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Optimizing Performance by Improving Core Stability and Core Strength

Angela E. Hibbs,[1,3] *Kevin G. Thompson*,[1,4] *Duncan French*,[1] *Allan Wrigley*[2] and *Iain Spears*[3]

1 English Institute of Sport, Gateshead, UK
2 Canadian Sport Centre Pacific, Vancouver, British Columbia, Canada
3 University of Teesside, Middlesbrough, UK
4 School of Psychology and Sports Science, Northumbria University, Newcastle, UK

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Abstract

Core stability and core strength have been subject to research since the early 1980s. Research has highlighted benefits of training these processes for people with back pain and for carrying out everyday activities. However, less research has been performed on the benefits of core training for elite athletes and how this training should be carried out to optimize sporting performance. Many elite athletes undertake core stability and core strength training as part of their training programme, despite contradictory findings and conclusions as to their efficacy. This is mainly due to the lack of a gold standard method for measuring core stability and strength when performing everyday tasks and sporting movements. A further confounding factor is that because of the differing demands on the core musculature during everyday activities (low load, slow movements) and sporting activities (high load, resisted, dynamic movements), research performed in the rehabilitation sector cannot be applied to the sporting environment and, subsequently, data regarding core training programmes and their effectiveness on sporting performance are lacking.

There are many articles in the literature that promote core training programmes and exercises for performance enhancement without providing a strong scientific rationale of their effectiveness, especially in the sporting sector. In the rehabilitation sector, improvements in lower back injuries have been reported by improving core stability. Few studies have observed any performance enhancement in sporting activities despite observing improvements in core stability and core strength following a core training programme. A clearer understanding of the roles that specific muscles have during core stability and core strength exercises would enable more functional training programmes to be implemented, which may result in a more effective transfer of these skills to actual sporting activities.

1. Definition of Performance, Core Stability and Core Strength

Core stability and core strength have been subject to research since the early 1980s.[1-7] What is referred to as the core varies between studies, with many studies including upper and lower sections of the body including the shoulders, trunk, hips and upper leg.[8-11] Furthermore, many studies also fail to distinguish between core stability and core strength, two concepts that are fundamentally very different. The confusion over the precise definition of core stability and core strength is largely because what is included in these definitions differs greatly depending on the context in which they are viewed. For example, in the rehabilitation sector, the focus is on rehabilitation following injuries causing lower back pain (LBP), arm and leg pain and enabling the general population to perform everyday (low load) tasks using exercises that emphasize the control of spinal loading. This requires less core stability and core strength than elite and highly trained athletes in the sporting sector who have to maintain stability during highly dynamic and, in many cases, highly loaded movements.[12] The anatomy involved during sporting tasks includes much more of the body, i.e. shoulders and knees, which contribute to the transfer of forces through the body to produce effective sporting techniques resulting in a different definition of core stability and core strength. Therefore, although the process of core stability and core strength can be defined, what is anatomically included in these definitions varies.

Panjabi[13] suggested that core stability is the integration of the passive spinal column, active spinal muscles, and the neural control unit, which when combined maintains the intervertebral range of motion within a safe limit to enable activities to be carried out during daily living. Kibler et al.[14] summarized core stability in a sporting environment as "the ability to control the position and motion of the trunk over the pelvis to allow optimum production, transfer and control of force and motion to the terminal segment in integrated athletic activities." Akuthota and Nadler[15] defined core strength as the muscular control required around the lumbar spine to maintain functional stability. This is different to the traditional concept of strength in the sporting sector, which has been suggested by Lehman[8] as the maximal force that can be generated at a specific velocity by a muscle or muscle group. Faries and Greenwood[16] provide clearer definitions as to the difference between core stability and core strength for the rehabilitation sector by suggesting that core stability refers to the ability to stabilize the spine as a result of muscle activity, with core strength referring to the ability of the musculature to then produce force through contractile forces and intra-abdominal pressure.

