Engel T[1], Arampatzis A[2], Moreno Català M[2], Kopinski S[1], Mayer F[1]

Perturbations in Prevention and Therapy of Low Back Pain: a New Approach

Perturbationsgestütztes Training in der Prävention und Therapie von Rückenschmerzen

REVIEW

ACCEPTED: June 2018
PUBLISHED ONLINE: July 2018
DOI: 10.5960/dzsm.2018.334

Engel T, Arampatzis A, Moreno Català M, Kopinski S, Mayer F. Perturbations in prevention and therapy of low back pain: a new approach. Dtsch Z Sportmed. 2018; 69: 247-254.

1. UNIVERSITY OF POTSDAM, *University Outpatient Clinic, Centre of Sports Medicine, Potsdam*
2. HUMBOLDT-UNIVERSITÄT ZU BERLIN, *Department of Training and Movement Sciences, Berlin*

Summary

- **Background:** This overview provides an introduction to neuromuscular adaptations by exercise interventions based on random perturbations. It is outlined that specific therapeutic intervention based on perturbations may improve spine stability during disturbances as well as neuromuscular control errors and thereby may increase the efficiency of treatment in low back pain.
- **Methods:** Specific experimental approaches to assess neuromuscular control of trunk stability during and after perturbations are presented. Further, evidence of neuromuscular adaptations after perturbation-based exercise interventions is given. Finally, a concept to transfer perturbation-based exercises from laboratory conditions to low-back pain therapy settings is introduced.
- **Results and Discussion:** Well-established (e.g. quick-release experiments) and novel (e.g. walking perturbations) techniques could indicate neuromuscular deficits in low-back pain compared to asymptomatic controls in response to sudden perturbation experiments applied during quick-release experiments, during perturbed isokinetic strength testing and during sudden stumbling incidents in walking. A novel perturbation training, induced by continuously variable and unpredictable disturbances, successfully served to increase the neural noise in the nervous system. Evidence indicated that neural networks that have been formed in the presence of noise would be more robust and efficient to cope with environmental changes. Finally, the development and evaluation of a perturbation-based training program consisting of core-specific exercises which can be carried out without expensive laboratory perturbation equipment is outlined.

Zusammenfassung

- **Hintergrund:** Dieser Übersichtsartikel stellt den Ansatz eines perturbationsgestützten Trainings zur Prävention und Therapie von Rückenschmerzen vor. Es wird dargelegt, dass eine spezifische therapeutische Intervention basierend auf zufälligen Störungen der Wirbelsäulenstabilität die neuromuskuläre Kontrolle verbessern und dadurch die Effizienz der Behandlung bei Rückenschmerzen steigern kann.
- **Methoden:** Spezifische experimentelle Ansätze zur Beurteilung der neuromuskulären Rumpfstabilität während und nach Störungen werden vorgestellt. Nachweise neuromuskulärer Anpassungen nach perturbationsbasierten Bewegungsinterventionen werden erbracht. Abschließend wird ein Konzept vorgestellt, wie perturbationsbasierte Übungen außerhalb von experimentellen Laborbedingungen in ein allgemeines Therapie-Setting übertragen werden können.
- **Ergebnisse and Diskussion:** Bewährte (z.B. Quick-release Experimente) und neue (z.B. Stolperlaufband) Techniken konnten neuromuskuläre Defizite bei Menschen mit Rückenschmerzen im Vergleich zu asymptomatischen Kontrollpersonen als Reaktion auf plötzliche Störungen während Quick-release Experimenten, perturbierten isokinetischen Krafttests und Stolper-Experimenten beim Gehen belegen. Ein neuartiges Perturbationstraining, durch kontinuierlich variable und unvorhersagbare Störungen induziert, diente erfolgreich dazu, neuronale Prozesse zu modulieren, die einen robusteren und effizienteren Umgang des Nervensystems mit plötzlich an der Wirbelsäule auftretenden Störreizen erlaubte. Abschließend wird die Entwicklung und Evaluierung eines Interventionsprogramms vorgestellt, welches den Transfer des perturbationsgestützten Trainings vom Labor in die Praxis ermöglicht, ohne dabei auf teures Spezial-Equipment angewiesen zu sein.

