVD adaptations. Notably, running, another sport involving high-impact IVD loading patterns, was shown to be associated with greater lumbar IVD hypertrophy compared to non-sporting referents¹⁵. Measurements of intradiscal pressures in running²⁶, and therefore also presumably loading on the IVD during running in basketball and soccer, are likely within the potentially beneficial range of 0.3-1.2 MPa²⁴. Potentially, the ability to maintain the lumbar lordosis during IVD loading may play a role in our current findings seen in these upright sports. Our observations regarding soccer conflicts with a previous study¹³ in which the sport was associated with greater lumbar IVD degeneration and pathologies compared to shooter referents (i.e. light-moderate physical activity). Comparison with this prior work is challenging as the prior study¹³ evaluated athletes more than 30 years after participation in elite sport and did not appear to implement blinding to athletic group during evaluation of MR images. Overall, our findings suggest that basketball and soccer may be associated with beneficial adaptations in the IVDs of younger athletes assessed at the time of their participation in the sport.

Our findings add to the emerging notion that specific types of exercise training may be capable of eliciting physiological responses in the lumbar IVD. This suggests that future studies should consider exercise training-based adaptations to the IVD and not limit outcomes to only markers of degeneration. Establishing exercise training that may be therapeutically utilised to improve IVD health, similar to that for muscle³ and bone⁴, has potential public health implications. For example, IVD degeneration is one postulated causal effect of chronic low back pain²⁷; therefore, eliciting IVD hypertrophy through exercise training, similar to the use of progressive resistance exercise training for muscular atrophy, may reduce burden of disease.

The current study was strengthened by the blinded nature of MRI analyses, the diversity of sport exposure across the athlete groups, as well as the large sample size. The matched-analyses were also strengthened by accounting for back pain status, which reduced potential confounders regarding the deconditioning hypothesis. Furthermore, the use of level stratification accounted for potential variance in individual IVDs outcomes²⁸. The limitations, however, should also be considered when interpreting these data. First, the cross-sectional design precludes the inference of causality between sport exposure and IVD characteristics. Second, the current study relied on subjective reports of sport involvement and thus the potential of recall bias cannot be entirely dismissed. Thirdly, a notable aspect of the current work is that the findings differed depending on whether the whole collective or matched-pairs were considered. Specifically, when the whole collective was considered, swimming and baseball were associated with better IVD characteristics, which contrasts with prior findings^{14,20}. This underscores the importance of controlling for potential confounders when recruiting subjects for quantitative measurements of the IVD. Further, based on age, the sample recruited for the current study may not have reached IVD maturity and subsequent age-related degeneration, which may begin during the

third decade of life ^{29–31}. However, this may also be viewed as a strength given that the age of the current sample allows the quantification of IVD health independent of the deleterious effects of the ageing process. Given the age of our participants, comparisons with studies of older adults is challenging. The findings of the current study cannot be generalized to conclude that specific sports have a general lifelong positive or detrimental effect on the IVD. Given the rate of tissue turnover in the IVD ^{32,33}, it is unclear how long an exercise intervention is required for changes to occur in the intervertebral disc. A recent 6 month randomised controlled trial of exercise ³⁴ led to equivocal results and further interventional studies are needed. Disc properties vary in a diurnal fashion ³⁵ and the reduction of spine length (and presumably disc height, hydration and disc T2) occurs to 50% within the first hours of rising and is complete within the first 3–4 hours of rising ³⁶. Whilst we did not require scanning to occur at a specific time of day, most of the scanning occurred in the afternoon, after the young (university student) population had finished their classes for the day and we do not anticipate an impact of this on our findings. Future studies should control, or at least log, the time of day relative to rising when assessing the IVD.

In conclusion, this study provides evidence of a positive effect of some, but not all, types of sport on the IVD in comparison to non-athletic controls. Specifically, basketball and soccer were associated with beneficial IVD parameters after accounting for variations in height across sporting groups. These data add to the body of evidence that specific types of exercise, when performed over a longer period, may be able to have a positive anabolic impact on the IVD.