Due to the different demands placed on the body during sporting activities, more complex core exercises are trained (usually highly dynamic movements with added resistance) compared with those used for training the general population (mostly static in nature). As a result, the research findings performed in patients with LBP and the general population cannot be extended to the athletic and elite sports performer. This inability to generalize findings along with inconsistent definitions makes the collection and application of meaningful data difficult and has arguably lead to the inconclusive and contradictory findings reported to date. It has been suggested, however, that it is important to have sufficient strength and stability for the body to function optimally in both everyday and sporting environments[17] and that by having sufficient stability and strength, athletic performance could be enhanced.[4]

To establish whether training core stability and/or core strength are important in everyday and sporting activity, research needs to establish what impact training in these areas can have on resulting performance. What is termed as performance, as with the definitions of core ability (core stability and core strength), differs between the rehabilitation and athletic sectors. In the rehabilitation sector, an improved performance for a patient with LBP would be the ability to perform everyday tasks pain free;[9,18] whereas in the sporting sector, an improved performance may be characterized by not necessarily being pain free, but by improving technique in order to run faster, throw further or jump higher,[4] although it could also include the reporting of fewer injuries, which enhances performance in training.[19,20]

Research performed to date has highlighted benefits of training core stability and core strength for patients with LBP and for carrying out everyday activities. However, less research has been performed on the benefits of core training for elite athletes and how this training should be carried out to optimize sporting performance. Although many studies have reported contradictory findings and conclusions,[3,6,8,16,21-25] many elite athletes continue to undertake core stability and core strength training as part of their training programme.

2. Functional Anatomy of the 'Core' as it Relates to Athletic Performance

A number of models have been published that try to describe the core musculature and the complex integration of the separate processes that work together to bring about core stability. Physiologically, what is included as 'the core' varies from study to study[26] depending on the context (rehabilitation or athletic) that it is viewed in. The core has been described as a box or a double-walled cylinder[27] with the abdominals as the front, paraspinals and gluteals as the back, the diaphragm as the roof and the pelvic floor and hip girdle musculature as the bottom.[28] Meanwhile, other researchers focusing on sports performance define the core as including all of the anatomy between the sternum and the knees with a focus on the abdominal region, low back and hips.[7] Other researchers conclude that the core musculature should include the muscles in the shoulder and pelvis as they are critical for the transfer of energy from the larger torso to the smaller extremities, which may be more involved in sporting movements rather than everyday tasks.[26,27,29,30] Leetun et al.[12] supports this by reporting that hip muscle activation significantly influences the ability to generate force in the upper leg muscles and it has been identified that hip muscle activation is important when looking at core stability and trying to improve core strength.[31] Elphinston[11] and Wilson[32] consider the gluteus maximus to have an essential role in core stability and hip control. A weak gluteus maximus muscle has an influence on the alignment of the lower knee and ankle, resulting in greater medial and rotational movement, which leads to an increase in strain on the joints, predisposing to a greater injury risk.

Panjabi[13] summarized the contributors to spinal stability into three groups: passive (e.g. vertebrae, ligaments and intervertebral discs), active (muscles and tendons around the joints) and neural (CNS and other contributing nerves). Bergmark[33] developed a model to summarize the role of the trunk muscles and their contribution to core stability. Bergmark's model labels muscles as 'local' (those with attachments to the lumbar vertebrae and which therefore influence inter-segmental control) and 'global' (those with attachments to the hips and pelvis and which therefore influence spinal orientation and control the external forces on the spine). It is important that both systems are integrated to establish normal movement function, for example, if only the global mobilizer muscles are trained, a muscular imbalance occurs because they 'take over' the role of the stabilizer muscles, resulting in restricted and compensatory movement patterns that are less efficient.[27] Stabilizing muscles are responsible for posture holding and distributing and absorbing force in the body, whereas mobilizing muscles contribute to rapid movement, force and power[33] because of their multi-joint positioning and large moment arms. All of these above processes are important to train, whether in the rehabilitation or sporting sector, as they all contribute to performing movements safely and correctly.

Lee[34] suggested that stability is not about the 'quantity of motion' and the 'quality of the end feel', but about the control of systems that allow load to be transferred and movements to be smooth and effortless. This may be true for sporting movements where the individual is looking solely to optimize their technique and not necessarily worry about pain, but for patients with LBP and the general population, the range of movement and 'quality of the end feel' (i.e. no pain) are more important. Brown[22] suggests that core stability is achieved by the muscular system of the trunk providing the majority of the dynamic restraint along with passive stiffness from the vertebrae, fascia and ligaments of the spine. Akuthota and Nadler[15] provide a detailed summary of the anatomy of the lumbar spine and the contribution of these parts to core stability and they draw attention to the contributions of the thoracolumbar fascia, osseous and ligamentous structures, paraspinals, quadratus lumborum muscle, abdominal muscles,[35,36] hip girdle musculature, diaphragm and the pelvic floor muscles.

