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REVIEW ARTICLE

Core Stability in Athletes: A Critical Analysis of Current Guidelines

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Abstract Over the last two decades, exercise of the core muscles has gained major interest in professional sports. Research has focused on injury prevention and increasing athletic performance. We analyzed the guidelines for so-called functional strength training for back pain prevention and found that programs were similar to those for back pain rehabilitation; even the arguments were identical. Surprisingly, most exercise specifications have neither been tested for their effectiveness nor compared with the load specifications normally used for strength training. Analysis of the scientific literature on core stability exercises shows that adaptations in the central nervous system (voluntary activation of trunk muscles) have been used to justify exercise guidelines. Adaptations of morphological structures, important for the stability of the trunk and therefore the athlete's health, have not been adequately addressed in experimental studies or in reviews. In this article, we explain why the guidelines created for back pain rehabilitation are insufficient for strength training in professional athletes. We critically analyze common concepts such as 'selective activation' and training on unstable surfaces.

Key Points

Most exercise specifications for core stability have not been tested for effectiveness nor compared with the load specifications normally used for strength training.

So far, exercise guidelines have focused on adaptations in the central nervous system (voluntary activation of trunk muscles), whereas adaptations of morphological structures have not been adequately addressed in experimental studies or reviews.

Guidelines created for back pain rehabilitation are insufficient for professional athletes.

We recommend the use of classical strength-training exercises as these provide the necessary stimuli to induce the desired adaptations.

1 Introduction

The terms 'core stability' and 'functional training' have been used intensively in fitness, health, and professional sports for the last couple of decades. Exercising the trunk muscles is supposed to prevent injuries and improve sports performance. Whereas exercising the trunk prevents injury via protection of the spinal column, an association between trunk muscle strength and sports performance has not been clearly proved [1–6]. Although only small correlations between running, jumping, and sprinting performance and various strength parameters—such as trunk extension, flexion, rotation, or lateral flexion [2, 3, 7]—have been

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reported, the importance of the trunk muscles can be logically inferred [8–13]. They transfer and develop energy, which is necessary for postural control. Interest in how to exercise this body part has been increasing, as has the number of suggestions for interventions over the last 20 years, particularly because the number of patients with back pain has also been increasing. Back pain has often been associated with a weakness of the trunk muscles [14, 15], but this cannot be the only reason behind these symptoms [16] because it has not always been possible to detect a deficit in core muscle strength. Ezechieli et al. [17] presented the results of trunk strength testing in trained athletes that gave reason to assume they would require preventive core muscle training. As the scientific evidence for core stability programs seems low [18, 19], this review attempts a critical analysis of common concepts, including the classification into 'local' and 'global' trunk muscles, 'selective activation', and training on unstable surfaces.

2 What is Meant by 'Core Stability'?

The term 'core stability' has no clear definition. Depending on the author(s), core stability muscles may only include extensors, flexors, lateral flexors, or rotators of the spinal column. A more complex approach includes all muscles between the shoulders and pelvis. As hip position influences alignment of the spinal column and therefore modulates trunk muscle activity [20–22], this article favors the latter approach. However, training methods presented here are valid for every muscle to be strengthened as the adaptive mechanisms remain the same [9, 23, 24].

The terms 'stabilization', 'strengthening', and 'muscle activation' are often used side by side as if they are independent goals in training; however, stabilization is a result of muscle forces [12, 25]. The activation of trunk muscles and their contractile potential (muscle mass) produces those forces and therefore lead to stable and secure positions of the spinal column. Muscle mass is the morphological basis determining how much force can be produced [26–42]. This potential must be retrieved via the central nervous system (CNS). The full potential of the muscle is only revealed if the muscle or several muscles are activated adequately, in a task-specific way, which is called intra- or inter-muscular coordination. Therefore, stabilization is the result of muscle mass (contractile potential) and its activation through the CNS (usage of that potential) (see Fig. 1), whereas strengthening refers to improvements in force production.