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FIGURES

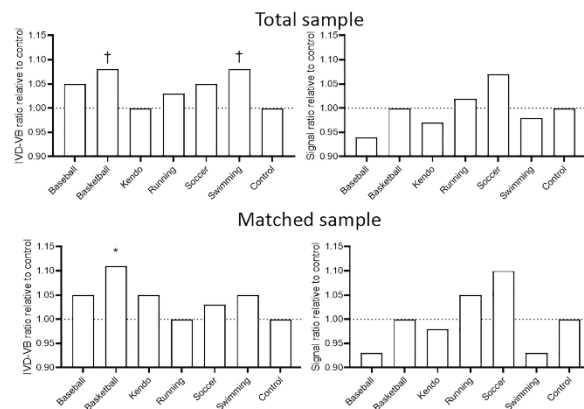
Figure 1. Intervertebral disc (IVD) quantification.

After manually segmenting the IVD, height and signal intensity of the lumbar IVDs (L1-2 to L5-S1) was calculated. Furthermore, five IVD subregions from anterior to posterior were assessed (see inset). The vertebral bodies L1 to L5 were also traced and height measured. To assess the relative hydration of the nucleus the ratio of signal intensity in the nuclear region to the mean of anterior and posterior annulus (subregions 1 and 5) was calculated. To illustrate, we show two examples: the top most IVD in the scan has a signal intensity ratio (Ratio_{SI}) of 2.8, implying the signal intensity in the central nuclear region is 2.8 times that of the average of the anterior and posterior aspects of the IVD. In the L4/5 IVD, the ratio is 4.7, implying the nucleus is likely more hydrated in this IVD. As a measure of IVD hypertrophy, the height of the IVD was divided by that of the superior vertebral body. See *Methods* for more detail.



Figure 2: Intervertebral disc parameters compared to control in the sporting groups in the whole collective (top panel) and matched sample (bottom panel)

To show relative differences, values are mean average lumbar IVD values in each athletic group divided by the mean in the control group. * $P < 0.05$, † $P < 0.01$ compared to control. See Table 2 and Table 3 for more details.



Tables

Table 1. Participant characteristics of the total (n=379) and matched sample (n=154).

	Basebal l	Basketba ll	Kendo	Runnin g	Socce r	Swimmin g	Contro l
<i>Total sample</i>							
N	57	63	51	43	47	47	71
Age, yr	20 (1)	20 (1)	20 (1)	19 (1)	19 (0)	19 (1)	19 (1)
Height, cm	174.8 (6.7)‡	175.9 (9.1)‡	169.1 (7.7)†	170.5 (7.5)‡	172.4 (7.4)‡	173.7 (8.6)‡	164.9 (9.0)
Back pain, n(%)	3 (5.3)	1 (1.6)	0 (0.0)	5 (11.6)†	2 (4.3)	4 (8.5)*	0 (0.0)
Level of competitio n, n(%)	0 (0.0)	5 (7.9)	0 (0.0)	4 (9.8)	3 (6.4)	6 (12.8)	-
Internation al							
National	12 (21.1)	28 (44.4)	34 (66.7)	11 (26.8)	11 (23.4)	36 (76.6)	-
Regional	45 (79.0)	30 (47.6)	16 (31.4)	24 (58.5)	33 (70.2)	5 (10.6)	-
Other	0 (0.0)	0 (0.0)	1 (2.0)	2 (4.9)	0 (0.0)	0 (0.0)	-
Career duration, years	10.73 (2.11)	9.19 (1.84)	12.89 (2.03)	7.57 (1.40)	10.89 (1.73)	13.08 (3.04)	-