Lehman[8] identified certain muscles that are essential to monitor when analysing core stability and core strength. These include the transverse abdominis (TrA), rectus abdominis (RA), external oblique (EO), internal oblique (IO), erector spinae, quadratus lumborum and latissimus dorsi. The contribution of these abdominal muscles to stability is related to their ability to produce flexion, lateral flexion and rotation movements and control external forces that cause extension, flexion and rotation to the spine.[24,33] Comerford and Mottram[36] emphasise the importance of the RA muscle and believe that this muscle has a high recruitment threshold and is important in bracing the spine for high-load activities such as pushing or lifting heavy loads. The EO and IO have a lower threshold of recruitment and mostly contribute to posture and stability. The contribution to and precise roles of these muscles in core stability and core strength is not clear and future research needs to be performed to establish these links.[15] For example, McGill[9] found that the psoas muscle (the largest muscle in the lower lumbar spine[37]) does not provide much stability, whereas Gibbons[37] reported that this muscle does have a stability role through axial compression and suggested that it was involved with lateral flexion, rotation and extension as well as hip flexion. Despite the apparent confusion and complexity outlined here, it would seem reasonable to suggest that when training the core, it is essential to understand the contribution to stability and strength that all of the musculature, neural and other structures have, and subsequently to train each section depending on the requirements for that individual (i.e. whether they are an athlete needing higher stability and strength or from the general population and require the ability to maintain stability at lower loads).

3. Types of Core Training

Core training programmes include processes that target muscular strengthening and motor control of the core musculature.[5] Core strengthening exercises are very popular in rehabilitation programmes despite little scientific evidence existing as to their efficacy on improving subsequent performance,[1,6,30] although some research has suggested that a number of methods can enhance neuromuscular control. These include joint stability exercises,[38] contraction exercises (concentric, eccentric and isometric),[39] balance training,[6] perturbation (proprioceptive) training,[40-43] plyometric (jump) exercises (plyometric training emphasises loading of joints and muscles eccentrically before the unloading concentric activity)[3] and sport-specific skill training.[8] In the field of physiotherapy, proprioceptive training is believed to be important and, consequently, programmes use methods and exercises that challenge proprioception using equipment such as wobble boards, roller boards, discs and Swiss balls.

Comerford[27] believes, however, that to train core stability and strength it is important to perform both low- and high-load threshold training.[17] Comerford[27] identified the following sub-areas of core training that all need to be included when training core stability and strength:

1. Motor control stability: low-threshold stability where the CNS modulates the efficient integration and low-threshold recruitment of local and global muscle systems.
2. Core strength training: high-threshold and overload training of the global stabilizer muscle system and leads to hypertrophy as an adaptation to overload training.[44]
3. Systematic strength training: traditional high-threshold or overload strength training of the global mobilizer muscle system.

Comerford[27] argues that it is essential for local muscles to be targeted and for low-load threshold training to be performed to avoid any muscle recruitment imbalance, which may lead to movement dysfunction and injuries. It is proposed that initial core strengthening programmes should enable people to become aware of motor patterns and allow them to learn to recruit muscles in isolation (it is possible to use biofeedback devices or verbal cues). Programmes can then progress to functional positions and activities.[15] Akuthota and Nadler[15] stated that re-learning the motor control of inhibited muscles may be more important than strengthening in patients with LBP. In this case, it may be that improvements in performance are a result of improved neural co-ordination and recruitment rather than specific improvements in core strength or stability. Careful performance measures are required in studies to identify which of these is ultimately targeted following intervention programmes.

The choice of exercise is important as the magnitude of the muscle activation and the recruitment pattern of the motor units determines whether core stability or core strength is developed. Vezina and Hubley-Kozey[45] suggest that an activation of >60% maximal voluntary contraction (MVC) is required to result in strength benefits,[46] with stability and muscle endurance benefits resulting from MVCs of <25%.[21,45] Vezina and Hubley-Kozey[45] used surface electromyography (sEMG) on three abdominal and two trunk extensor muscle sites and performed three low-load core exercises; pelvic tilt, abdominal hollowing and level 1 of the trunk stability test[47] to compare muscle activation. They identified that the three exercises recruited the five muscles differently, with the external oblique muscle showing the highest activation levels during the pelvic tilt (25% MVC). They concluded that the activation during these exercises would not elicit any strength benefits, but these exercises could be used to form an assessment of an individual's core stability to formulate a more demanding training programme. Similarly, Davidson and Hubley-Kozey[48] observed muscle electromyogram (EMG) activity of 3–7% MVC during a progressive leg extension exercise test, which suggests that this exercise is not sufficient to result in muscle strength improvements, but would be sufficient to establish and maintain trunk stability.[23]

Comerford[27] suggests that core stability training should range from isolated activation of the deep abdominal muscles to lifting weights on uneven surfaces. This is due to the different functional roles of the muscles during exercises and therefore it is advised[33] that a range of exercises be performed to challenge the core musculature in all three planes and ranges of movement to develop total core stability. For example, flexion (targeting hip flexors, back extensors, abdominal and glutei muscles, e.g. curl-ups, leg raising and squats with rotation), extension (e.g. targets hip extensors and hamstrings) and rotational exercises[49] should be included. Stephenson and Swank[26] believe that a core strength development programme should include: flexibility of the abdominal and lower back, hip extensor and flexor muscles; exercises in an unstable environment; as well as isometric and dynamic exercises.