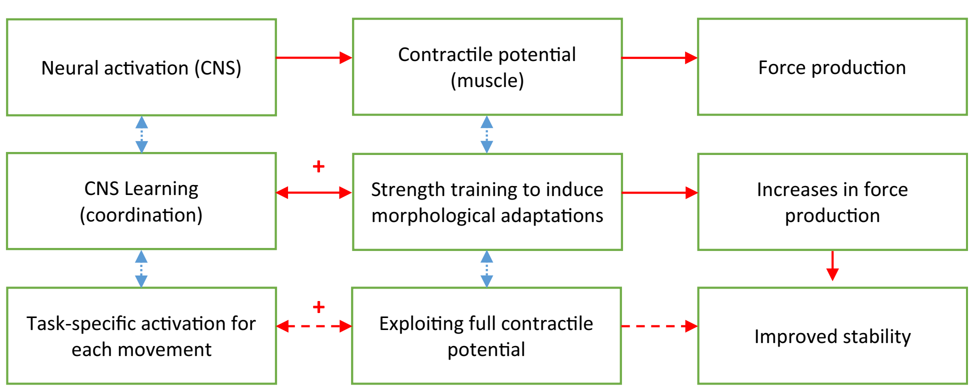
The level of force necessary for trunk stabilization depends on the motor task. Reviewing the literature on core stability training, it would appear only muscular activation is important. Unfortunately, high activation but small muscle mass still only produces a small level of force. Sometimes, training goals are created using force values determined in standing and walking [16]; however, these are not sufficient for activities of daily living or for sports. The requirements of the neuromuscular system in everyday life, e.g., lifting, carrying, and dragging, exceed the demands of standing, walking, and some training exercises—which have often been used in training interventions—for the trunk [43]. To estimate the forces with which the trunk muscles must contend, ground reaction force (GRF) measurements in sports should be considered—bearing in mind Newton's third law (for every action, there is an equal and opposite reaction)—which reach values of 6- to 17-fold body mass [44–51]. This is one reason why guidelines extracted from therapy for patients with back pain are inappropriate for professional athletes. Particularly in sports but also in everyday life, stabilizing the trunk demands forces that far exceed target criteria for therapeutic interventions. We emphasize that force production is the basic requirement for stabilization of the spinal column.

3 Core Stability: Concepts and Evidence

3.1 'Global' and 'Local' Muscle Systems

For many investigators studying back pain, the focus of interest is the deeper-layered muscles of the trunk. In this

Fig. 1 Schematic representation of the association between force production and stability



context, trunk muscles have been classified as ‘global’ and ‘local’, a classification system that can be traced back to Bergmark [52]. O’Sullivan [53] nominated the rectus abdominis, the obliquus externus, and the thoracic part of the lumbar iliocostalis—among others—as part of the ‘global’ muscle system because they may produce high torques and affect vertebral orientation without being directly anatomically connected to them, therefore, supporting trunk stabilization even without (direct) segmental influence. Thus, the ‘global’ muscle system represents the prime movers of the trunk, whereas the ‘local’ muscle system consists of muscles whose insertion and origin are attached to the spinal column and therefore control single vertebral segments and are responsible for their stabilization [53, 54]. Following this, specific training exercises are often recommended that especially emphasize the ability to selectively activate multifidus muscles, the transversus abdominis, and, sometimes, the obliquus internus abdominis. As selective activation of certain muscles is supposed to be key, back pain interventions mostly use body weight exercises without external loads. This also suggests that those particular muscles would not be sufficiently strengthened in other training exercises. Hibbs et al. [55] even warned that extensively exercising the ‘global’ muscles would induce imbalances; these muscles would take responsibility for stabilization of the spinal column, leading to restricted and compensatory movement patterns. However, there is no scientific evidence to support this statement. Lederman [16] wrote of the ‘global’ and ‘local’ muscle classification system: “Such classification is anatomical but has no functional meaning.” and “The division of the trunk into core and global muscle system[s] is a reductionist fantasy, which serves only to promote CS [core stability]”, a view shared by others with an interest in back pain and/or strength and conditioning training [19, 56]. Stokes et al. [57, 58] reported—based on calculations with a new anatomical model that includes all muscles of the abdominal wall (rectus abdominis, obliquus internus and externus, transversus abdominis) and lumbar back extensors in different trunk movements (extension, flexion, lateral flexion, and rotation)—that an increase in intra-abdominal pressure reduces lumbar compression forces, whereas increased activity of the transversus abdominis does not improve stability of vertebral segments. Other authors have also come to this conclusion [59, 60]. The stability of the spinal column is obviously secured by direction-specific and synergistic cooperation of ‘global’ and ‘local’ muscles [60–63].

