Core stability in sports
- its association to and effects on sport performance

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Acknowledgements

I would like to thank my former tutor Dr Dave Cook, course director at LSBU and former colleague Chris Joyner, Strength & Conditioning Coach/Master Personal Trainer for their knowledge and inspiration that has helped me develop in the field of scientific and applied sport science.

To my family Anna, Emelie and Julia, thank you for your support that helped me to finish this project, you are the best!
Abstract

Aim
The aim of this paper was to investigate if there is sufficient evidence that core strengthening/strength effects on sport performance in a positive way through an analysis of the scientific literature up to date.

Method
The articles analysed in this paper were gathered through a search of the databases SportDiscus and PubMed carried out between 02.12.11 and 13.12.11. The search words chosen were, abdominal strength, athletic performance AND core, core training, core training AND efficacy, core stability AND athletic function, core AND athlete, trunk stability, trunk stability AND effect. As a complement to the database research, articles were included that could be found in the reference lists from incorporated articles. After an evaluation through exclusion and inclusion criteria, in total 16 articles were included. Descriptive articles and intervention studies were presented separately.

Results
Five of the 16 articles were descriptive studies and 9 intervention studies. While most studies showed no association between core strength/stability and sports related performance or benefit from core training, adding core training to a program was beneficial for throwing and striking skills in five studies. Core strength/stability was assessed in many different ways and there is no consensus in the literature today regarding valid tests or the very definition of core strength and stability.

Conclusions
The limited quality and number of studies on the relationship between core strength/stability and sport performance makes it hard to draw any clear conclusion. Although some support was found to substantiate that core strengthening might positively affect throwing and striking skills. Most core stability measurements focused on muscle endurance while sport performance, more likely, demands power and explosive core stability. More research is needed with different subject groups and more sport specific core strength tests before conclusions can be drawn.
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1. Introduction

Does core training have an often claimed positive effect on sport performance, or has the current trend in the field of sport and exercise overrated the role of core training? This is a very relevant question since the fitness industry over the last 10 years has taken a swing towards “Functional training” with the use of different core training methods without presenting any clear evidence for its often highly claimed benefits (42). This trend has also influenced the athletic world and there have emerged numerous books and articles claiming the benefit of different core training regimes for better health, reduced injury rate and sport performance, but seldom with any clear evidence presented (12).

The two components in core training philosophy today are in general the use of exercises that focus on core endurance and the use of unstable training rather than power and strength (47). Regarding unstable training devices, the Swiss Ball (also known as Pilates ball) has become very popular. The reason being the alleged claim that one can stimulate the deeper or “stabilising” core muscles in the right way with this device for the best improvement of core stability (11).

The rationale for the approach of a high focus on core training often relates to the assumption that specific core muscles such as the transversus abdominis muscle and the multifidus play a key role in stabilising the spine and therefore play a key role in enhancing sport performance (5). This has led to the claim of specific training approaches, exercises and programs that will bring the best result for better sport performance with little or no scientific evidence (6-8, 29). There are probably many reasons to why there does not exist a consensus regarding core training principles for sport (20). First of all, the nature of a specific sport may play a key role but there are other issues such as the basic definition of the “core” and core stability and strength (29).

In North America the role of core training in sports performance has been debated over the last 10 years resulting in very different viewpoints. At one end of the spectrum one can find coaches who advocate that core training in its self does not improve performance but has its place in a training program, in a limited form as every other part of a good training regime (51). Often the main focus is put on resistance training and multi joint strength training for the
best sport specific physic. The rationale behind this is due to fact that some coaches have not found a high crossover effect from specific core training and explosive multidirectional sport motions. The reason being that most standard core training exercises often are of an aerobic/endurance nature (6, 8, 51).

At the other side of the spectrum regarding the role of core training, one can find coaches and fitness practitioners who are highly influenced from the clinical rehabilitation field. The very strong focus on core training, independent of the client being trained is proposed due to the notion that one needs a strong and “stable core” to prevent injury and enhance performance (11). Often this means that one is training the core musculature in a step-by-step approach when one has to score a certain “result” in order for a step-up in exercise intensity and difficulty (11, 26).

Those who propagate this training approach often propose the incorporating of unstable devices such as the Swiss Ball and wobble boards with a claimed high crossover effect on sport performance (11). These exercises in general put a sole focus on endurance, time and repetition to total exhaustion (11).