KEY WORDS:
MiSpEx, Perturbation Training, Neuromuscular Control, Low Back Pain

SCHLÜSSELWÖRTER:
MiSpEx, Perturbationstraining, neuromuskuläre Kontrolle, Rückenschmerzen

CORRESPONDING ADDRESS:
Tilman Engel
Universität Potsdam Hochschulambulanz
Zentrum für Sportmedizin, Freizeit-, Gesundheits- und Leistungssport
Am Neuen Palais 10, Haus 12, Raum 0.11
14469 Potsdam
: tiengel@uni-potsdam.de

Introduction and Theoretical Considerations

Low-back pain (LBP) is a worldwide-recognized problem that creates major issues for public health systems with dramatic consequences for the quality of life of the affected patients (14, 23). Epidemiological studies have evidenced that all age groups, from teenagers to young and old adults, are affected by LBP (19, 37). It is reported that the lifetime-prevalence of LBP is higher than 80% and that chronic low-back pain affects about 23% of the population (1). Furthermore, about 11-12% of the humans worldwide become disabled due to chronic LBP (1). In Germany, during the last ten years the number of community members that consulted medical care due to LBP has increased by ~46% (48). Moreover, the annual costs for medical expenses as well as compensation for abstinence from work have been ~50 billion € (48).

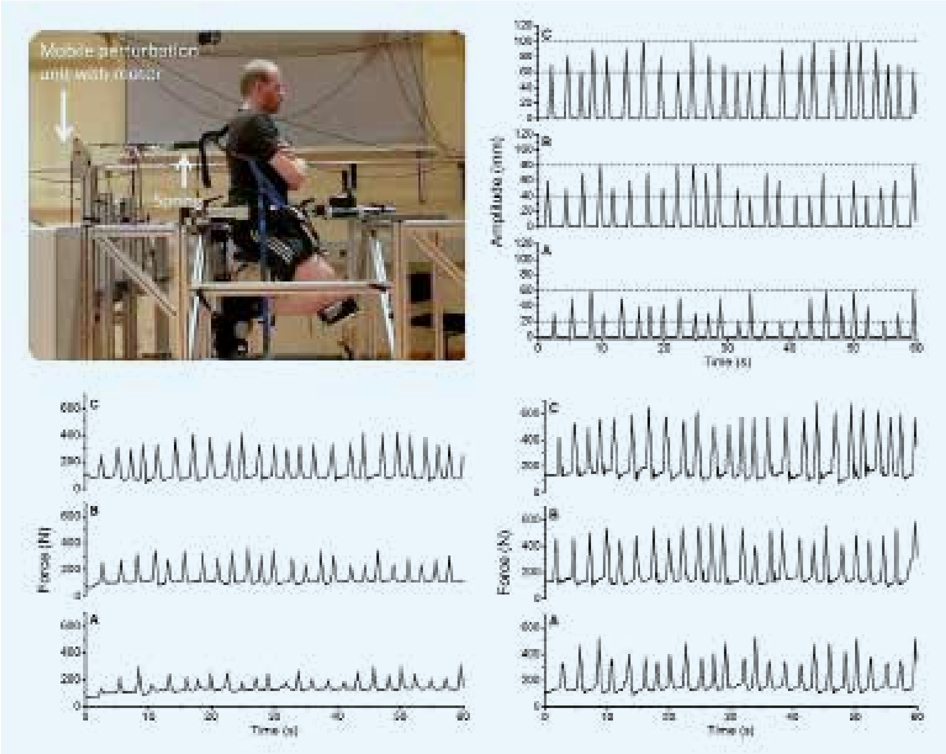

Figure 1

Top left: the specially developed device that induced continuously variable and unpredictable disturbances in the anteroposterior and mediolateral axes of the trunk with the mobile motor unit and the spring. Top right: an example of the pre-programmed randomized triangle perturbation trials altered in amplitude (A: Low 20-60mm; B: moderate 40-80mm; C: high 60-100mm). Bottom: The resulting force during episodes of randomized trunk perturbations at different intensity levels using the low stiffness (3.9kN/m, left) and the high stiffness spring (5.9kN/m, right). (A) low amplitude perturbation; (B) moderate amplitude perturbation; (C) high amplitude perturbation (Arampatzis et al., 2017, with permission from Springer).

In 85-95% of the LBP patients, the diagnosis of a recognizable, specific pathology based on infection, structural deformity, tumor, trauma or inflammatory disorder is lacking (47). For this reason, these patients are all diagnosed with "non-specific" LBP.