Grenier and McGill [59] showed a significant increase in stability (32 %) of the spinal column through co-contraction of trunk muscles (i.e., bracing) without significant contribution from the transversus abdominis. Vera-Garcia et al. [64] confirmed these results in a comparison with abdominal hollowing. In contrast, abdominal hollowing does not increase the stability of the spinal column [59, 64]. Stanton and Kawchuk [65] reported improved segmental stiffness (measured at thoracic vertebra 4) through co-contraction of the trunk muscles, with significantly increased normalized surface electromyography (EMG) amplitudes of the rectus abdominis, the obliquus externus and internus, and thoracic and lumbar erector spinae. Moreover, their participants were not able to perform abdominal hollowing without activation of the obliquus internus. Vera-Garcia et al. [64] made the same observation for the obliquus externus and the rectus abdominis. Therefore, these findings prove the opposite of that proposed by Hodges and Richardson [66]: abdominal hollowing does not produce a preparatory stabilization of vertebral segments protecting them from shear forces—which can occur through movements of the torso and the extremities—by a selective activation of the transversus abdominis [67]. As the combination of compression and shear forces introduces the danger of disk prolapse [68], the use of abdominal hollowing in trunk and complex barbell exercises in rehabilitation as well as in sports should therefore at least be questioned and perhaps discounted altogether in exercise and sports medicine literature.

Based on their findings, Cholewicki and VanVliet [61] stated, “the often-used classification of muscle into ‘local’ (deep, inter-segmental) and ‘global’ (superficial, multi-segmental) systems […], as the way to discriminate between muscles responsible for inter-segmental stability and spine motion, is incorrect.”. Instead, the trunk musculature should be seen as a functional unit, the activation levels of which shift depending on the motor task [16, 22, 43, 56, 60, 69–76].

3.2 Myth of Selective Activation

Segmental stability training is a particular area of interest for an Australian group led by Hodges. Along with several other investigators whose main field of study is back pain therapy, they have made incorrect assertions they believe could be deduced from studies of their patients. Those studies focus on multifidus muscles and transversus abdominis and claim their selective activation, which is, unfortunately, a misinterpretation of results. For example, Hodges and colleagues [67, 77–80] found the transversus abdominis being activated first—in a feed-forward manner—in several different motor tasks. In ballistic movements of the upper extremities, the transversus abdominis was active before its agonists (prime mover) [77–79], whereas the onset of the rectus abdominis, obliquus internus and externus, and multifidus muscles altered depending on the movement direction. Sometimes, they were even partially activated after their agonists. This preprogrammed activity of the transversus abdominis supposedly produces a preparatory stability of the vertebrae [80] through inducing a high intra-abdominal pressure [81–84], thereby causing an increase in stiffness and stability of the lumbar vertebral segments through horizontal tension of fascia thoracolumbalis [85, 86]. Furthermore, 'local' and 'global' muscle systems would be innervated by different motor control systems [87], with the 'local' system securing intervertebral stiffness whereby the spinal column is prepared for contractions by the 'global' system [67]. As this feed-forward activation of the transversus abdominis had been delayed—or had only been determined after agonist activity—in patients [66, 78, 80, 87], Hodges and Richardson [66] believe that, in this case, reactive shear and rotational forces resulting from movements of the extremities act on unprotected segments.

Where ballistic movements were performed with the lower extremities, a direction-independent and preprogrammed activity pattern for the transversus abdominis and the obliquus internus and externus [66, 79] was shown, whereas the onset for the erector spinae and the rectus abdominis were altered, for example, between hip flexion and extension. It is already obvious from these studies that the transversus abdominis is not the only and first muscle to be (pre)activated. The mechanical (stabilizing) effect of the transversus abdominis is supposedly bound to simultaneous bilateral activation (in vivo investigation with evoked contractions of the transversus abdominis in pigs [88]). The results supposedly proving this segmental, bilateral, and movement-direction-independent 'corset-like' stabilization of vertebral segments through the transversus abdominis are unfortunately only based on unilateral EMG recordings [66, 78–80, 89–92]. Hence, the theoretical construct was an over-interpretation from the beginning.

