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Perturbation-based exercise for prevention of low-back pain in adolescent athletes

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The purpose of this study was to assess the effectiveness of a perturbation-based exercise intervention on the prevention of chronic non-specific low-back pain in adolescent athletes over 1 year. In a 2-year prospective research design, thirty-seven adolescent athletes (13-18 years) were recruited. In the first year (control), the athletes performed their usual training program, while in the second year (intervention), a perturbation-based trunk exercise intervention was implemented (two times per week for 25 minutes). Low-back pain incidence, trunk muscle strength, lumbo-pelvic alignment, and kinematics were measured four times per year. The 3 months prevalence of low-back pain reduced by 49% in the intervention compared to the control year. Further, low-back pain intensity decreased ($P = .019$, d = 0.524) and muscle strength of the trunk extensors ($P = .040$, d = 0.585) and trunk flexors ($P = .002$, d = 0.515) increased in the intervention year. Finally, a reduction ($P < .001$, d = 1.401) of strength imbalances between the flexor and extensor muscles was observed. Lumbo-pelvic alignment and kinematics during forward bending did not alter ($P > .05$) due to the intervention. The findings evidence beneficial effects of a perturbation-based exercise intervention on the prevention of low-back pain. This underlines the need for the implementation of specific interventions of trunk muscles in the training process.

KEYWORDS
KINGS project, low-back pain intensity, low-back pain prevalence, lumbo-pelvic ratio, spine alignment, trunk strength imbalances

1 | INTRODUCTION

Low-back pain is a worldwide-recognized problem with dramatic consequences for the quality of life of the affected people.[1,2] Epidemiological studies evidenced that all age groups, from teenagers to young and old adults, are affected by low-back pain.[2,3] In 85%-95% of the low-back patients, the diagnosis of a recognizable, specific pathology based on infection, structural deformity, or inflammatory disorder is lacking.[4] For this reason, all these patients are diagnosed with "non-specific" low-back pain. The absence of a clear and recognizable pathology results in a large variation of intervention outcomes.[5,6] Systematic reviews show that effect sizes of most treatments for non-specific low-back pain are

quite low and that only physical exercise interventions show consistent treatment success.[7,8]

Imbalances in trunk muscle strength and alterations in lumbo-pelvic alignment (higher lordosis) and lumbo-pelvic kinematics (higher pelvic rotation) during forward bending have been suggested as risk factors for low-back pain.[9] Specific training programs that support a balanced strength development of the trunk muscles and contribute to lumbo-pelvic stability have been recommended to be beneficial not only for the general population, but also for well-trained athletes.[10,11] Low-back pain prevalence is quite low in children; however, it increases steeply in adolescence and approaches values as documented for adults in late adolescence.[2,3,12] Athletes of both sexes show on average a higher prevalence of low-back pain compared to non-athletes,[13] although there are also reports of similar back pain prevalence between young athletes and age matched non-athletes.[14] The loads and movements associated with competitive sports may pose a challenge for the neuromuscular control of spine stability, affecting low-back pain prevalence and intensity in athletes. Considering that the incidence of low-back pain increases after the age of 13 in both non-athletes[15] and athletes,[3,16] we can argue that preventive intervention strategies are needed to prevent low-back pain in adolescence, particularly in adolescent athletes. Although there are some reports on the effects of exercise interventions on low-back pain incidence in adolescent athletes,[17,18] most information regarding the effectiveness of exercise interventions is based on secondary prevention programs of low-back pain with adult patients.[19] Whether the outcomes in adults and the resulting recommendations are also appropriate for adolescent athletes is yet unknown.

Recently, we found that a perturbation-based functional exercise intervention can reduce low-back pain intensity in chronic non-specific low-back pain patients.[20] Furthermore, the intervention improved the strength of trunk muscles and the neuromuscular control of spine stability during sudden loading. The positive effects of the perturbation-based intervention on both muscle strength and neuromuscular control are particularly relevant, because a direct transfer of muscle strength improvements from classical resistance training to the motor control of the spine in response to sudden loading is questionable.[21] The specificity of the perturbation-based training regarding the perception and processing of sensory information within the motor system may increase the effectiveness of this transfer. Indeed, there is evidence that the presence of unpredictable fluctuations and disturbances in the neural information processing facilitates the ability of the nervous system to detect and transmit weak sensory signals[22,23] and to form neural networks that are more robust and more efficient to cope with environmental changes.[24]

The purpose of the current study was to assess the effectiveness of a perturbation-based exercise intervention on the prevention of chronic non-specific low-back pain in adolescent athletes over a 1-year period. We hypothesized a reduction of low-back pain prevalence and low-back pain intensity as consequence of the applied exercise intervention. Further, we expected improvements in strength of trunk extensor and trunk flexor muscles and in lumbo-pelvic alignment and coordination.