Two important factors related to the occurrence of back-pain are trunk strength, as well as trunk neuromuscular control (2, 8, 29). Both are contributing to trunk stability, as the capacity to adequately respond to environmental changes (8). Decreased strength capacity of the trunk muscles has been linked to the occurrence of LBP in a variety of investigations (12, 40, 46, 51). However, back muscle strength alone is not necessarily a significant predictor of LBP (45) and trunk muscle strength is not always impaired in LBP patients (6). Appropriate neuromuscular control of the spine is crucial for spinal stability and thus for optimal function and protection of the spine, especially in situations which require prompt and excessive muscle force generation (15, 34). Sudden and unexpected loading incidents have been repeatedly linked to low back injuries, such as during slips, trips and falls, as well as bending and twisting while lifting, or moving heavy objects (10, 31, 35, 45). Experimental investigations simulating sudden loading incidents by perturbation of the trunk revealed deficits in neuromuscular control of trunk stability in people with LBP (11, 22, 35). In addition, impaired neuromuscular control of the trunk in response to perturbations has been found to increase the risk of sustaining a LBP injury (11). Feedback- as well as predictive-based motor control using information about the "state" (i.e. displacement and velocity) of the system is used to stabilize the spine during different activities. It has been reported that the ability of the spinal system to compensate for small mechanical perturbations and for neuromuscular control errors in order to maintain spine stability during daily life tasks may be related to the initiation of LBP (16, 17, 49, 50). The probability of such motor control errors depends on the particular capacities of the human system (musculoskeletal and neural) as well as on the environmental conditions. The importance of the interaction between performers and physical environment for the initiation of LBP is thus emphasized. However, although trunk muscle strength and neuromuscular control of the trunk associate with low-back pain, it is not yet possible to say whether muscle weakness and changes in neuromuscular control are primary or secondary causes of LBP.

The optimal treatment strategy for people suffering from LBP is still a matter of debate. Exercise including muscle strength and sensorimotor training of the trunk, however, is widely accepted as a mandatory component of therapy interventions in LBP (8, 21, 41, 43, 47). Both factors are considered essential for maintaining posture and for contributing to the stability of the trunk (2, 8, 29). Especially, in situations that require compensation of sudden and high loadings of the spine, e.g. induced by external perturbations, trunk stability has been found to be challenged (8, 26, 36, 39). Consequently, implementation of random/irregular functional perturbation training induced by disturbances on the spine that are unpredictable and continuously variable in amplitude and frequency would improve both trunk muscle strength and neuromuscular control of spine stability. The underlying mechanisms for the expected improvements are (a) an increase in the activation level of the trunk muscles and (b) an increase in the demand of the nervous system to perceive sensory signals and to generate appropriate motor commands. Perturbation induces increase in muscle activation, reinforces muscle loading and initiates muscle adaptation. The perturbation-based increased demand in the neural information processing facilitates the ability of the nervous system to detect and transmit weak sensory signals and to respond with appropriate motor commands (14, 32).

The purpose of the present overview article is to provide a framework for neuromuscular adaptations by exercise interventions based on as well as completed with random/irregular perturbations. In the first part, specific experimental approaches that assess neuromuscular control of trunk stability after and during perturbations are presented. Secondly, evidence of neuromuscular adaptations after perturbation-based interventions developed within the National Research Network for Medicine in Spine Exercise (MiSpEx-Network) is discussed. Finally, the transfer of perturbation-based training from a laboratory setting to a specific therapy regime in low-back pain patients will be introduced.

Experimental Approaches – Perturbations in Testing and Training

Perturbation Experiments

Several experimental perturbation setups have been developed to investigate neuromuscular alterations in people with LBP (18, 22, 35). In general, these setups investigate muscular responses after sudden loading or unloading of the trunk. Muscular activities are therefore commonly studied by electromyography (EMG), assessing response times and amplitude of the EMG activity of individual muscles (11, 35, 36). Furthermore, kinematic and kinetic analyses serve to investigate resulting compensation mechanisms, such as trunk movements, trunk stiffness or resistive forces following sudden load changes (3, 20, 26).

One of the most common experimental approaches, adopted by several research groups, is a custom build quick-release apparatus, which allows for testing muscular responses of major trunk muscles subsequent to an unexpected load release at the trunk in a (half) seated position (3, 11, 34, 35, 36). This testing situation enables to study trunk responses with direct load applications at the trunk under highly standardized conditions.

In addition to earlier presented experimental designs a new perturbation approach applying sudden perturbations during a baseline task of isokinetic movements has been developed in the MiSpEx research network. Two different isokinetic setups are used to apply perturbations either directly at the trunk during isokinetic trunk flexion/extension (standing position) or indirectly via a lever arm attached to the upper extremities in a rotational isokinetic trunk task (seated position). Perturbations are induced by unexpected and short timed alterations of movement velocity. Still measuring in a very controlled environment, these perturbation tasks allow assessing neuromuscular trunk function under dynamic maximum effort conditions.