Training, days/week	5.87 (0.32)	5.42 (0.67)	5.88 (0.43)	5.45 (0.63)	5.85 (0.34)	6.02 (0.15)	-
Training, hours/day	3.96 (0.71)	2.61 (0.64)	2.04 (0.22)	2.93 (0.77)	2.03 (0.23)	2.87 (0.82)	-
Lordosis angle, degrees	35.19 (8.05)	36.57 (8.44)	33.46 (7.99)	35.25 (7.76)	36.73 (6.81)	29.08 (10.86)‡	34.58 (6.67)
IVD height, mm							
AvLx	8.9 (0.8)†	9.4 (0.8)†	8.4 (0.8)	8.6 (0.8)	8.8 (0.7)†	8.9 (0.7)†	8.3 (0.8)
L1-L2	7.1 (0.8)†	7.5 (1.0)†	6.6 (0.7)	6.8 (0.9)	7.1 (0.9)*	7.0 (0.9)	6.6 (0.8)
L2-L3	8.2 (0.9)†	8.8 (1.0)†	7.7 (0.9)	7.9 (0.9)	8.1 (0.9)†	8.1 (0.9)†	7.4 (0.9)
L3-L4	9.5 (1.1)†	10.1 (1.0)†	8.9 (1.1)	9.1 (1.0)	9.2 (1.0)*	9.4 (0.9)†	8.6 (1.1)
L4-L5	10.3 (1.4)†	10.7 (1.3)†	9.8 (1.2)	10.0 (1.3)	10.1 (1)*	10.3 (1.4)*	9.5 (1.1)
L5-S1	9.3 (1.4)	9.9 (1.6)*	8.8 (1.3)	9.1 (1.3)	9.2 (1.5)	9.7 (1.1)	9.1 (1.1)
IVD width, mm							
AvLx	28.1 (2.2)†	28.3 (2.7)†	27.3 (2.6)	26.3 (2.2)	27.1 (2.2)	27.2 (2.5)	26.5 (2.8)
L1-L2	28.0 (2.8)†	27.3 (3.3)*	27.4 (3.4)*	26.0 (2.8)	26.8 (3.2)	25.0 (3.6)	25.7 (3.3)
L2-L3	29.3 (3.5)	30.0 (3.2)†	28.3 (3.6)	27.5 (2.6)	28.1 (3.1)	27.9 (3.4)	27.7 (3.9)
L3-L4	29.6 (3.2)	30.6 (3.5)*	29.0 (3.4)	28.1 (3.0)	29.1 (2.8)	28.4 (3)	28.7 (3.4)
L4-L5	29.2 (2.9)	29.4 (4.0)	28.4 (3.4)	27.7 (2.9)	28.4 (3.5)	29.0 (3.7)	27.8 (3.3)
L5-S1	24.3 (3.0)*	24.3 (3.3)*	23.2 (3.3)	22.4 (2.6)	23.3 (2.8)	25.6 (4.0)†	22.8 (3.0)
<i>Matched sample</i>							
N	22	22	22	22	22	22	22
Age, yr	20 (1)	20 (1)	20 (1)	19 (1)	19 (0)	19 (1)	20 (2)
Height, cm	171.5 (4.6)	171.8 (5.0)	171.4 (4.7)	171.5 (5.6)	171.3 (5.5)	171.9 (5.6)	171.5 (5.7)
Back pain, n (%)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Level of competition, n(%)							
International	0 (0.00)	2 (9.09)	0 (0.00)	1 (4.55)	0 (0.00)	3 (13.64)	-
National	7 (31.82)	9 (40.91)	17 (77.27)	6 (27.27)	6 (27.27)	17 (77.27)	-

Regional	15 (68.18)	11 (50.00)	5 (22.73)	15 (68.18)	16 (72.73)	2 (9.09)	-
Other	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	-
Career duration, years	9.62 (1.90)	9.50 (2.13)	13.13 (1.86)	7.56 (1.28)	11.18 (1.71)	12.31 (3.62)	-
Training, days/week	5.91 (0.29)	5.59 (0.67)	5.91 (0.43)	5.43 (0.58)	5.82 (0.36)	6.05 (0.22)	-
Training, hours/day	4.05 (0.72)	2.75 (0.55)	2.05 (0.21)	2.93 (0.66)	1.99 (0.12)	2.98 (0.80)	-
Lordosis angle, degrees	35.59 (8.20)	37.21 (7.88)	31.62 (7.05)	35.45 (7.33)	38.55 (6.45)	31.32 (9.95)	33.36 (5.37)
IVD height, mm							
AvLx	8.8 (0.9)	9.3 (0.8)*	8.6 (0.7)	8.5 (0.8)	8.6 (0.7)	8.7 (0.6)	8.5 (0.9)
L1-L2	7.1 (0.8)	7.3 (0.9)	6.7 (0.7)	6.8 (0.8)	6.9 (0.6)	7.0 (0.8)	6.9 (1.0)
L2-L3	8.1 (0.9)	8.6 (1.0)*	7.7 (0.8)	7.8 (0.8)	8.0 (0.7)	8.0 (0.8)	7.7 (1.1)
L3-L4	9.4 (1.1)	10.1 (0.9)†	9.2 (1.2)	9.0 (1.0)	9.0 (0.9)	9.3 (0.7)	8.9 (1.2)
L4-L5	10.0 (1.5)	10.7 (1.0)*	10.1 (0.9)	9.8 (1.1)	10 (1.1)	9.8 (1.4)	9.9 (0.9)
L5-S1	9.3 (1.3)	9.9 (1.4)	9.3 (1.3)	9.2 (1.4)	9.4 (1.6)	9.6 (1.2)	9.4 (1.0)
IVD width, mm							
AvLx	27.8 (1.9)	27.6 (1.8)	27.5 (2.0)	26.9 (2.1)	26.9 (2.3)	26.8 (2.2)	27.8 (2.3)
L1-L2	27.3 (2.5)	26.4 (2.3)	27.6 (2.6)	26.7 (2.7)	26.6 (3.3)	25.1 (3.4)	27.3 (2.9)
L2-L3	28.9 (2.5)	29.5 (2.9)	28.4 (3.0)	28.2 (2.4)	28.4 (3.2)	27.1 (2.8)	28.6 (3.4)
L3-L4	29.8 (3.2)	29.9 (2.8)	28.5 (3.1)	28.4 (3.0)	28.4 (2.8)	28.1 (3.1)	29.7 (2.8)
L4-L5	28.8 (2.1)	28.4 (3.5)	28.8 (2.9)	28.3 (3.0)	28 (3.6)	28.1 (3.2)	28.8 (3.5)
L5-S1	24.1 (3.5)	23.7 (2.1)	24 (3.1)	22.9 (2.9)	23 (2.6)	25.6 (4.5)	24.3 (3.2)