Moseley et al. [93] took one step further and claimed that the superficial fibers of lumbar multifidus were responsible for spine orientation, whereas deeper-layered fibers controlled inter-segmental motion. Such a refined deduction from EMG recordings (needle and surface) is quite a surprise given the methodological limitations. In fact, in light of the small muscle mass and therefore relatively small force production capacity of multifidus muscles, the rather superficially aligned large muscle areas of the erector spinae must be assumed to be the basis of any kind of spine stabilization, as only those muscles have the capacity to produce enough force to counteract gravity. Again, the minor importance of the 'global' muscle system is incorrectly extracted from EMG recordings showing those muscles to produce—in stance and gait—only 1–3 % of activity compared with maximal voluntary contraction (MVC) [18, 94–99]. The fact is, the effects of fatigue mean humans are unable to maintain an upright posture for several hours if the trunk muscles are required to sustain higher levels of activity (force) in both stance and gait. A low activation level in some tasks does not mean this particular muscle plays a minor role; it shows only that, in the specific situation in which these measurements have been collected, fewer motor units were activated. This could be (very) different in another motor task (e.g., lifting or carrying).

Several studies that have relied on bilateral EMG recordings and shown fewer methodological inadequacies prove the aforementioned 'feed-forward activation' to be a misinterpretation [18, 95–99]. For example, Morris et al. [97, 98] found a direction-specific diagonal activity pattern for the synergistically working contralateral transversus abdominis, obliquus internus, and the ipsilateral obliquus externus in asymmetric arm movements. Bjerkefors et al. [100] confirmed the asymmetric activation of the transversus abdominis in asymmetric core stability exercises on the floor. According to Richardson and Jull [54], the transversus abdominis was selectively active but the rectus abdominis was silent in a quadrupedal position with abdominal hollowing. Their assumptions were based on surface EMG recordings by Strohl et al. [101], who, interestingly enough, had not been able to perform selective measurements of the transversus abdominis. By contrast, Goldman et al. [102] used needle EMG in a horizontal posture and found synchronous activity in the rectus abdominis, the transversus abdominis, and the obliquus internus and externus when subjects were coughing or holding their breath. Furthermore, studies using intramuscular EMG recordings have shown the transversus abdominis being activated together with the obliquus internus [102, 103] and externus [102, 104] in abdominal hollowing. Bjerkefors et al. [100] found an increase in activity of the transversus abdominis when performing static exercises on the floor while using abdominal hollowing. However, they observed no decrease in rectus abdominis activity. Interestingly, Bjerkefors et al. [100] determined the highest values in integrated EMG for most of their participants performing maximal isometric trunk flexion or static exercises on the floor, each in combination with the Valsalva maneuver, but not through abdominal hollowing.

Several groups have been unable to verify a dominant role for the transversus abdominis in enhancing the stability of the trunk [58–60]. Instead, the stability of the spine is secured by a direction-specific and synergistic interaction of 'global' and 'local' muscles [60–63]. In this context, Hodges et al. confused the chronology of activity, which varies between movement tasks, with a voluntary selective activation of one muscle, and therefore overvalued the importance of a single muscle. The authors only noticed the differences in chronological order, but changes in task-dependent force contribution were not addressed.

Other publications indicate a highly variable activity pattern of the transversus abdominis depending on the motor task [95–99]. Therefore, a universally valid statement—as made by Hodges' research group, for example—cannot be made since the activity of muscles is always task specific [16, 22, 60, 95]. The results of Hodges' group would differ if participants were allowed to breathe normally. This is only to clarify that their measurements were performed in impractical (dysfunctional) special conditions.