Studies including perturbation setups enable to study isolated trunk responses as well as reactive responses to sudden external loading (4, 38). Since, sudden loads during daily life are rarely applied directly at the trunk, but rather transferred via upper or lower extremities in events such as slips or trips , different responses in compensation strategy and muscle activity related to load exposure can be assumed (25, 38). In summary, the transfer of experimental approaches to clinical settings as well as daily life situations should be emphasized. Respective experimental setups used for example movable plates or sudden obstacles dropped on the walk-way to provoke sudden load conditions at the trunk (9, 44). Within the MiSpEx research network, a protocol has been introduced to apply sudden perturbations during treadmill walking causing unexpected stumbling incidents on a custom build split-belt treadmill (13, 28). This way, particularly short timed perturbations (sudden alterations of treadmill belt velocity) can be applied to study muscular reflex responses subsequent to a stumbling event in a situation resembling everyday conditions.

Perturbations during Exercises

Systematic reviews show that effect sizes of most treatments for non-specific LBP are quite low and that only exercise therapies seem to have the possibility to be successful (7, 41). Nevertheless, the lack of a clear and recognizable pathology to non-specific LBP has resulted in a large variation in the outcomes of investigated therapies (5). It is widely accepted that resistance training aiming to improve trunk muscle strength is a successful therapeutic modality for reducing LBP and improving functional outcomes (19, 41). Although muscle strengthening has the potential to improve the trunk function and stability, a direct transfer of improvements in motor control of the spine after sudden unexpected perturbations and/or control errors initiated from deficits in the perception and processing of sensory information within the motor system is questionable (41). A more specific therapeutic intervention based on perturbation training may increase the effectiveness of this transfer due to its specificity, thus improving spine stability during disturbances and/or neuromuscular control errors. Furthermore, if a perturbation-based therapy is able to improve muscle strength akin to a conventional resistance exercise intervention, it would increase the efficiency of the therapy.

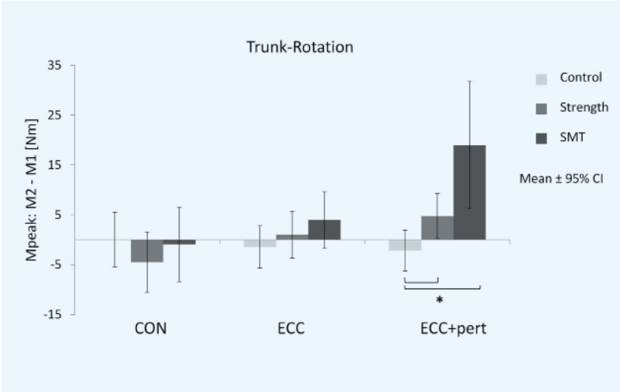

Figure 2

Intervention effect on trunk rotation strength/load resistivity in concentric (CON), eccentric (ECC) and perturbation (ECC+pert) testing mode. Depicted are differences in maximum peak force (Mpeak) between measurements pre and post (M1 and M2) intervention for control group (control), strength training group (strength) and sensorimotor training group (SMT). (*$p<0.05$).

While a variety of methodological setups for perturbation experiments are available, investigations in perturbation training related to LBP are rare. Therefore, the MiSpEx research network focused particularly on the integration of perturbation-based exercises, introducing sudden load stimuli to exercises in a variety of ways. As one of the main approaches, perturbations have been super-imposed to core-specific sensorimotor baseline exercises (27). A selection of varying exercises were established, containing perturbations applied directly at the trunk or indirectly transferred via the extremities by unexpected support surface displacements. For example, participants performed a bird dog exercise (diagonal arm and leg movement in all-fours position), during which perturbations were randomly applied by unexpected, distinct movements of the support surface in anterior-posterior direction.

As another primary approach, a novel perturbation training induced by continuously variable and unpredictable disturbances was implemented and applied in non-specific LBP patients within the MiSpEx consortium (3). The application of the variable and unpredictable disturbances was realized using a specific device in the anteroposterior and mediolateral axes of the trunk (figure 1). A harness around the patient's thorax was connected via cable to a software-controlled electric motor. The amplitude and frequency of the disturbances was controlled electronically. Further, the intensity of the applied perturbations was regulated using springs with different stiffness mounted in series with the cable (for more details see (3)).