2 | MATERIALS AND METHODS

2.1 | Participants and research design

We used a 2-year prospective research design to evaluate the effect of the perturbation-based exercise intervention on low-back pain prevention in adolescent athletes, with the first year serving as control period and the second as intervention period. To determine the appropriate sample size for the study, we conducted an a priori power analysis in G*Power (Version 3.1.6; HHU, Düsseldorf, Germany) using the outcomes of our earlier intervention in low-back pain patients.[20] The size of the effect observed on pain in that study ($d = 0.6$) was adjusted to the expected prevalence of low-back pain in the present cohort (60%; ie, $d = 0.35$ or $f = 0.175$). Due to the four measurement time points that constitute 1 year of observation in our design, the main effect of year (control vs intervention) calculates to $f = 0.35$,[25] which provides a sample size of n = 19 to achieve a power of >0.8 (using an alpha level of 0.05 and a correlation between measures of 0.5). To account for a potential drop-out, we recruited thirty-seven high-level adolescent athletes from the disciplines canoe racing (n = 18, 4 females), swimming (n = 11, 6 females), and athletics (throwing disciplines, n = 8, 6 females) for the study. The athletes trained more than 12 hours per week and participated regularly in national competitions. Inclusion criteria were 13-18 years of age and no recognizable, specific pathology based on infection, structural deformity, trauma, or inflammatory disorder. Exclusion criteria were a previous history of a spinal surgery, prolapse, herniated disks, mental, neurological, cardiovascular diseases, sensory motor deficits, and continuous dependency on pain relief medication or physiotherapist treatment. All participants and their legal guardians signed informed consent for their participation in the study, which was approved by the ethics committee of the Humboldt-Universität zu Berlin (HU-KSBF-EK_2018_0003).

In the first year, the athletes performed their usual training program without any additional intervention and this year served as control year. In the second year (intervention year), a specific perturbation-based trunk exercise intervention was implemented in the training program of the athletes two times per week for 25 minutes. The total training time did not increase in the second year due to the trunk training. We measured low-back pain prevalence, trunk muscle strength,

and lumbo-pelvic kinematics four times per year to evaluate the perturbation-based intervention. The four measurements were done in the end of the second and last month of the preparation period, in the last month of the competition period, and in the second month of the transitional period. The first measurement in both years was done in the end of the second month of the preparation period, and therefore, the athletes had already been training for 7 weeks with the perturbation-based exercise in the intervention year. This means that possible effects of the perturbation-based intervention in the second year would be present already in the first measurement. We used this design to investigate possible associations between low-back pain prevalence and training period and the possible influence of the perturbation-based intervention. The athletes who participated at least in six measurements (three for every year) were considered in the final evaluation. Finally, twenty athletes (age: 15.5 ± 1.2 years, body height: 180.1 ± 6.8 cm, body mass: 71.1 ± 7.2 kg, body mass index: 21.9 ± 1.0 kg/m^2) completed the requirements (12 canoe racing, 2 female; 5 swimming, 1 female; 3 athletics, 2 females). Twelve athletes participated in all 8 measurements, six in 7, and two in 6 measurements.

2.2 | Exercise intervention

The applied training program included exercises for the trunk muscles, in which variable and partly unpredictable disturbances were continuously applied during execution. For the development of the perturbation-based program, we used a four-component approach, where we modified training device, type of exercise, complexity of exercise, and type of perturbation. We included 7 different training devices (soft pads, balance cushions, bosu balls, inverted bosu balls, swiss balls, slashpipes, and sling trainers), 8 different types of exercises (balance in laying, balance in sitting, double and single leg standing, side-ups, push-ups, squats, and jumping), 2 levels of exercise complexity (with and without

trunk rotation), and 2 types of perturbations (unilateral and bilateral perturbations). Figure 1 shows an example of our training approach on a bosu ball with the 8 different types of exercises and the two types of perturbations. The possibilities of combinations in our four-component approach (7 devices, 8 types of exercises, 2 levels of complexity, and 2 types of perturbations) resulted in a repertoire of 224 different exercises which were applied in the training period of the intervention year. The high amount of different exercises and the wide range of exercise challenges allowed a progressive regulation and adjustment of training according to the skills of the athletes based on the following criteria: (a) the performed exercise did not provoke any low-back pain in the athlete, (b) the athlete was able to execute the exercise technically correct, and (c) the performed exercise was perceived as challenging. In every training session, the athletes performed three sets of 1 minute training from four different exercises with 1 minute break between each execution.

2.3 | Evaluation

The primary outcome measure for the evaluation of the intervention was the chronic pain intensity (CPI) score[26] to assess the low-back pain prevalence and intensity of the included athletes. The secondary outcome measures were (a) trunk extension/flexion moments during maximum voluntary isometric contractions and (b) lumbo-pelvic kinematics in the upright standing position and during forward trunk bending.