Data are mean (standard deviation) or number (n; percentage). IVD: intervertebral disc. * P<0.05, † P<0.01, ‡ P<0.001 compared to control. AvLx: average of all lumbar levels. To mitigate risk of false positive, P-values were adjusted by the false discovery rate method.

Table 2. Intervertebral disc (IVD) parameters compared between athlete groups and control in the total sample (n=379).

	Baseball (n=57)	Basketball (n=63)	Kendo (n=51)	Running (n=43)	Soccer (n=47)	Swimming (n=47)	Control (n=71)
<i>Nucleus-annulus signal intensity ratio</i>							
AvL _x	3.91 (0.66)	4.19 (0.66)	4.03 (0.66)	4.25 (0.65)	4.46 (0.65)	4.07 (0.65)	4.17 (0.69)
L1-L2	3.61 (0.83)	4.02 (0.84)	3.62 (0.83)	3.99 (0.82)	4.17 (0.82)	3.59 (0.83)	3.78 (0.87)
L2-L3	4.40 (0.94)	4.35 (0.95)	4.35 (0.94)	4.39 (0.93)	5.02 (0.93) †	4.51 (0.93)	4.40 (0.98)
L3-L4	4.63 (1.04)	5.05 (1.05)	4.88 (1.04)	4.89 (1.03)	5.19 (1.03)	4.94 (1.03)	4.96 (1.09)
L4-L5	3.88 (1.27)	4.09 (1.28)	4.22 (1.27)	4.57 (1.25)	4.35 (1.25)	4.13 (1.26)	4.34 (1.33)
L5-S1	3.13 (1.11)	3.54 (1.12)	3.28 (1.11)	3.56 (1.10)	3.70 (1.10)	3.20 (1.10)	3.47 (1.16)
<i>IVD height to vertebral body height ratio</i>							
AvL _x	0.40 (0.04)	0.41 (0.04) †	0.38 (0.04)	0.39 (0.04)	0.40 (0.04)	0.41 (0.04) †	0.38 (0.05)
L1-L2	0.31 (0.04)	0.33 (0.04) *	0.30 (0.04)	0.31 (0.04)	0.32 (0.04)	0.36 (0.04) †	0.31 (0.04)
L2-L3	0.35 (0.05)	0.38 (0.05) †	0.34 (0.05)	0.35 (0.05)	0.36 (0.05) *	0.37 (0.05) †	0.33 (0.05)
L3-L4	0.41 (0.05) *	0.43 (0.05) †	0.39 (0.05)	0.40 (0.05)	0.40 (0.05)	0.41 (0.05) †	0.38 (0.05)
L4-L5	0.46 (0.07)	0.46 (0.07)	0.44 (0.07)	0.45 (0.06)	0.46 (0.06)	0.47 (0.06)	0.43 (0.07)
L5-S1	0.43 (0.07)	0.45 (0.07)	0.40 (0.07)	0.42 (0.07)	0.42 (0.07)	0.45 (0.07)	0.43 (0.08)

Data are mean (standard deviation). * P<0.05, † P<0.01 compared to control. AvL_x: average of all lumbar levels. To mitigate risk of false positive, P-values were adjusted by the false discovery rate method.