Lehman[8] believes that because only a minimal level of muscle contraction is required to stabilize the spine (1–3% MVC), muscle endurance may be more important than muscle strength. Lehman[8] identified exercises such as the curl up, bird dog, side and front support and loaded squat to develop core muscle endurance as these challenge all of the anterior, lateral and posterior trunk muscles and all sufficiently stress the muscle, but do not exceed the thresholds for compression and shear loading, which may predispose the body to injuries. This is supported by McGill,[9,50] who suggests that muscular endurance is more important to stability than muscle strength, and by Faries and Greenwood,[16] who suggest that endurance should be trained before strength while focusing on establishing the correct motor control systems prior to increasing the bodies stabilization strength. Faries and Greenwood[16] suggest that endurance training focuses on low load, longer (30–45 seconds), less demanding exercises, while strength exercises are based on high-load, low-repetition exercises.

Speed, direction and order of limb movement during exercise are seen as critical factors when training. For example, the speed at which an exercise is performed will affect the gravitational and mechanical resistance experienced on the body. This is due to fast movements recruiting the fast motor units in the muscles when performing a movement optimally. Slow motor units of the muscle are utilized during low-threshold recruitment in postural sway and movements involved with unloaded limbs. It is important for optimum motor control to train both the fast and slow motor units in a muscle to optimize core stability and core strength.[24] The direction and order of limb movements also has a profound effect on muscle activation. Cresswell[51] found that the abdominal muscles, the RA, EO and IO were only active during acceleration, when they generated the movement, and deceleration, when they opposed the movement. The magnitude of movement has also been investigated; for example, feed-forward response in these muscles was identified when movements of the elbow and shoulder were performed, but not when the wrist and thumb were moved.[24] Furthermore, when the arm is moved, the onset of TrA activation precedes the deltoid by 30 ms,[52] when the leg is also moved, activation of the TrA precedes the deltoid by more than 100 ms.[53] This highlights the effect on muscle activity that increasing the demand on the core to maintain stability has on certain core muscles. Research suggests that limb movement is delayed in tasks where the postural demand is increased[54,55] due to the extra time needed to prepare the body for the resultant forces.[24] Research on the optimum speed and order of loading on the muscles is limited; therefore, it remains unclear what speed and direction of movement should be used, only that it should be functional and sport-specific for the individual's needs.[8,12] Future research should try to establish these characteristics to enable the most effective training programme to be implemented and to maximize the potential for the skills and training benefits to be transferred into performance.[56-58]

Due to the many factors mentioned above in the paragraph above, the ability to train the muscles to improve core stability and/or strength relies on the training being functional and specific to the everyday or sporting movement that is to be performed. Any improvements in training can then be translated into improvements in performance. Therefore, whether the targeted movements are to be low or high load will have a significant effect on the type of training programme implemented. The apparent contradiction between the traditional dynamic approach of the strength and conditioning coach compared with the more modest movements prescribed by physiotherapists has typically led to confusion as to which method is most effective. Prior to any training programme being initiated, the exercises included and intensity of the programme should be carefully evaluated depending on the individual involved and their goals (i.e. to be pain free to improve sporting performance). Therefore, future research should focus on establishing which exercises are sufficient for improving each part of core stability (i.e. neural, passive and active systems) and core strength (e.g. neural adaptations) to be able to target these performance goals more effectively.