2.3.1 | CPI score

For the assessment of low-back pain intensity, we used the validated German version of the "Chronic Pain Grade Questionnaire."[27] The CPI score presents a normalized and average score of three different items including the current, worst, and mean pain in the last 3 months and ranges between 1 and 100.

FIGURE 1 Illustration of the eight different types of exercises (balance in laying, balance in sitting, double and single leg standing, side-ups, push-ups, squats, and jumping) with one (upper series) or two (bottom series) sources of perturbations, without trunk rotation and using the bosu ball as the main device. Written informed consent was obtained from the individuals for the publication of these images

2.3.2 | Trunk muscle strength and lumbo-pelvic kinematics

The forces during maximum isometric trunk flexion and extension contractions were measured (1000 Hz) with a custom-made mobile measuring device using a force sensor (Megatron Elektronik AG & Co., KM1506 K 2 kN). The participants were seated with the trunk orthogonal to the floor and wore a chest belt which was connected to the pole of the measuring device via a pulley, adjustable in height in order to place the force sensor vertical to the trunk.[11] The participants performed two maximum isometric contractions for extension and two for flexion in a randomized order with steadily increasing effort from rest to maximum, followed by a plateau at maximum of 2-3 seconds. Between each contraction, a two-minute break was approved. The maximum force was calculated as average force signal at peak force ± 250 ms, and the force lever arm was measured as the distance between the surface of the seat (as axis of rotation) and the position of the chest harness. The trial with the higher moment value was included in the analysis.

The lumbo-pelvic kinematics in the upright standing position and during forward trunk bending were measured using two 3-dimensional acceleration sensors (Biovision, Wehrheim; size $1 \times 1 \times 1$ cm, 1000 Hz) attached to the skin at the level of thoracic vertebrae 12 (T12) and sacral vertebrae 1 (S1). The pelvic ($Base_{pelvic}$) and trunk ($Base_{trunk}$) angle in the upright stance were calculated in the sagittal plane using the orientation of the local coordinate system of the attached sensors in S1 and T12, respectively, with respect to the global coordinate system. Positive values of the two angles indicate a forward-rotated orientation (with respect to the vertical), while negative values indicate a backward-rotated orientation of sacrum or trunk. The lumbar angle ($Base_{lumbar}$) was then calculated as the difference between $Base_{trunk}$ and $Base_{pelvic}$ with negative values indicating the magnitude of lumbar lordosis. The range of motion (RoM) of the pelvic (RoM_{pelvic}) and trunk (RoM_{trunk}) of the participants was measured in the sagittal plane during a controlled maximum forward trunk bending. The lumbar spine RoM (RoM_{lumbar}) was calculated as the difference between RoM_{trunk} and RoM_{pelvic}. The lumbo-pelvic ratio (LPR) was calculated as the ratio of the changes in lumbar spine orientation to the changes of pelvic orientation. LPR was calculated for the whole forward bending motion (full) as well as for the first (early), second (middle), and final (late) third of the RoM.

2.4 | Statistics

Normal distribution of the data was examined using the Kolmogorov-Smirnov test with Lilliefors correction. A two-way ANOVA for repeated measures was performed with year (control and intervention year) and training period (second and last month of the preparation, last month of the competition and second month of the transitional period) as within-subject factor. Age and body mass index increased during the study and, therefore, we included age and body mass index as covariates in our statistical analysis. A Bonferroni-corrected *post-hoc* analysis was conducted in the case of a significant interaction of the factors *year* and *training period*. To examine relationships between parameters, the Pearson correlation coefficient was used. The level of significance for all comparisons was set to $\alpha = 0.05$. Furthermore, to estimate the strength of potential alterations of the investigated parameters following the exercise, the Cohen's effect size (d) was calculated. Values of $d < 0.2$ indicate small effect sizes, $0.2 \leq d < 0.8$ indicate medium effect sizes, and $d \geq 0.8$ indicate large effect sizes.[28]

To evaluate the agreement between flexion and extension trunk moment for the control and intervention year, we performed a linear mixed regression model (equation see below) for each year with its four measurements ($j = 1,\ldots,4$). Flexion moment M_{ij}^{flex} of each participant ($i = 1,\ldots,n$) was used as predictor for the corresponding extension moment M_{ij}^{ext}. The model included fixed effect coefficients of intercept (c) and slope (b) and random effect coefficients of intercept (c_i) and slope (b_i)–modeling the individual differences between participants in the relationship. The equation was as follows:

$$M_{ij}^{ext} = c + b \times M_{ij}^{flex} + c_i + b_i \times M_{ij}^{flex} + \varepsilon_{ij}$$