In the middle of the different stated viewpoints one can find coaches who has come up with a “middle way” with influences from both side of the spectrum. This means incorporating a step by step approach in developing strength and strength endurance in the core muscles, without letting this take away any time and focus from “traditional” strength and conditioning components. The idea is that the specific core training together with a strong focus on multi joint exercises such as Olympic lifts, squat and dead lift will build the best core stability and strength for enhanced performance (49).

The fact that there exist different approaches in the Strength and Conditioning community regarding the role of core training in relationship to performance makes it a very interesting topic to study. This is especially the case since the scientific evidence backing up different approaches is often missing (12). It is with this background that this paper is carried out with the aim of summarizing the knowledge from the scientific data up to date.
1.2 Definition of core stability

The definition of core stability varies between authors, depending on if one talks from a clinical perspective or in a sport/fitness context. In the field of health, fitness and sport it seems as if core stability and balance (dynamic/static) have been more or less integrated into the concept and definition of core stability (42). This is probably due to the fact that research has showed an increase in muscle tension in certain core muscles during unstable training conditions by the use of EMG (19). Coaches and researches have then taken this as evidence for the integration of balance into the concept of core training and stability. As a result of this one can often find unstable training in the core training exercises used when analysing core training effect on sport performance (8). In this paper the concept of static and dynamic balance will be left out since it is regarded as a topic of its own, although both factors are integrated into the core stability definition (33, 36).

The core definition used in this paper has taken its principles from a more clinical perspective and states as follows (33, 36):

“Core stability is the notion of keeping the spine (vertebrae) in an aligned state with the natural S-curve from pelvic to cranium during static and dynamic motion”.

The definition above is based on the model put forward by Panjabi who has defined the three following components that are working in a complex process for a stable spine (33, 36):

- Neuromuscular control (neural elements)
- Passive subsystem (osseous and ligamentous elements)
- Active subsystem (muscular elements)

Exactly how the interaction between the central nervous system and the passive and active muscular system works is not clear due to the complexity of distinguishing which muscle is active before or in relationship with another (9). Exactly why this is the case and how the anatomy is thought to work during active static and dynamic human movement is not a topic for this review. But in order to get an overall picture of which muscles one is talking about regarding core function and stability, one can divide the major active muscles into two groups (18):
• Global muscle: superficial that induce movement
  - Rectus abdominis, lateral fibres of external obliques, psoas major, erector spineae, iliocostalis (thoracic portion)

• Local muscles: deeply placed muscles that stabilise the spine
  - Transversus abdominis, multifidi, internal oblique, medial fibres of external oblique, quadratus lumborum, diaphragm, pelvic floor muscles, iliocostalis and logissimus (lumbar portions)

1. 3 Definition of Sport Performance

The definition for “Sport performance” for this paper has been limited down mainly to direct sport action such as sprinting, jumping, rowing, cycling and technique and complex sports (throwing, pitching, and golf). Examples of activities not included are; walking, day to day activities and different forms of exercises that might be used to train different sport motions such as none multi joint resistance training.

1. 4 Previous reviews and research

Surprisingly, not many studies exist regarding the efficacy of core training on athletic performance despite the claim of enhanced performance (47). In recent years a few review articles have dealt with this topic but not with a systematic approach. One has therefore not been given a complete picture of how broad the data is and how the selection of the analysed articles has been done.

In 2008 Hibbs et al. (21) analysed nine studies and the possible benefit of performance from core training. The main conclusions they came up with was the need of reliable methods when analysing core exercises, how core muscles need to be activated to bring optimal stability and the need for established and clear definitions of core strength and core stability in order to be able to compare research data (21). This is evident when one compares the methods in the analysed studies. The data were selected in a very diverse way by intramuscular EMG, video analysis, force platform, stability platform, dynamometer and speed/strength/jump performance tests.
Another factor that makes comparison difficult in their review was the broad range of training protocols, low/high intensity, strength/endurance and type of exercise (body weight or aided resistance). However, there were two common components, the training of core muscles to exhaustion (endurance) and the subject groups selected was made up with different types of athletes (21).