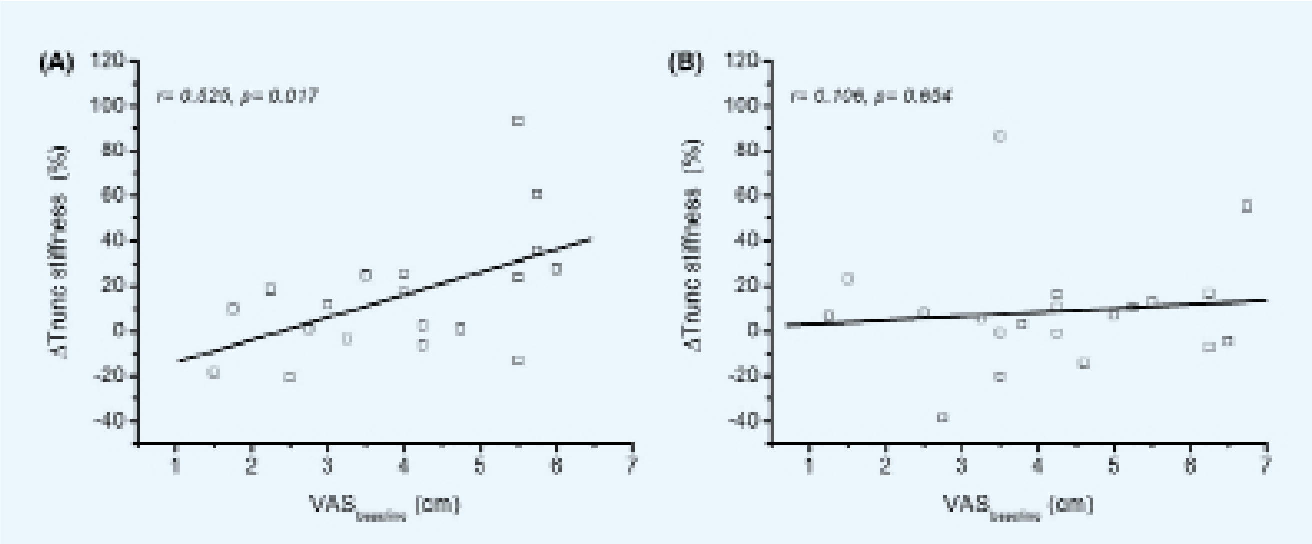

Figure 3

Relationship between percentage change of trunk stiffness (ΔTrunk stiffness) during the quick-release test and baseline pain score ($VAS_{baseline}$) in the perturbation (A) and control (B) groups (Arampatzis et al., 2017, with permission from Springer).

The random and unpredictable perturbations served to increase the neural noise in the nervous system. In the presence of neural noise the neuromuscular control of trunk stability was exercised by asking the patients to maintain the upright position and to actively resist the repeated perturbations. Thereby, the evidence that the presence of noise in the nervous system facilitates the detection and transmission of sensory signals to appropriate motor commands was adopted (32). Further, evidence indicates that the neural networks that have been formed in the presence of noise would be more robust and efficient to cope with environmental changes (14).

Neuromuscular Alterations and Adaptations to Perturbation-Based Training

Neuromuscular Alterations in LBP

As described before a variety of changes in neuromuscular responses to sudden external loadings are evident in people with LBP. Cross-sectional investigations of muscular activity pattern during a quick-release task at the trunk revealed delayed shut-off times of agonistic muscles in LBP patients compared to control subjects (33). Moreover, the corresponding response pattern demonstrated a change in co-contraction strategies between agonistic and antagonistic muscle activities. Activity levels of muscular responses prior to and reflexive of sudden perturbations were also found to be changed in LBP patients compared to asymptomatic control subjects.

However, the findings are conflicting, as some studies reported of an elevated activation and others of a decreased activation in LBP (22, 24, 42). Research results of cross-sectional investigations within the MiSpEx network are in line with these findings. More precise, altered muscular response strategies could be demonstrated, not only in highly standardized laboratory conditions such as during quick-release experiments, but also in conditions resembling dynamic everyday situations. For example, perturbed treadmill walking revealed delayed reflex activities and changes in trunk kinematics in response to the provoked stumbling incidents in LBP context (26).