The average absolute residuals ε_{ij} (expressed in percent of M_{ij}^{ext}) of each participant were used for further analysis as a measure of imbalances between flexion and extension moments. It has to be mentioned that often the ratio of the flexion to the extension moment is used for the assessment of imbalances in trunk muscle strength.[29,30] In our opinion, it is very difficult, if possible, to define a clear optimal strength ratio and, therefore, in the current study, we evaluated the agreement in the adaptation process between trunk flexor and trunk extensor muscle strength over time. Assuming a balanced relationship of trunk flexion and extension strength, there should be a linear relationship between them, and therefore, the absolute residuals of the linear mixed regression model of the four measurements can be used to quantify an imbalance of flexion and extension strength development, irrespective of the direction of the strength deficit (ie, a deficit in flexion or extension). A paired *t*-test was performed to check the differences of the residuals between the control and intervention year. For the graphical representation of the outcomes, we used boxplots depicting the median and the 5th and 95th percentile as whiskers.

TABLE 1 Anthropometric characteristics of the involved participants (average value ± standard deviation)

Parameter	Control year				Intervention year			
	Preparation 1	Preparation 2	Competition	Transitional	Preparation 1	Preparation 2	Competition	Transitional
Age (y)	15.5 ± 1.1	-	-	-	16.7 ± 1.4	-	-	-
Body mass (kg)*	71.1 ± 7.2	72.9 ± 6.6	73.1 ± 6.2	73.9 ± 6.9	74.8 ± 7.2	76.1 ± 7.1	75.4 ± 7.1	75.1 ± 6.9
Body height (cm)	180.1 ± 6.8	180.6 ± 7.2	181.4 ± 7.0	181.2 ± 7.2	181.1 ± 7.4	181.0 ± 7.1	181.6 ± 7.1	181.1 ± 6.9
Body mass index (kg/m^2)*	21.9 ± 1.9	22.4 ± 1.8	22.2 ± 1.5	22.5 ± 1.8	22.8 ± 1.9	23.2 ± 1.9	22.9 ± 1.8	22.9 ± 2.0

Note: Preparation 1: second month of the preparation period, Preparation 2: last month of the preparation period, Competition: last month of the competition period, Transitional: second month of the transitional period.

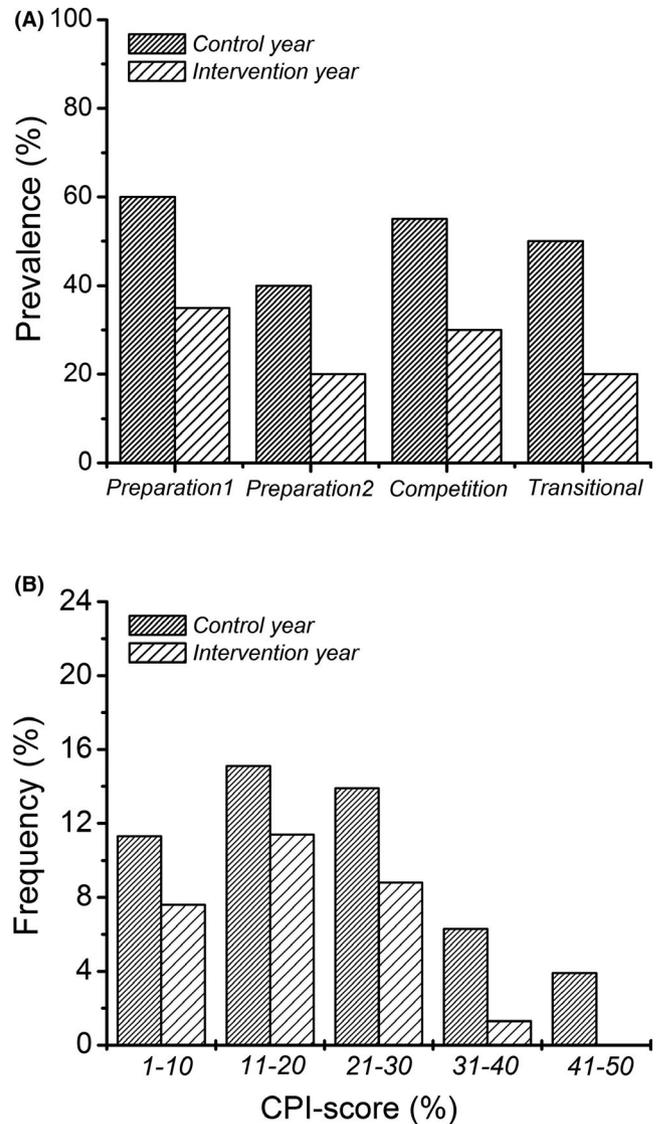*Statistically significant difference between control and intervention year ($P < .05$).

FIGURE 2 (A) Three months prevalence of low-back pain examined in the second (Preparation1) and last month (Preparation2) of the preparation period, last month of the competition period (Competition), and second month of the transitional period (Transitional), (B) frequency of the chronic pain intensity score (CPI score) calculated in 10% intervals of the CPI score in the control and intervention year. Note that the first measurement in both years was done in the end of the second month of the preparation period. Therefore, the athletes had already been training for 7 wk with the perturbation-based exercises in the intervention year.