Table 3 Intervertebral disc (IVD) parameters compared between athlete groups and control in the matched sample (n=154)

	Baseball (n=22)	Basketball (n=22)	Kendo (n=22)	Running (n=22)	Soccer (n=22)	Swimming (n=22)	Control (n=22)
<i>Nucleus-annulus signal intensity ratio</i>							
AvL _x	3.84 (0.69)	4.14 (0.65)	4.04 (0.79)	4.36 (0.61)	4.56 (0.51)	3.85 (0.62)	4.14 (0.78)
L1-L2	3.61 (0.69)	4.02 (0.89)	3.67 (1.11)	4.15 (0.62)	4.19 (0.68)	3.43 (0.74)	3.80 (0.86)
L2-L3	4.31 (1.06)	4.34 (0.69)	4.47 (0.84)	4.46 (0.77)	5.36 (0.68) †	4.31 (0.80)	4.35 (0.78)
L3-L4	4.57 (1.24)	4.87 (0.57)	4.88 (1.59)	4.97 (0.84)	5.45 (0.95)	4.62 (1.14)	5.13 (0.89)
L4-L5	3.75 (1.23)	4.07 (1.19)	4.16 (1.24)	4.63 (1.35)	4.50 (1.09)	4.07 (1.67)	4.35 (1.51)
L5-S1	3.06 (1.23)	3.45 (1.21)	3.28 (1.12)	3.73 (1.11)	3.54 (0.77)	2.82 (1.23)	3.14 (1.21)
<i>IVD height to vertebral body height ratio</i>							
AvL _x	0.40 (0.04)	0.42 (0.05)*	0.40 (0.04)	0.38 (0.04)	0.39 (0.04)	0.40 (0.04)	0.38 (0.05)
L1-L2	0.32 (0.04)	0.33 (0.04)	0.30 (0.03)	0.31 (0.03)	0.31 (0.03)	0.35 (0.05)	0.31 (0.05)
L2-L3	0.36 (0.05)	0.38 (0.05)	0.34 (0.04)	0.34 (0.05)	0.35 (0.04)	0.36 (0.05)	0.33 (0.06)
L3-L4	0.40 (0.05)	0.44 (0.05)†	0.41 (0.05)	0.39 (0.04)	0.40 (0.05)	0.41 (0.05)	0.38 (0.06)
L4-L5	0.44 (0.07)	0.48 (0.06)†	0.47 (0.05)	0.43 (0.06)	0.45 (0.06)	0.44 (0.07)	0.43 (0.05)
L5-S1	0.42 (0.07)	0.46 (0.08)	0.43 (0.07)	0.41 (0.07)	0.43 (0.07)	0.44 (0.07)	0.42 (0.05)

Data are mean (standard deviation). * P<0.05, † P<0.01 compared to control. AvL_x: average of all lumbar levels. To mitigate risk of false positive, P-values were adjusted by the false discovery rate method.

Table 4: Correlation analyses between training variables and disc and spine variables

Variable	Lordosis Angle	IVD height	IVD width	IVD-VB ratio	Signal ratio
<i>Pearson's correlation co-efficient</i>					
Age	-0.053	0.138*	0.168†	0.099	-0.177‡
Height	-0.116*	0.580‡	0.654‡	0.200‡	0.212‡
Career duration	-0.155*	-0.044	0.073	0.070	-0.175†

Training (d/wk)	0.017	-0.125*	-0.121	-0.039	0.073
Training (hr/d)	-0.026	0.075	0.030	0.093	-0.159†
<i>Pearson's partial correlation co-efficient (controlling for age, height and sex)</i>					
Career duration	-0.026	-0.024	0.063*	0.032	-0.096‡
Training (d/wk)	-0.001	-0.009	0.000	0.002	0.016
Training (hr/d)	-0.002	0.014	-0.018	0.046	-0.088‡

* P<0.05, † P<0.01, ‡ P<0.001. Given that body height and age correlate with a number of IVD and spine parameters, we focus on partial correlations for assessing the association between training variables and IVD parameters. Correlations are with average lumbar IVD variables.