Neuromuscular Adaptations to Perturbation-Based Training in LBP

Longitudinal interventions within the MiSpEx research network, investigating in training related neuromuscular adaptations, confirmed the benefits of sensorimotor and strength training in people with and without LBP (N=49, age 29±11, m/f: 15/20). Sensory motor training (3 times a week, 4 exercises with each 4 sets of 60 seconds duration) consisted of trunk balance tasks during which disturbances of stability were introduced via upper and lower extremities. During these exercises visual biofeedback of targeted and resulting limb movements and trunk control (positioning) were provided. Strength training (3 times a week, 3 exercises with each 3 sets of 8 repetitions at 85% Fmax) consisted of strength tasks performed in trunk flexion/extention, lateralflexion and rotation (dynamometer, hyperextension bench, trunk rotation machine).

Following a 6-week intervention phase of either sensorimotor or strengthening exercises, both groups revealed a statistically significant increased capacity of resistive load compensation following an unexpected perturbation during isokinetic trunk flexion/extension and trunk rotation, whereas no changes were evident in control participants. Furthermore, increased peak torque outputs exposed to indirect perturbations during an isokinetic trunk rotation task could be shown after strength and sensory motor training (figure 2). Positive effects were also evident for underlying neuromuscular activity resulting in altered compensation strategies ventral of the trunk during perturbed walking trials.

Applying a novel perturbation therapy based on variable perturbations on the spine for 13 weeks in non-specific LBP patients in another MiSpEx study could show a clinically significant increase in muscle strength, reduction in low-back pain and improvements in the neuromuscular control of spine stability after sudden perturbations (3). Furthermore, evidence that the perturbation-based therapy showed advantageous effects on patients with higher LBP was found (figure 3). With these findings the proposed therapy has the potential to enhance both trunk muscle strength as well as sensory information processing within the motor system during sudden loading for spine stability.

Figure 4

Example of a sensorimotor exercise in quadrupedal position, with minimized support surfaces and additional motor task of the upper extremities to provoke perturbations of postural control.

Another perturbation study is currently running within the MiSpEx research network, aiming to identify the dose response relationship and minimal dosage required for a sensorimotor training including perturbation elements. As outcome measures, this study assesses peak torque and muscular activity in isokinetic flexion/extension and rotation tasks with and without perturbations. First, unpublished results confirm that perturbations should be applied with a minimum of 6 sessions in 3 weeks. Weekly frequencies as well as differences in sets and repetitions seem to be of minor importance when overall volume is constant.

Finally, a multi-center RCT aiming to evaluate the feasibility and efficacy of an individualized sensorimotor training with perturbations is conducted within the MiSpEx research network at present (30). In this study, overall N=1580 chronic unspecific LBP patients and healthy control participants (aged 18-65 years, both genders) have been included at six investigation sites in Germany. The intervention consists of a 12-week (3 weeks supervised center-based and 9 weeks home-based) individualized sensorimotor exercise program including perturbations. Pain, pain-associated function as well as motor function serve as main outcome parameters, measured at five time points within a 12-month period. The primary goal of this multi-center investigation is the transfer from laboratory insights of perturbation training to training routines that are applicable in therapy and prevention settings such as in training centers or rehabilitation clinics. Therefore, the developed perturbation exercise program consists of exercises which can be easily carried out using standard therapy settings, without the need of expensive laboratory perturbation equipment. All core-specific exercises are based on the principles of a perturbation-based sensory motor training, proven to be effective in the enhancement of neuromuscular function. Perturbation elements are introduced to those exercises by minimizing the support surfaces (increased instability), increasing the complexity via additional motor tasks (distraction of postural control) and implementing additional loads to the exercises (figure 4). In detail, the intervention program consists of four basic exercises which each are adapted regarding the severity (training start and progression) by 12 standardized levels. Two of those exercises are conducted in standing position (one leg stance and front rowing) with instability/perturbations introduced via upper or lower limb movements (with and without additional weights). The other two exercises are performed in quadrupedal or side planking position with instability/perturbations applied via additional motor tasks such as throwing/catching a ball or via additional limb movements. During all exercises varying foam pads and foot positions (e.g. standing on rear or forefoot) are used to increase the level of postural instability. All elements in combination create a training situation, which necessitates a continuous demand of compensatory movements, adjusting the repeatedly occurring uncontrolled displacements while performing the exercise. Thus, this exercise program enables to train neuromuscular control mechanisms which are required in daily life situations, where often trunk control is challenged by external disturbances.

Förderung

Das MiSpEx-Netzwerk wird gefördert aus Mitteln des Bundesinstituts für Sportwissenschaft (BiSp) aufgrund eines Beschlusses des Deutschen Bundestages [Förderkennzeichen ZM-VI1-080102A/11-18].

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