3 | RESULTS

A significantly higher body mass ($P = .025$, d = 0.395) and body mass index ($P = .021$, d = 0.387) were observed in the intervention compared to the control year. There was no difference in body height between the 2 years ($P = .755$), and there was not any year-by-training period interaction in all three parameters ($P > .05$, Table 1). In the control year and considering all four measurement time points, 14 of the 20 athletes reported low-back pain. In the intervention year, four of

TABLE 2 Chronic pain intensity score (CPI score), maximum trunk extension moment ($Moment_{ext}$), and maximum trunk flexion moment ($Moment_{flex}$) during the isometric contractions (average value ± standard deviation)

Parameter	Control year				Intervention year			
	Preparation 1	Preparation 2	Competition	Transitional	Preparation 1	Preparation 2	Competition	Transitional
CPI score (%)*	16.1 ± 10.6	10.0 ± 14.3	12.0 ± 15.3	12.1 ± 15.3	7.1 ± 10.6	5.1 ± 10.5	6.8 ± 10.3	4.4 ± 9.5
$Moment_{ext}$ (Nm/kg)*	8.04 ± 1.04	7.27 ± 0.92	8.14 ± 0.76	7.95 ± 1.27	8.27 ± 1.51	8.44 ± 1.09	8.76 ± 1.18	8.53 ± 1.28
$Moment_{flex}$ (Nm/kg)*	4.03 ± 0.39	3.75 ± 0.53	4.05 ± 0.67	3.93 ± 0.58	4.26 ± 0.66	4.16 ± 0.73	4.27 ± 0.63	4.30 ± 0.61

Note: The first measurement in both years was done in the end of the second month of the preparation period. Therefore, the athletes had already been training for 7 wk with the perturbation-based exercise in the intervention year.

Preparation 1: second month of the preparation period, Preparation 2: last month of the preparation period, Competition: last month of the competition period, Transitional: second month of the transitional period.

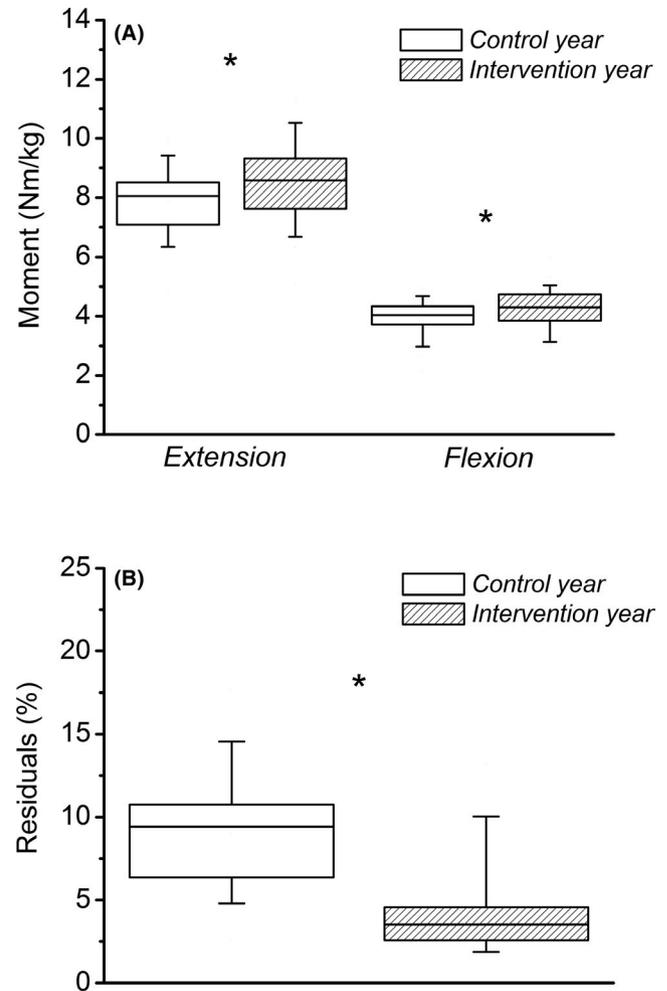*Statistically significant difference between control and intervention year ($P < .05$).

FIGURE 3 (A) Maximum trunk extension and trunk flexion moments during the isometric contractions in the control and intervention year (averaged over the respective four measurement time points). (B) Residuals of the linear regression model predicting the extension moment by the flexion moment in percent of the maximum extension moment in the control and intervention year. *significant difference between control and intervention year ($P < .05$)

them became pain free and no one from the others developed pain. The 3 months prevalence of low-back pain assessed from "Chronic Pain Grade Questionnaire" during the four training periods is presented in Figure 2 and was in average 51% for the control and 26% for the intervention year. The CPI score was significantly lower ($P = .019$, d = 0.524) in the intervention year without any training period effect or year-by-training period interaction ($P = .879$, Table 2). Further, the frequency of athletes with low-back pain was reduced in all pain intensity intervals during the intervention year (Figure 2).