3.3 Activation Deficit and Selective Atrophy

The basic assumption that—in patients with back pain—multifidus muscles or the transversus abdominis show an activation deficit compared with ipsilateral working muscles or a selective atrophy is without evidence [22]. The studies usually cited in this context cannot verify this hypothesis. Still, the beliefs or interpretations of these authors are replicated uncritically [25, 53–55, 105–117]. Closer inspection of these papers occasionally shows serious deficiencies, including that the statistical analyses are not suitable for the kind of data [108, 118–121] and that comparisons of results and between muscles, which were classified within the 'global' and 'local' system, were neither calculated nor statistically validated [54, 55, 73, 105, 108, 110, 111, 113, 114, 122–125]. Especially astonishing is the interpretation of data from muscles that were not part of the experimental protocol. Some studies only examined multifidus muscles but claimed a dominant role of these muscles compared with others in the discussion [73, 108, 114, 117, 123, 126]. Furthermore, many articles cite studies that supposedly show the exceptional roles of transversus abdominis and multifidus muscles, even though no proof is provided. Other studies referred to for justification purposes while formulating hypotheses also lack proof. Some longitudinal studies used questionable procedures for intensity determination [118, 119, 121, 122, 125–127] and performance testing, meaning their reliability and validity must be questioned (e.g., the Sorensen Test [121, 128–130]). Therefore, it is surprising that no investigation has compared the effectiveness of so-called functional exercises from back pain rehabilitation with that of, for example, barbell training, which supposedly only stresses the 'global' muscles, over an extended period. On the other hand, plenty of articles claim a superior impact of specific exercises for the 'local' system without actually verifying this or citing studies that do verify it [53, 55, 73, 110, 113, 122, 125]. Therefore, positive effects after some kind of training intervention are randomly assigned to the deeper core muscles [125]. In addition, in several cases, a more careful interpretation of EMG data would be preferable since recordings are methodologically very challenging. Problems include, for instance, crosstalk [70, 131], thickness of subcutaneous fat tissue [132], and the necessity of normalization with MVC measurements [133].

A selective deficit to activate certain extensor muscles on the painful side of the body compared with the non-painful side has not been proven. Furthermore, from a neurophysiological viewpoint, if there is a deficit of activation of certain synergists then one could expect this to be the result of an inhibition initiated through pain, but certainly not because the CNS was unable to activate the muscle. If a deficit in muscle activation is found, it should be regarded as the result rather than the cause of pain. However, it is possible that missing stimuli in everyday life lead to very low levels of activation, which can also be attributed to either the extensors or the flexors. Strength training can counteract this problem. Therefore, training of the 'local' muscles, which has not even been shown to positively affect the deeper core muscles, is not needed [16, 116]. From a neurophysiological viewpoint, whether a selective activation of task-specific synergists is at all possible is questionable [16, 64, 102–104, 134–140]. It is certainly unnecessary. A side-of-the-body-specific atrophy of single muscles in comparison with the non-painful contralateral side has not been empirically shown. Further, no diagnostic findings have reported a selective atrophy or deficit in activation of single trunk flexors or extensors on the ipsilateral side [16, 19, 22, 43, 56, 60, 63, 69–72, 74, 76, 116, 124]). In this context once again, no data from pain-free subjects could be found, which would justify the assumption of an unequal development of different trunk muscles with the same function (i.e., synergists). Further, McGill [22] points out that patients with back pain also exhibit different patterns of activation for other muscles. Therefore, a special importance of multifidus muscles and transversus abdominis or the classification into 'local' and 'global' muscle systems—as proposed by several authors [53–55, 78, 109, 113]—cannot be justified. Several other authors have described the isolated activation of a single core muscle—if at all possible—to be dysfunctional and therefore unsuitable as a training goal [16, 22, 107]. Willardson [56] stated, "A common misconception is that the local and global muscles can and should be trained separately. Such statements are in contrast to research that clearly demonstrates the synchronized function of both local and global muscles during a wide variety of movement tasks."