4. Evidence of Core Training Benefits

Spinal instability and injuries to muscles (e.g. the core) and joints (e.g. knee, hips) sustained during movements are associated with insufficient strength and endurance of the trunk-stabilizing muscles and inappropriate recruitment of the trunk and abdominal muscles.[45] It is important that any trunk-stabilizing muscle weakness is identified and corrected as this significantly increases an individual's muscle and joint injury risk.[44] Neural adaptations from core training include: more efficient neural recruitment patterns, faster nervous system activation, improved synchronization of motor units and a lowering of neural inhibitory reflexes.[59] High-threshold strength training results in hypertrophy of the muscles (structural change) and neural adaptations (e.g. of the motor units in the muscles) of the muscles, which benefits performance by increasing the possible force generation, CNS facilitation, improved intrinsic muscle stiffness and improved tissue mobilization.[15]

Research stating whether there are any benefits of specific core stability or core strength exercises in activating muscles is limited and conflicting because of the wide variety of data collection methods, exercise techniques and subjects used for analysis. There is not one single exercise that activates and challenges all of the core muscles; therefore, a combination of exercises is required to result in core stability and strength enhancements in an individual.[23] Future research needs to identify which of these exercises are most effective in resulting in benefits depending on the performance goal.

4.1 Rehabilitation Sector

Most research in the rehabilitation sector focuses on how core stability influences LBP,[28,60-63] with many conditioning programmes being based around training the abdominal muscles to improve their strength and subsequently the stability of the spine.[64] This is based on the knowledge that strong abdominal muscles provide support for the lumbar spine during day to day activities.[64] Jeng[65] reported that the occurrence of LBP may be decreased by strengthening the back, legs and abdomen to improve muscular stabilization. Pollock et al.[39] showed that resistance training with pelvic stabilization improved development of lumbar extension strength, which may lead to an improvement in core stability and therefore reduce the risk of LBP. One of the main muscles associated with 'the core' is the TrA. This is the deepest abdominal muscle and provides specific support to the lumbar spine and has been shown to be impaired in those with LBP.[24,36,52,53,61,66-68] Hodges and Richardson[53,69] observed that TrA activity in healthy individuals precedes that of arm and leg movement by approximately 30 and 100 ms, respectively, suggesting that this muscle has a preparatory stabilizing effect and assists in stabilizing the trunk, thereby enabling force production at the extremities. The TrA muscle is also found to be active regardless of body movement direction, unlike other core muscles such as the RA, EO and IO.[24] Therefore, theoretically, training the abdominal muscles and improving their strength should have beneficial effects on resultant stability and performance.

Rehabilitation programmes have used Swiss balls to improve core stability with some benefits being documented.[70,71] Behm et al.[38] suggest that using a Swiss ball provides an unstable surface, which challenges the core muscles to a greater extent and improves trunk stability and balance. Cosio-Lima et al.[6] tested two groups of subjects, one training on the floor and one using a Swiss ball and found that the Swiss-ball group had a significantly greater change in muscle EMG activity during flexion and extension and greater balance scores than the floor-exercise group. Behm et al.[38] suggested that the Swiss ball can be used to increase stability, balance and proprioceptive ability, but not muscle strength.[24] As a result, many researchers advocate using a Swiss ball only as a low-threshold rehabilitation tool to improve joint position sense, balance, posture and proprioception.[40,41,43] This has led to modern day rehabilitation programmes using a mixed conditioning approach, which includes a range of methods to improve core stability and core strength. Saal and Saal[72] investigated the effectiveness of an exercise training programme on patients with LBP, which consisted of a flexibility programme, joint mobilization of the hip and the thoracolumbar spinal segments, a stabilization and abdominal programme (low-load exercises[73]) and an aerobic gym programme. The authors reported successful recoveries for 50 of the 52 subjects (96%). However, it is not possible to conclude how much of this improvement was directly due to the core stability work (other factors such as medication, injections and healing over time would all have had an additional effect).

Whether a training programme results in an improved performance or not depends on the effectiveness of the core exercise performed. This may explain why some research has resulted in contradictory research on the efficacy of some rehabilitation programmes to strengthen core muscles.[24,74] The effectiveness of an exercise is determined by factors such as functionality/specificity of the movement, intensity/threshold, familiarization and frequency. Different core exercises that challenge the core musculature at different intensities of muscle activation are required to result in stability or strength enhancements,[8] but these must be specific to the performance goals to result in any enhancement. In summary, research in the rehabilitation sector has been conducted, which has begun to assess how core muscles respond to low-load core stability exercises and their effect on LBP, and suggests that by performing core training exercises, performance relating to injury risk and recovery can be improved (table I). How core muscles respond to higher threshold exercises and movements/demands, seen regularly in sporting environments, however, cannot be elucidated by such methodologies.