A similar review from 2010 by Behm and colleagues analysed 10 studies and the effect of core training on athletic performance. This time, studies that used static and dynamic balance (unstable training) component in the training protocol were reviewed. The main conclusion they came up with was that athletes should focus on traditional free weight training instead of “Functional” (unstable) core training since they could not find a clear transfer from this type of core training to enhanced sport performance (6,7).

Overall the training intervention of the studies in the review by Behm et al. 2010 (6) had a more diverse component of core strength, endurance and power. They also had a focus on analysing the relationship between core training and different types of sport performance such as vertical jump, sprint time and distance running time. Another aspect that was different from many of the studies in the review by Hibbs et al. 2008 (21) was that the selected studies included in this review where all controlled trials (6).

These two previous reviews described above are the only one in recent years that has had a more comprehensive and detailed table of selected articles with information regarding method, aim and result regarding the effect of core training and sport performance. A review by Willardson presented a result table of selected articles that analysed core “stability” and possible enhanced performance (47). The main conclusion was similar to those made by Behm et al. 2010 (7), namely that athletes should focus on traditional free weight training in order to develop strength, power and incorporate sport specific core training (47).

In an article by Cissik a small number of studies were reviewed (12) and they included both core training and its effect in rehabilitation and the possible positive effect on sport performance. Once again this was done without a clarification of how the selection of research papers was made and how broad the research field is in this topic (12). The conclusion was that there is not enough research data that support the idea that one benefits in a sport performance context from extra time spent on this type of training.
Other reviews and research papers of the topic of core training and its effect on sport performance have been carried out in a broader context, often including core stability definitions and rehabilitation interventions. Behm and colleagues stated in a “Position stand” (7) the viewpoint that core training under unstable conditions is suited for rehabilitation and the main focus for athletes should be on Olympics lifts and multi joint free weight training. This is backed up by the fact that intensity, force, power, velocity and range of motion is hampered by unstable core training (6-8).

Finally, a review by Lederman “The myth of core stability” highlights several problems and difficulties regarding the definitions of core stability/strength function in a very critical way. The author argues with backup of research data, that many of the hypothesised biomechanical models and concepts fall short or need much more research in order to stand as facts (24). This includes the proposed positive effects from core training on sport performance and rehabilitation interventions. The main points against the benefits of core training for athletes is linked to the critical analysis of the relationship between muscle activation, motor control and skills learning regarding transfer from core training exercises and specific sport performance (24).

1. **Aim**

The aim of this paper is to answer the following questions through a research of the scientific literature up to date:

- The efficacy of core training on sport performance
  - Is there any scientific data to support that core training improves performance measures related to sports or that core strength/stability is correlated to such measures?
- What methods are used to assess core strength/stability in the studies investigating effects of core strength/stability on sport performance?

The hypothesis is that there exist no scientific data supporting effects on sports performance.
2. Method

2.1 Literature search

The articles analysed in this paper were gathered through a search of the databases SportDiscus and PubMed. The search of the two databases was carried out between 02.12.11 and 13.12.11. In this process certain search words were chosen in order to include research articles on trunk/core training. These were, abdominal strength, athletic performance AND core, core strength, core training AND efficacy, core stability AND athletic function, core AND athlete, trunk stability, trunk stability AND effect. The different combinations gave very similar result and as a complement to the database research, articles were included that could be found in the reference lists from incorporated articles.

2.2 Inclusion criteria

Articles included in this paper met the following criteria. (a) Research looking on the effect of core training on sport performance. (b) Research methods that met the stated sport performance definition. (c) Whole article published in English language Scientific Journals. The above stated inclusion criteria ensured accepted validity and reliability in terms of requested data was obtained and evaluated through established test protocol.

2.3 Exclusion criteria

The following topics were excluded from the article research: (a) Rehabilitation, (b) Muscle activation, (c) Unstable static and dynamic training (functional training) and (d) Articles published in training and magazines.
3. Literature search result

The initial database research resulted in 3205 articles. Of these, 3152 were excluded after an initial screening of the title and topic. The remaining 53 articles were then examined for inclusion and exclusion criteria. Eleven of these articles were excluded based on study design and measured variables. This was due to the fact that these studies did not investigate the relationship of core training and its effect on the defined sport activity. For example did some of these studies focus on the relationship between core strength and static/dynamic balance. Further, two studies were excluded since they were not published in English speaking journals.