The maximum trunk extension and trunk flexion moments normalized to body mass were greater in the intervention compared to the control year (extension: $P = .040$, d = 0.585; flexion: $P = .002$, d = 0.515), and there was no training period effect or year-by-training period interaction ($P > .05$, Table 2 and Figure 3). The residuals from the linear

TABLE 3 Pelvic (Base$_{pelvic}$), lumbar (Base$_{lumbar}$), and trunk angles (Base$_{trunk}$) during the standing position, range of motion of pelvic (RoM$_{pelvic}$), lumbar (RoM$_{lumbar}$), and trunk (RoM$_{trunk}$) during the maximum forward trunk bending motion and lumbo-pelvic ratio during the full (LPR$_{full}$), early (LPR$_{early}$), middle (LPR$_{middle}$), and late (LPR$_{late}$) part of the forward trunk bending motion (average value ± standard deviation)

Parameter	Control year				Intervention year			
	Preparation 1	Preparation 2	Competition	Transitional	Preparation 1	Preparation 2	Competition	Transitional
Base$_{pelvic}$ (°)	11.0 ± 8.2	10.8 ± 8.9	9.2 ± 5.2	9.7 ± 5.1	9.5 ± 6.1	7.8 ± 6.7	9.1 ± 8.2	12.2 ± 9.4
Base$_{lumbar}$ (°)	−16.2 ± 10.6	−16.9 ± 11.3	−14.6 ± 8.9	−16.3 ± 8.5	−13.4 ± 12.6	−12.6 ± 9.1	−16.8 ± 10.7	−17.5 ± 11.6
Base$_{trunk}$ (°)	−6.1 ± 4.6	−6.1 ± 4.2	−6.7 ± 4.9	−6.1 ± 4.6	−4.5 ± 5.1	−4.8 ± 3.8	−7.7 ± 4.6	−5.2 ± 3.3
RoM$_{pelvic}$ (°)	65.7 ± 16.6	65.4 ± 14.5	66.3 ± 14.8	67.7 ± 13.5	68.4 ± 14.8	70.5 ± 15.1	71.6 ± 12.8	70.4 ± 16.9
RoM$_{lumbar}$ (°)	55.6 ± 12.9	58.2 ± 11.8	62.4 ± 11.8	62.6 ± 7.1	59.4 ± 7.6	60.5 ± 7.7	60.3 ± 10.1	59.4 ± 9.0
RoM$_{trunk}$ (°)	120.8 ± 19.4	123.7 ± 17.1	130.6 ± 15.3	130.4 ± 14.3	128.1 ± 15.9	131.1 ± 14.5	131.9 ± 17.2	129.8 ± 14.5
LPR$_{full}$	0.89 ± 0.30	0.94 ± 0.32	0.99 ± 0.29	0.96 ± 0.24	0.91 ± 0.24	0.91 ± 0.28	0.87 ± 0.19	0.92 ± 0.39
LPR$_{early}$	1.80 ± 1.55	2.42 ± 1.52	2.83 ± 1.76	2.12 ± 1.43	2.02 ± 1.22	1.91 ± 0.83	1.85 ± 0.82	2.64 ± 2.33
LPR$_{middle}$	1.37 ± 0.72	1.27 ± 0.56	1.59 ± 0.46	1.46 ± 0.48	1.35 ± 0.47	1.35 ± 0.58	1.22 ± 0.42	1.38 ± 1.16
LPR$_{late}$	0.39 ± 0.27	0.32 ± 0.26	0.23 ± 0.20	0.35 ± 0.28	0.31 ± 0.21	0.32 ± 0.31	0.31 ± 0.21	0.31 ± 0.24

Note: Preparation 1: second month of the preparation period, Preparation 2: last month of the preparation period, Competition: last month of the competition period, Transitional: second month of the transitional period.

mixed regression model were lower in the intervention year ($P < .001$, d = 1.401), indicating a higher association between trunk extension and flexion muscle strength in the intervention compared to the control year (Figure 3). We did not find a significant association between the increase in maximum trunk extension moment ($r = 0.001$, $P = .999$), maximum trunk flexion moment ($r = −0.372$, $P = .234$), and decrease in the residuals ($r = 0.256$, $P = .423$) with the reduction in CPI score.

Pelvic, lumbar, and trunk angle in the standing position as well as pelvic, lumbar, and trunk RoM during the forward trunk bending did not show any year or training period effects ($P > .05$), and there was no year-by-training period interaction in all these parameters ($P > .05$, Table 3). The LPR decreased systematically ($P < .001$) from the early to the late part of the maximum forward trunk bending motion, but there were no year or training period effects or year-by-training period interactions ($P > .05$, Table 3).