3.4 Trunk-Rotation Exercises

Another assertion made in the context of 'functional strength training' is the performance of trunk-rotation exercises [141–144]. It is possible to perform trunk-rotation exercises with fixed hips or with a rotation of the pelvis. If rotation of the hip region is allowed, it is sometimes difficult to evaluate how much of the rotational movement of the body is due to trunk rotation. Independent of this problem in movement execution, it seems questionable whether trunk rotation, which elicits high shear forces on intervertebral disks, is at all rational. Many authors regard the mentioned shear forces to be the main reason for disk damage and back pain and hypothesize that even very small shear forces at the vertebral level are harmful [68, 112, 145–151]. Axial rotational movements between vertebral segments are primarily restricted through fibers of the annulus fibrosus [152], from which only about 50 % produce torque for each rotational direction [153]. In combined rotation and ventral flexion, only the already bent fibers are stressed [153]. Therefore, in a combined axial compression, torsion, and ventral flexion, only half of the mechanical stability of intervertebral segments is available [153], resulting in an increased risk for herniated disks [154]. Intervertebral segments and therefore intervertebral disks, which deal with ventral flexion and rotation, lose 50 % of their mechanical stability in axial compression [152, 153]. Depending on the condition of disks and vertebrae, tolerable compression forces of disks up to 6000 N have been reported before potential damage risk increases, which primarily affects vertebrae (fracture) but not disks [153, 155–157]. On the other hand, Bader and Bouten [145] reported shear forces of 150 N and axial rotation forces of 20 N as harmful for intervertebral discs. In specimens, it has been shown that, in rotations after 20°, resistance increases due to passive structures [158] and therefore rotational range is small [153, 159]. The fibers of the annulus fibrosus seem to be threatened, mostly because they have already been bent by small rotational movements [149]. Danger increases even further if other forces besides rotational forces affect the spinal column. Unfortunately, this is almost always the case, especially in sports. Several authors have reported that a combination of compression and rotation particularly endangers the fibers of the annulus fibrosus [112, 149, 154, 160]. Panjabi [12, 13] identified increased mobility of the spinal column (greater than what he termed the ‘neutral zone’ relative to the normal range of spinal motion) as being problematic and an underlying cause of back pain. Consequently, the movement range should not be increased through rotational exercises of the trunk, which decreases resistance of passive tissues (e.g., ligaments, fibers of the annulus fibrosus) against rotation. In contrast, sports that demand a wide range of rotational movement in the spinal column (e.g., golf) must be regarded as problematic [22]. The main duty of core stability muscles is to reduce or at least limit rotational movements as much as possible [22]. The integration of rotational movements in strength and conditioning training is not at all ‘functional’ and only increases the possibility of overuse damage and injury. From a practical viewpoint, everybody switches instinctively to movement behaviors with a fixed trunk and a rotation coming from the hip if load is increased. Nobody voluntarily works against high loads with a rotated trunk. Rare exceptions to this may be found, for example, at the end of the discus or hammer throw, when the athlete tries to propel the object being thrown in the right direction.

In addition, the statement that muscles responsible for rotation would have to be exercised through rotational movements must be questioned. If it was necessary to specifically exercise rotational movements then they should be performed with the trunk fixed—to avoid a rotation of the spinal column—so the pelvis could rotate against high loads. In humans, the same muscles are responsible for trunk rotation and trunk rotation avoidance; only the muscle activation patterns differ. Therefore, we propose that training of these muscles is performed to avoid any kind of rotation in the spinal column. Interestingly, descriptions of strength-training exercises only include warnings against hollow back or lordosis. The two most dangerous situations for intervertebral disks—rotation and straightening from a flexed position of the vertebral column against high loads [22, 147, 161]—are frequently recommended, even in strength training and performance testing. The training exercise ‘rolling up the spine’, which is often suggested in training as well as in diagnostics is actually endangering the health of the disks and should be avoided. Erroneously, it is claimed that this movement task would exercise the deeper trunk muscles selectively. The same argument is used when propagating training on unstable surfaces.

4 Training on Unstable Surfaces

For two decades, performing resistance-training exercises on unstable surfaces has been in fashion. The basic idea is that when performing a training exercise on an unstable surface, smaller loads are necessary to create the same amount of activity in the target muscles than when exercising on a stable surface. Furthermore, it has been assumed that the resulting higher coordinative demands require more intense activity in the stabilizing muscles of the trunk, which is supposed to lead to more effective strength training. Most scientific training interventions use squats on an unstable surface as a training exercise and usually record the EMG activity of the core muscles and the leg extensors. The higher activity levels observed compared with a stable surface condition have been interpreted as a result of higher force production and therefore an adequate training stimulus. Unfortunately, no longitudinal study has been conducted to demonstrate significant improvements in the performance of core muscles through training on an unstable surface [19, 23, 56, 162]. Thus, no study has shown a superiority of exercising on unstable surfaces compared with stable surfaces.