The 16 articles were made up by the following research methods: One training study of pilot character (17), one study of acute effects of training (1), 5 correlation studies (30-32, 41, 46) and 9 training studies (10, 15, 23, 25, 39-40, 43-45). Of the training studies, four had an intervention of six weeks (22, 30-31, 34), two lasted for eight weeks (38-40) and one each lasted nine (10), ten (15) and 12 weeks (23).
The population selected in the articles consisted of an athletic population in 14 cases. The athletes were of College Division I to III or higher level in all cases but one in which high school athletes were the subjects (39). In the remaining two studies the subjects used were of a “healthy” population (44, 45). In order to make the analysis most effective, the studies were divided into two tables, 1 and 2 due to the research design used (cross sectional and training studies).
Table 1. Correlation studies

<table>
<thead>
<tr>
<th>Authors</th>
<th>Sport performance</th>
<th>Subjects</th>
<th>Performance test</th>
<th>Core stability test</th>
<th>Effect within group</th>
<th>Correlations with P-values</th>
<th>Conclusion by authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nesser et al 2008</td>
<td>Athletic performance</td>
<td>29 College Division I football players</td>
<td>The correlation of core strength and countermovement vertical jump, Shuttle run, 10, 20 and 40 yard sprint, 1 RM: bench press, squat and Power clean</td>
<td>McGill core test (29) measurement in time</td>
<td>Yes</td>
<td>Moderate to weak positive correlations for: 1 RM Bench press: -0.217 (P&lt;0.05) 1 RM squat: -0.470 (P&lt;0.05) 1 RM power clean: 0.041 (P&lt;0.05) Countermovement vertical jump: 0.591 (P&lt;0.01) Sprints 40 yards: - 0.604 (P&lt;0.01) Shuttle run 10 yards: - 0.551 (P&lt;0.05) Shuttle run 20 yards: -0.539 (P&lt;0.01)</td>
<td>Core strength will most likely not enhance athletic performance significantly and should therefore not be the main focus in a training program</td>
</tr>
<tr>
<td>Nesser and Lee 2009</td>
<td>Athletic performance</td>
<td>16 female College Division I soccer players</td>
<td>The correlation of core strength and vertical countermovement jump, Shuttle run, 20 and 40 yard sprint, 1 RM: bench press and squat</td>
<td>McGill core test (29) measurement in time</td>
<td>No significant correlation (r-values), no P-values presented, according to author they were P&gt;0.05 Vertical countermovement jump: -0.276 Shuttle run: -0.424 Sprint 20 yards: 0.326 40 yards: -0.367 1 RM max bench press: -0.099 Submaximal: 0.298 1RM max squats: - 0.139 Submaximal: 0.099</td>
<td>Core strength will most likely not enhance measured variables and the core is not more important to train than any other body part</td>
<td></td>
</tr>
<tr>
<td>Okada et al 2011</td>
<td>Functional movement and performance</td>
<td>28 recreational athletes, male and female</td>
<td>The correlation of core strength and functional movements (14) and performance: overhead medicine ball throw, T-agility run and single leg squat</td>
<td>McGill core test (29) measurement in time</td>
<td>Contradictive correlations between core stability and 10 abdominal muscle measurements and overhead medicine ball throw, T-agility run and single leg squat depending on which core muscle and one investigated</td>
<td>Functional movement and specific core training should not be the primary emphasis of any training program</td>
<td></td>
</tr>
<tr>
<td>Sharrock et al 2011</td>
<td>Athletic performance</td>
<td>34 College athletes Division II, male and female</td>
<td>The correlation between a core stability test and 40 yard sprint, medicine ball throw, T-agility run and vertical jump</td>
<td>Double leg lowering test (47) measurement in degrees</td>
<td>No significant correlation except a negative one for core stability and medicine ball throw for both men and women: T-agility run: 0.052, (P&gt;0.05) 40 yard sprint: 0.13, (P&lt;0.05) Vertical jump: -0.172, (P&gt;0.05) Medicine ball throw (distance): -0.389 (P&lt;0.05)</td>
<td>More research is needed to prove a positive relationship between high levels of core stability and athletic performance</td>
<td></td>
</tr>
<tr>
<td>Wells et al 2009</td>
<td>Golf shot performance</td>
<td>15 men and 9 women, elite amateurs</td>
<td>The correlation of different types of golf shots and core strength</td>
<td>Plank and side plank test (28) measurement in time</td>
<td>Significant associations between anterior and side abdominal muscle performance for grouped result: Driver carry distance: 0.38 (P&lt;0.05) Putt distance after a chip shot*: -0.44 (P&lt;0.05) Putt distance after a chip shot**: -0.43 (P&lt;0.05) Putt distance after a sand shot: -0.59 (P&lt;0.05) Anterior core muscles* None dominant oblique**</td>
<td>Core strength may be important for driver performance, although a negative correlation was found for the short game</td>
<td></td>
</tr>
</tbody>
</table>
3.1 Analysis of the correlation studies