4 | DISCUSSION

The proposed perturbation-based exercise intervention of the trunk muscles, applied for 1 year in adolescent athletes, led to an improvement in trunk muscle strength and a reduction of strength imbalances between the flexor and extensor muscles. More importantly, the intervention significantly reduced low-back pain prevalence and low-back pain intensity. The findings support our hypotheses and evidenced the success of the perturbation-based training for the prevention of low-back pain in athletes at this age.

We found in average a 3 month low-back pain prevalence of 51% in the control year, which is in agreement with values for athletes in comparable age reported earlier.[3,31] The pain prevalence reduced to 26% in the intervention year indicating a relevant effectiveness of the intervention on low-back pain prevention. The pain intensity assessed by the CPI score was also lower in the intervention than in control year (in average 34%). The CPI score ranged between 0% and 50% in the control year showing that the intensity of low-back pain in our investigated athletes was rather low and moderate at worst. The found decrease of athletes low-back pain frequency in all CPI-score intervals, however, shows the positive effect of the intervention in a wide range of pain intensities. Although the effect size of d = 0.584 in the CPI score indicates a moderate exercise effect on pain intensity, this value is similar to the largest effect sizes reported in studies investigating the beneficial effects of exercise programs in chronic low-back pain treatment.[7,8] Moreover, 4 out of 14 athletes that reported pain in the first year were symptom free in the following intervention year and all others symptomatic athletes but one demonstrated a decrease in CPI score. These results show that almost all athletes benefited from the applied perturbation-based

exercise intervention integrated in the usual training program of the athletes.

Our plan was to design a functional perturbation training for the trunk muscles based on the continuous application of varying and partly unpredictable disturbances and to integrate these exercises into the usual training program of adolescent athletes. We expected an increase in trunk muscle strength as well as an improvement in the neuromuscular control of spine stability and, as a consequence, a reduction of low-back pain and injury risk. Challenging conditions, as for example the exposure to external perturbations, enhance the demand for the sensorimotor system to perceive sensory signals and to generate appropriate motor commands. It has been reported that external perturbations increase movement instability and challenge the neuromotor system during motion.[32-34] As a response, the neuromotor system modifies the motor control and increases the systems robustness (ie, ability to cope with perturbations[32,33]). Recently, we found that, in the presence of perturbations, the central nervous system generates fuzzier, less unstable, and less complex basic activation patterns of muscle groups, which makes the motor execution less prone to the influence of disturbances.[35] Furthermore, we observed this modification in motor control in wild-type mice but not in genetically modified mice that lacked feedback from proprioceptors,[36] which shows the relevant contribution of proprioception in the modulation of motor control in the presence of perturbations. These reports indicate that the exposure to perturbations leads to a specific modulation of motor control and reorganization of neural networks, strongly influenced by proprioceptive input. Such modifications in regulating motor function in challenging settings might be related to the efficacy of the applied exercise intervention, by improving the ability of the motor system to modulate effective robustness in demanding conditions and in response to environmental changes during the training and daily life.

We found an increase in the body mass-normalized maximum trunk extension (30%) and trunk flexion (8%) moments in the intervention year, indicating an improvement in trunk muscle strength. The improvement of muscle strength in the intervention year might have occurred not only due to the applied exercise intervention but also the increased calendar age of the athletes. However, in our statistical analysis, we considered the normalized trunk moments and we included age and body mass index as covariates in the comparisons. With this methodological approach, we can confidently assume a contribution of the intervention to the muscle strength improvements. Furthermore, we found lower residuals in our regression model in the intervention year. The lower residuals evidence a more consistent association between the trunk flexor and extensor muscles, which indicates lower imbalances in the development of muscle strength within the trunk muscles. Discrepancies in the strength development of the trunk muscles have been suggested as possible risk factor

for spine pathology and low-back pain,[9] and well-developed trunk muscles can be important in athletes for improving trunk stability and reducing low-back pain.[10,18]

In the current study, we were not able to identify a direct relationship between the improvement in trunk muscle strength or decrease in the residuals with the reduction of pain intensity, and therefore, the found alterations in trunk muscle strength did not explain the low-back pain reduction in the intervention year. Several studies reported inconsistent associations between trunk muscle strength and low-back pain in children and adolescence.[37,38] The origin of low-back pain is multifactorial, and currently, there is not a clear factor or concert of factors that explain and precisely predict the occurrence of low-back pain.[2] Most of the variance in low-back pain remains unexplained and relates to unknown or unmeasured factors.[39] On the other hand, a plethora of systematic reviews and meta-analyses report beneficial effects of resistance and coordination programs, which aimed to improve trunk muscle strength and trunk stability, on low-back pain and functional outputs.[6-8] Demanding conditions during training and competition in athletes challenge the neuromuscular control of spine stability, which increases the need of an enhanced and balanced muscle strength development of trunk extensor and trunk flexor muscles for the appropriate control of spine stability compared to the normal population. Although we cannot argue that the found low-back pain reduction in the intervention year was necessarily due to the increased and more balanced strength of the trunk muscles, our findings give evidence to the idea that preventive intervention strategies are needed and can be effective in adolescent athletes.