4.2 Athletic Sector

There is a lack of research looking at the effect of core stability on athletic performance.[22] Although some studies have implied that there is an advantageous effect on performance by improving core stability and strength, these conclusions are largely assumptions based on basic testing.[16,77,78] Roetert[79] reported that core stability and balance are critical for good performance in almost all sports and activities. This is due to the 3-dimensional nature of many sporting movements, which demands that athletes must have good strength in the hip and trunk muscles to provide effective core stability. Some sports require good balance, some force production, and others body symmetry, but all require good core stability in all three planes of motion.[79] A lack of core strength and stability is thought to result in an inefficient technique, which predisposes the athlete to injury.[80] For example, LBP is a common problem in any sport that requires significant rotatory or twisting motions, repetitive flexion and/or extension.[81-83] In swimming, the maintenance of posture, balance and alignment is thought to be critical in maximizing propulsion and minimizing drag, yet it is not common practice for core muscles to be trained, with most strength programmes favouring arm exercises.[7] Leetun et al.[12] found that 41 (28 women, 13 men) of 139 athletes (basketball and track) sustained 48 back or lower extremity injuries during the season (35% of the women, 22% of the men). They identified that the athletes who sustained an injury generally had poor core stability (i.e. weaker hip abduction and external rotation strength, which decreased their ability to maintain stability) and also concluded that there were greater demands on the female lumbo-pelvic musculature, which resulted in a greater injury risk to the lower back for females (this is supported by previous research).[19,20,84,85] Subsequently, core training could play an important role in injury prevention, especially in females.

Physiologically, core strength and stability training is believed to lead to a greater maximal power and more efficient use of the muscles of the shoulders, arms and legs.[8] This theoretically results in a lower risk of injury and positive effects on athletic performance, in terms of speed, agility, power and aerobic endurance.[30] Training programmes attempting to correct weak links in an individual's core ability include strategies that regain control of the site and direction of the deficiency at the appropriate threshold of training. Typically, programmes are designed to:

- increase joint range and muscle extensibility;
- improve joint stability;
- enhance muscle performance;
- optimize movement function.[86]

Table I. A selection of research on core training and resultant benefits on core stability, core strength, muscular endurance and performance

Study	Result	Performance measure used/findings	Data collection method	Subjects	Training programme/exercises used
Liemohn et al.[75]	Stability improved	Time out of balance. Concluded exercises should be repeated over 4 d	Stability platform	16 healthy college students (9 men, 7 women)	Forward and side bridge, plank, bird dog
Vezina and Hubley-Kozey[45]	Stability improved	Repeated tests 6 wk later. Found improved TST level 1 results	Surface EMG (3 abdominal and 2 trunk muscles)	24 healthy men	TST level 1, pelvic tilt, abdominal hollowing
Urquhart and Hodges [76]	Stability effects	EMG muscle activity; found posture and stance affected muscle activity of the abdominal muscles. Muscles had different contributions/activity to each movement	Intramuscular EMG (TrA, EO, IO), surface EMG (RA)	11 healthy non-athletic subjects	Rapid, unilateral shoulder flexion in sitting and standing
Cosio-Lima et al.[6]	Increased muscle activity but no strength increase	EMG muscle activity. Strength on Cybex machine (back, abdominals, knee). Found Swiss-ball group had greater change in EMG activity, but no strength changes	Surface EMG (RA and ES) vs intramuscular EMG (TrA)	30 untrained college women	5-wk Swiss-ball training programme; curl-ups and back extensions
Nadler et al.[5]	Strength increase and fewer injuries	Strength increased and fewer injuries observed for males. Observed gender differences in response to the training on injuries reported	Force plate, dynamometer	>200 college sports players	Structured core-strengthening programme
Leetun et al.[12]	Poor strength led to more injuries	Weakness in hip abduction/external rotation led to more injuries	Video, dynamometer, force, EMG	140 basketball and track athletes (80 women, 60 males)	Hip abduction strength (sit and hold with hips at 60°), abdominal muscle activity, back extensor endurance
Tse et al.[30]	Improved muscle endurance but no effect on performance	Vertical jump, shuttle run, 40-m sprint, overhead medicine-ball throw, 2000-m ergo test. Found improved endurance, but no effect on performance	EMG	45 college rowers	8-wk programme; trunk extension and side flexion
Stanton et al.[1]	Improved stability, but no effect on performance	Sahrmann core stability test, stature, $\dot{V}O_{2max}$ test, running economy. Found significant effect on core stability, but no significant improvement on resultant performance measures	Surface EMG (RA, EO, ES), video	18 young male athletes	6 week programme; Swiss-ball exercises
Myer et al.[4]	Improved stability, strength and resultant performance	Single-leg hop and hold, and distance test used. Distance jumped and held increased following training programme. Found stability and strength improvements and enhanced performance following programme	Video, speed/strength and jump tests	41 female college athletes (basketball, soccer, volleyball)	6-wk programme; plyometric and movement, speed, core strengthening, balance and resistance training

EMG = electromyography; **EO** = external oblique muscle; **ES** = erector spinae muscle; **IO** = internal oblique muscle; **RA** = rectus abdominis muscle; **TrA** = transverse abdominis muscle; **TST** = trunk stability test; $\dot{V}O_{2max}$ = maximal oxygen uptake.