Four of the studies in table 1 investigated the relationship between core strength/stability and athletic performance via parameters such as sprint time, power and strength. Only Wells et al. 2009 (46) studied a specific sport action i.e. golf shot performance and it’s correlation to core strength and other athletic parameters. Athletes were used as subjects for the studies by Nesser et al. 2008, 2009 (30, 31) and Sharrock et al. 2011 (41). In the study by Okada (32) recreational athletes was used and in the study by Wells and colleagues (46), elite amateur golfers were used. The number of subjects used varied from 16 to 34 and no control groups were used.

The study design was fairly similar for all the correlation studies, a test of core stability/strength by the use of a muscle endurance type of test. The two studies by Nesser and colleges and the one by Okada and colleges used a core test by Stuart McGill (26). This test measure core endurance through static strength by the use of plank and back exercises. The test score is measured in time to exhaustion and the test ends when perfect form is lost (26). A higher value in this test represents a better core strength/stability. Wells and colleges used a similar Plank test as a measurement for core stability but excluded the exercises for the back (46).

In the study by Sharrock and colleges the definition of core stability was set by the use of the double leg lowering test (47). The test is most often used for clinical purpose when one is looking at the muscle function of the deep core muscles. The result is measured with a goniometer and categorised in a scale to determine the core strength of the subject (47). Top score is set when the legs are parallel to the floor in a supine position when the lower back still have contact with the floor. A lower value in this test represents a better core strength/stability. Below in Table 2, there is a short overview of the different core test used in the correlation studies.
Table 2.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type of exercise</th>
<th>Units</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>McGill core test</td>
<td>Static plank and back tests</td>
<td>Time to</td>
<td>Failure when the hips/core drops out of alignment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>exhaustion/failure</td>
<td></td>
</tr>
<tr>
<td>Double leg lowering</td>
<td>Lowering of the legs when one is lying down</td>
<td>Degrees of the legs when failure is reached</td>
<td>Failure when there is no contact with the lower back when the legs are lowered</td>
</tr>
<tr>
<td>Plank/side plank test</td>
<td>Static plank test</td>
<td>Time to</td>
<td>Failure when the hips/core drops out of alignment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>exhaustion/failure</td>
<td></td>
</tr>
</tbody>
</table>

The athletic characteristics correlated with the core test data were fairly similar and consisted of commonly used exercises for conditioning and testing of sport performance, such as vertical jump, medicine ball throw and 40 yard sprint (4).

3.2 Effect and conclusion

Only in the study by Wells et al. 2009 (46) did the authors themselves conclude a positive correlation between core strength and some of the golf shots and different core muscles analysed regarding improved distance and accuracy for the driver for the whole subject group (46). A positive correlation was also established for the 5 iron and some short game shots (only for the female subjects). However, for the whole group, the correlation was negative for the short game shots (46). It is hard to find a conclusion to the mixed correlation for the short game shots. Maybe the muscle activation in the longer shot may require a higher muscles involvement in the oblique’s compared to putting and chipping, more comparative data could possible clarify this.

The four other studies did not show a clear correlation between core stability/strength and athletic performance. The studies by Nesser et al. 2008 (30) and Sharrock et al. 2011 (41) did however show significant correlation within the subject groups. The result was most likely related to the fitness level of the subjects and the difference between men and women’s fitness level in the study by Sharrock et al. 2011 (41). The use of athletes and a correlation study with commonly used exercises will most likely not show a possible significant positive statistical result compared to if one had used sedentary subjects.
Table 3. Training studies