4.1 Exercise Intensity

Studies using the squat on unstable surfaces show one similarity: loads used are not >50–70 % of one repetition maximum (1RM) [76, 163–172], above 10 RM [173], or only 60 % of body weight [163]. As a justification for this approach, authors have stated that movement execution could otherwise no longer be controlled, thereby increasing the risk of injuries [23, 173]. This observation is due to actual changes in movement execution. Several research groups reported that the more unstable the surface when performing a squat, the greater the loss in maximal performance, dynamic 1RM, and maximal movement velocity [163, 169, 173]. Furthermore, participants were no longer able to perform the parallel squat [173], which is why studies using the squat as a training exercise have not usually used a squatting depth beyond 90° knee angle. If deep squats were intended, the intensity would have to be reduced even further [174, 175]; however, to create an adequate stimulus, a deep squat is desirable [167, 174, 176, 177]. A combination of high loads with perturbations, such as unstable surfaces, is injury provoking [171, 173]. Therefore, it is no surprise that in unstable conditions several studies reported maximal loads (far) below measured values in stable conditions. Sometimes this goes hand in hand with less activation in the target muscles [164, 166, 167, 173, 178–182], and this could actually imply that activity in the core muscles has also been reduced [166, 183]. If 1RM is determined in both conditions (stable vs. unstable surface) and training loads are extracted based on these measurements, the problem of light intensities becomes even more obvious. As McBride et al. [184] and Saeterbakken and Fimland [185] reported, loads in unstable conditions are about 40 % lower than in stable conditions. Therefore, more activation can be found under stable conditions for most measured muscles. Given all of this, it seems reasonable to state that—in terms of the desired physiological responses in a long-term training process—training exercises on unstable surfaces do not lead to the desired stimuli [19, 162, 164, 178, 180, 181, 186, 187]. In light of the lack of evidence for strength-training efficacy on unstable surfaces, it is astonishing how frequently it is recommended.

4.2 'Specific' and 'Functional' Training Exercises

Another argument presented in favor of exercises on unstable surfaces has been that deeper core muscles of 'local' muscle systems were particularly strengthened. Again, no proof is available. Training on unstable surfaces has also been advocated because it supposedly mimics daily life and sport activities better than conventional resistance-training exercises, though everyday activities as well as most sports are performed on stable, non-moving surfaces [19, 162, 169, 187], and situations other than this are the exception. Consequently, performing training exercises on unstable surfaces must be regarded as unspecific since it does not represent stresses induced during sports. The same holds true for many exercises propagated in core stability programs, which sweepingly are called 'functional' and 'specific'. Strength training in prevention, rehabilitation, and strength and conditioning, often accompanied by the demand of training exercises, should be as similar as possible to everyday and sport-specific movements [188]. Looking at some of the recommendations, it seems surprising to find exercises such as kneeling hip extension and prone or side plank, since we cannot think of any situation, either in sports or in daily life, where those motor actions take place. Therefore, we conclude that these training exercises are neither 'specific' nor 'functional' and thus should not be recommended.

This is just one example of inconsistent arguments made by protagonists of core stability training. In their favor, it could be argued that core muscles need to be active in many different tasks in sports and daily life and that controlled movement execution, as usually advised in resistance training with high loads, cannot mimic fast, unexpected challenges. However, the CNS is even more task specific [189, 190]. The activity patterns used during training exercises on unstable surfaces still differ from those in sports and everyday life. Therefore, training in unstable conditions trains activity patterns in exactly those conditions. Shimada et al. [190] compared dynamic and static postural control and found very small correlations, which shows how task specific the human CNS actually is. It should be obvious now that caution is advisable when using the terms 'specific' and/or 'functional' in the context of training exercises.

It could still be argued that using unstable conditions trains the CNS to activate the core muscles in different motor tasks and therefore, basically, coordination is improved. Consequently, this argument holds true for any movement in which at least one core muscle is active, and this could then justify many other training exercises. However, to our knowledge, no studies have yet shown either a (positive, strong) correlation between performance in training exercises in unstable conditions and some kind of athletic performance [19, 162] or trunk muscle strength increases in longitudinal interventions. Furthermore, studies comparing resistance training under stable and unstable conditions and their effect on core stability in different motor tasks are lacking. In conclusion, training recommendations that include training exercises on unstable surfaces are not comprehensible since there is no evidence of superiority in either cross-sectional or longitudinal studies [19, 23, 56, 162, 171, 173].

4.3 Electromyography and Some of its Limitations

At this point, interpretations of EMG recordings, often used to determine the effectiveness of exercises on unstable surfaces, must be evaluated. Unquestionably, if higher forces need to be produced, a stronger efferent input to the muscle is necessary [191–195]. Producing higher forces is more demanding than producing lower forces, but it is not the only challenge where the CNS produces increased efferent drive. Whatever increases the complexity of a movement or if a new movement execution is learned, neural activation increases. All muscles involved in movement execution must be coordinated in terms of time of activation as well as amount of force produced, which leads to a specific activation pattern.