Many sport-specific training programmes fail to include low-load motor control training, which has been identified as an essential part of core strength training and improving core stability.[27] By neglecting the local muscles, the force produced by the global muscles will be too great for the local muscles to control and leads to greater injury risk.[16] It is believed that high-load training changes the muscle structure, whereas low-load training improves the ability of the CNS to control muscle coordination and hence the efficiency of the movement.[27] Therefore, by performing a well structured and functional programme using both low- and high-load training, improvements should be attained in all the processes contributing to core stability and core strength, which, it is reasoned, will in turn, impact on sporting performance. Low- and high-load training involves different types of movements; for example, low-load training involves less demanding, posture-related exercises that focus on muscle recruitment, whereas high-load training can involve exercises such as overhead weighted squats and hanging leg raises, which places a greater stress on the core musculature and also promotes core strength development.[87]

Many questions remain regarding what type of core training programme is most effective for improving core ability, but if future research can establish (i) clear definitions; (ii) reliable methods for summarizing the effectiveness of different core exercises; and (iii) the extent to which these muscles need to be active to bring about sufficient core stability and strength improvements, these training programmes would be more effective and we should expect to see fewer injuries and subsequently to observe improved sporting performances.

5. Measuring the Core and its Relation to Performance

Tse et al.[30] evaluated the effect of a core endurance programme (2 days a week for 30–40 minutes for 8 weeks) on 45 rowers. They measured trunk endurance (flexion, extension and side flexion tests) and functional performance tests including vertical jump, broad jump, shuttle run, 40-m sprint, overhead medicine-ball throw and a 2000-m maximum rowing test. The results revealed significant improvements in the side flexion tests of the core group; however, no significant differences were observed in the performance tests between the two groups. The authors stated that this may have been due to the margins for improvement in the subjects being relatively small in this highly conditioned group of athletes. Using a homogenous group of athletes, however, does enable a high level of sensitivity in the parametric statistic should any improvements be observed following an intervention programme, so the lack of significant differences in the study of Tse et al.[30] may also be due to the exercises performed not being functional enough to significantly improve performance. The length of intervention (8 weeks) may also have not been sufficient to elicit a performance enhancement (see figure 1).

Stanton et al.[1] investigated the effect of short-term Swiss-ball training on stature, bodyweight, EMG activity of abdominal and back muscles, treadmill maximal oxygen uptake, running economy and running posture. Each subject had familiarization sessions on the core activities to minimize the learning effect and then attended two sessions per week for 6 weeks. The authors used the Sahrmann core stability test[47] and a stabilizer pressure biofeedback unit (an inflatable pad that the subject lies supine on) and surface EMG from the RA, EO and erector spinae muscles. Stanton et al.,[1] Scibek et al.[88] and Cusi et al.[89] all observed significant effects on Swiss-ball stability; however, no significant differences in EMG activity or performance parameters were observed. Stanton et al.[1] speculated that the training may have had an effect on other muscles that were not analysed (e.g. pectorals, latissimus dorsi). Swiss-ball training alone, therefore, may not elicit the same performance advantage as explosive or high-intensity strength training. The lack of effect on performance observed in many studies may be due to the core training programmes not being functional enough to translate into improvements in sporting performance as a result of the poor understanding of the role that specific muscles have during these exercises. Future research needs to establish the