During the forward trunk bending, the LPR showed a continuous decrease, which indicates a greater lumbar than pelvic rotation in the early and middle part of the trunk bending. In the late part, the contribution of the pelvis dominated, which resulted in LPR-values lower than one. Forward bending of the trunk is a routine clinical examination to evaluate spine mobility, and both RoM and LPR have been often used for the assessment of spine dysfunction and examination of atypical trunk kinematics. It has been reported that less trunk, lumbar and pelvic RoM, lower LPR and greater lordotic posture during the forward bending associate to low-back pain.[40-42] In our study, we did not find any intervention effects on the investigated lumbo-pelvic kinematics. Spine alignment, RoM, and LPR remained unaltered despite the reduction of low-back pain and increase of trunk muscle strength in the intervention year. Similarly, Shahvarpour et al[43] were not able to identify significant changes of lumbo-pelvic kinematics after an 8 weeks of lumbar stabilization exercise program in adult low-back pain patients, despite improvements in functional outputs. It seems that the effects of exercise interventions of the trunk muscles on lumbo-pelvic posture and kinematics are quite inconsistent and that these kinematic measures may not be sensitive enough for screening improvements of

low-back pain, especially in young athletes with low to moderate pain intensity.

The proposed perturbation-based intervention is effective and attractive for low-back pain prevention in several aspects. First, the intervention reduced the intensity and prevalence of low-back pain and improved the strength of the trunk muscles in high-level adolescent athletes. Both outcomes are very important for the development of a healthy and successful athletic carrier. Less low-back pain prevalence and intensity through a year period can improve the training process and the training-induced musculoskeletal adaptation. Our young athletes trained more than 12 hours per week and participated regularly in national competitions. This amount of athletic activity poses an increased demand on the musculoskeletal system, which can lead to overload of the spine, particularly in adolescence. Well-developed trunk muscles and appropriate neuromuscular control of spine stability may act as protective elements against spine overload. Second, the intervention can easily be implemented in the usual training program of athletes. Two times per week for 25 minutes, trunk exercises were lower than 7% of the training volume in the investigated athletes and could smoothly be integrated as part of the usual resistance and coordination training. The specific design of the perturbation-based intervention made it possible through modifications of known and scheduled strength and coordination exercises, without an increase in the total training duration, to simultaneously stimulate muscle adaptation and neuromotor control. Finally, the four-component approach of the intervention with 7 different training devices, 8 different type of exercises, 2 levels of complexity, and 2 types of perturbations enabled us to create a repertoire of 224 different exercises with a wide range of diversity, intensity, and attractiveness. The high variety of exercises provided solutions for qualified trunk muscle training for all athletes. Furthermore, the training devices used to initiate perturbations are simple, not expensive, and easily implementable in the training praxis and, therefore, from a translational point of view highly effective.

A limitation of the study is the lack of a randomized controlled trial design. In the training praxis, it is very difficult to randomly assign athletes of the same team into either an intervention or a control group. The athletes of each team trained together with the same trainer, and it was not possible for us to differentiate two groups in the same team with different training modalities for 1 year. Therefore, we used a 2-year experimental design, where in the first year we monitored the athletes without any interference with the training and used this year as control for the second intervention year. The progressing age of the participants was accounted for in the statistical analysis of the main outcome parameters, including pain intensity. However, pain prevalence could not be adjusted with regard to age. Yet, due to the general increase of low-back pain prevalence with age, a potential risk of bias considering would tend toward an under- rather than overestimation of the intervention effect.

4.1 | Perspectives

We found that a specific training of trunk muscles applied two times per week for 25 minutes for 1 year can reduce low-back pain prevalence, low-back pain intensity, improve strength of the trunk muscles, and reduce imbalances in muscle strength between trunk flexors and trunk extensors in adolescent athletes. These findings evidence the beneficial effects of our perturbation-based exercise intervention on the prevention of low-back pain in adolescent athletes. Taken into consideration that low-back pain is a common problem in adolescent athletes and increases steeply in late adolescence, our results underline the need for the implementation of specific interventions and particularly perturbation-based exercises of trunk muscles in the training process. We propose that functional strength exercises in the presence of perturbations increase the demand for the sensorimotor system and trigger specific modulations in motor control to regulate the robustness of motor function, which may be beneficial for spine stability and might explain the improvements observed in the present study.

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