As an example, consider a marathon runner with poor technique and therefore an inefficient running style. Hence, the level of muscle activity is increased and/or the timely coordination of the lower extremity muscles is not ideal because some muscles are activated unnecessarily strongly. Therefore, one could deduce there is more activity that leads to training stimuli and this should increase force production. Unfortunately, this is incorrect because the runner still performs endurance exercises with lots of repetitions and relatively small loads, which induces different adaptations than strength exercises. Ballistic movements, for example, need a very strong efferent drive, but experiments have shown it is not possible to produce high forces/torques in very fast movements [196–198], which is why they are inadequate for strength training. This hint only shows that higher EMG activity levels do not always represent higher force production, which then could induce the type of adaptations desired in resistance training. Perry and Burnfield [199] write in this context, “On each situation, the ratio between EMG and force is altered.” The deduction of training intensities (% of 1RM) from EMG recordings (% of MVC) would require a linear dependency of both parameters and an intersection at the origin, which would contradict the idea of a resting tone in muscles. The idea of a linear dependency between those parameters is already a subject of controversy [191–195]. Unfortunately, this mistake has been made in many studies that did not use MVC or 1RM (or at least a number of repetitions) but deduced training intensity through EMG recordings, despite that several authors have emphasized that EMG recordings are unsuitable for determining intensity [19, 163, 178].

If MVC measurements are performed, there are three major problems concerning both the measured torque/force values and the EMG recordings. The determination of valid values requires participants who are very familiar with the testing exercise; otherwise, very high levels of activation cannot be expected and torque/force values will not be maximal. We emphasize that, even if measurements are reliable, they may not necessarily be valid. Depending on the testing exercise chosen, it may be necessary to practice movement execution often to reach high levels of activation, even if this is already possible in other testing exercises for the same muscles [200]. It is also possible that certain testing exercises are not appropriate to create a situation for maximal voluntary activation. This is the case, for example, if several muscles are assessed in the same testing exercise even though each of them fulfills different functions in the particular task.

This problem is accentuated when tests are performed in isometric conditions since measurements are restricted to one angle. Several research groups have been able to demonstrate angle-specific adaptations in longitudinal studies, which imply angle-specific activity patterns produced by the CNS [201–208]. Therefore, EMG recordings in MVC measurements—in a first step—deliver information about this particular task only. A normalization of an EMG signal by means of another EMG recording determined in a different motor task has only limited meaningfulness and may lead to false interpretations and conclusions. The efferent drive to muscles must be seen as task specific at all times [16, 95–99, 171]. Also, small deviations in electrode placement may lead to bold changes in EMG recordings. The assessment of those measurements seems especially problematic in patients with (back) pain since it should be expected that patients in pain (or at least scared of pain) do not completely activate or—in isometric conditions—perform evasive movements. As pain may or may not occur depending on the position, there can be differences between training and testing exercises. Therefore, we encourage people to be accordingly thorough and careful in recording and interpreting surface EMG data.

5 Conclusion

No proof has been found for special training exercises for deeper core or segmented stabilizing muscles. We were unable to find any diagnosis or articles reporting selective deficits of these muscles in strength-trained athletes (this is for core muscles with similar functions as described above, not for a comparison between flexors and extensors). Therefore, we wonder which type of data led to the demand for specific exercises to strengthen, in particular, the deeper trunk muscles or improve the ability to selectively activate them. Furthermore, there is no evidence that classical strength-training exercises, for example, squat, deadlift, snatch, and clean and jerk, affect ‘global’ muscles only or lead to imbalances between the muscles of the trunk [55]. Data proving this hypothesis do not exist for (back pain) patients, healthy controls, or athletes. Studies inspecting EMG recordings of several core muscles have shown simultaneous activity that varied in extent and on- and offset depending on the motor task. This is why stressing the importance of a few single muscles is not justified, and classification into ‘local’ and ‘global’ muscle groups is inappropriate [16, 19, 22, 43, 56, 60, 63, 69, 71, 72, 74, 76, 209]. Therefore, we recommend the use of classical strength-training exercises as these provide the necessary stimuli to induce the desired adaptations.

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Compliance and Ethical Standards

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