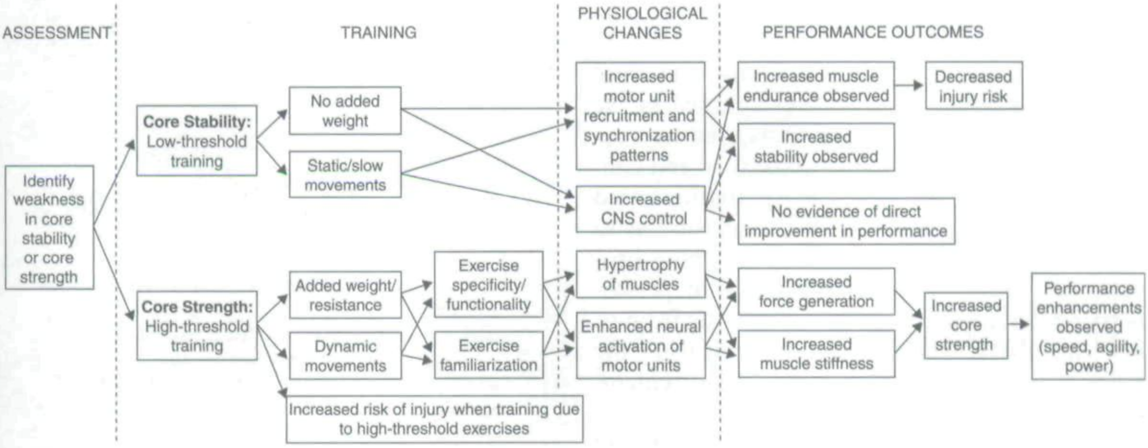

Fig. 1. Core training and potential performance benefits: principles of low- and high-load training with subsequent effects on core stability and core strength and the possible impact on performance as a result of scientific research carried out.

roles of specific muscles to be able to implement the optimum training programme for individuals. The lack of effect may also be due to the low-load exercises not being sufficient to result in a large enough improvement in core ability to affect the subsequent performance, and it may be that more demanding (high-load) exercises are required.

As stated in section 3, Davidson and Hubley-Kozey[48] suggest that loads need to be 60–100% of one repetition maximum to result in a strength enhancement of the truck musculature; however, this depends on the training status of the individual. Myer et al.[4] found improvements in performance (vertical jump, single-leg hop distance, speed and improved biomechanical range of motion) following a high-load training programme (including squats and bench-press exercises that focused on improving core strength), which suggests that the core training programme improved individuals' core ability and subsequently improved their ability to perform the tests. Nadler et al.[5] investigated how core strengthening influences hip muscle imbalance and LBP in trained athletes (by reducing the likelihood of segmental buckling).[8] Subjects performed a core-strengthening programme (abdominal, paraspinal and hip extensor strengthening) that included isolated abdominal strengthening (sit ups and pelvic tilts; rectus abdominis and abdominal obliques, squats and lunges (emphasizing multiple joint activation of ankle, knee and hip), leg press (to strengthen quadriceps and hamstring musculature and gluteus maximus) and strength training with free weights (dead lifts, hang cleans, using shoulder, upper leg and hip musculature). The study reported an increase in hip extensor strength for 90% of subjects, with the incidence of LBP decreasing by 47% in male athletes, but increasing slightly for females. This maybe due to the use of some unsafe exercises, such as the Roman chair exercise, and also due to females being more susceptible to LBP.[84] The exercises also only included frontal and sagittal plane movements and this may have affected the results by not being sport-specific enough to translate into improvements in sporting performance. Nadler et al.[5] concluded that the lack of significant findings in the study maybe due to the small number of subjects who reported LBP during the season, which may in itself reflect positively on the core training programme implemented.

In summary, it remains unclear as to which exercises best rehabilitate an individual back to normal health or are optimal for improving core strength or stability gains for improving sporting performance. Despite widespread acceptance that core stability and core strength impacts on sports performance, further research needs to be performed to establish whether this can be substantiated.

6. Conclusions

The definitions of core stability and core strength are yet to be clearly established in the rehabilitation and sporting sectors, and as a result, this has led to many contradictory and confusing findings in the area. These definitions need to be established before a clear conclusion as to which exercises and what type of training programme will most effectively result in performance enhancements, such as recovering from or lowering the risk of injury and improving the ability to perform everyday activities or enhancing sporting performance. If future research can establish clear definitions for core stability and core strength and reliable methods for summarizing the effectiveness of different core exercises, fewer injuries and subsequently improved performances in the rehabilitation and athletic sectors should be expected.

There are many articles in the literature that promote core training programmes and exercises for performance enhancement without providing a strong scientific rationale of their effectiveness, especially in the sporting sector. In the rehabilitation sector, it has been reported that improving core stability leads to improvements in lower back injury. Few studies have observed any performance enhancement in sporting activities despite observing improvements in core stability and core strength following a core training programme. It might be that improvements made in stability and strength only impact indirectly on sporting performance by allowing athletes to train injury free more often. A clearer understanding of the roles that specific muscles have during core stability and core strength exercises would enable more functional training programmes to be implemented, which may result in a more effective translation of core training into improvements in sporting performance.

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Correspondence: *Angela E. Hibbs*, English Institute of Sport, Gateshead International Stadium, Neilson Road, Gateshead, NE10 0EF, UK.
E-mail: angela.hibbs@eis2win.co.uk