<table>
<thead>
<tr>
<th>Author</th>
<th>Sport performance</th>
<th>Intervention subjects</th>
<th>Intervention</th>
<th>Control group</th>
<th>Core stability test</th>
<th>Effect from pre-post training test</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butcher et al 2007</td>
<td>Vertical jumping takeoff velocity</td>
<td>41 male and female athletes from different sports</td>
<td>9 weeks study of t three different training programs: leg strength, core and leg strength</td>
<td>Passive group, n: 14</td>
<td>Double leg lowering test (47) measurement in degrees</td>
<td>Improved (P&lt;.05) vertical jumping velocity from all programs, the core stability group also showed improvement (P&lt;.05) after 3 weeks.4 by-2 ANOVA</td>
<td>Specific core stability training does not seem to have any advantage on vertical jumping performance compared to leg or leg and core strength training</td>
</tr>
<tr>
<td>Cressey et al 2007</td>
<td>T-agility run, sprints (40 and 10 yards), Bounce drop jump and countermovement jump</td>
<td>10 male College Division I soccer players</td>
<td>10 weeks instability and core training</td>
<td>Active group, n: 9</td>
<td>Side Plank test (28) measurement in time</td>
<td>No difference in performance between the two groups (P≤.05). Five paired sample T-tests</td>
<td>Instability and core training is not the preferred form of strength &amp; conditioning variable for most sports, But play a role in rehabilitation</td>
</tr>
<tr>
<td>Kim 2010</td>
<td>Golf driver distance and club head speed</td>
<td>9 female golfers (professional)</td>
<td>12 weeks of specific training, core training included</td>
<td>Passive group, n: 8</td>
<td>Isometric strength test</td>
<td>Improved (P&lt;.05) club head speed, carry distance and improved (P&lt;.05) strength and flexibility. ANOVA</td>
<td>Improved driver performance, strength and flexibility with a specific training program.</td>
</tr>
<tr>
<td>Lust et al 2009</td>
<td>Baseball pitching accuracy</td>
<td>13 College Division III athletes</td>
<td>6 weeks of open/closed kinetic chain exercises, plyometric training and core training</td>
<td>Active group, n: 12</td>
<td>Side Plank test (28) and isometric abdominal test</td>
<td>Improved throwing accuracy (P&lt;.001) for all groups. No significant improved core stability (P&lt;0.008). ANOVA</td>
<td>The different training methods have similar effect on core stability and throwing accuracy</td>
</tr>
<tr>
<td>Saeterbakken et al 2011</td>
<td>Handball throwing velocity</td>
<td>14 female high-school handball players</td>
<td>6 weeks of core training</td>
<td>Active group, n: 10</td>
<td>Increased training intensity</td>
<td>Improved throwing velocity (P&lt;.01): 2 x 2 variance</td>
<td>Core stability training can improve throwing velocity</td>
</tr>
<tr>
<td>Sato and Mokha 2009</td>
<td>5000 m track running for time and running kinetics</td>
<td>14 (men and women), recreational and competitive runners</td>
<td>6 weeks specific core training</td>
<td>Active group, n: 14</td>
<td>Sahrmann core stability test (26) measurement by a 5 step scale</td>
<td>Improved running time (P&lt;.05) for 5000 m but no effect on ground reaction time (P≤.05) and lower leg stability. ANOVA</td>
<td>Indicates a relationship between core strength and running time.</td>
</tr>
<tr>
<td>Stanton et al 2004</td>
<td>Treadmill running economy and VO2max</td>
<td>8 male athletes</td>
<td>6 week specific core training</td>
<td>Active group, n: 10</td>
<td>Sahrmann core stability test (26) measurement by a 5 step scale</td>
<td>Improved core stability (P≤.05). No significant (P&gt;0.05) improved running time or VO2max. ANOVA</td>
<td>Swiss ball training improves core stability but had no positive effect on running economy or VO2max.</td>
</tr>
<tr>
<td>Thompson et al 2007</td>
<td>Golf club head speed</td>
<td>11 male senior golfers (amateur)</td>
<td>8 weeks of functional and core training</td>
<td>Active group, n: 7</td>
<td>Fullerton senior fitness test (36)</td>
<td>Improved club head speed and different fitness aspects (P&lt;.05), no specific core test. ANOVA</td>
<td>Significant improvements but more research is needed regarding specific training for senior golfers.</td>
</tr>
<tr>
<td>Tse et al 2005</td>
<td>Rowing and vertical jump, broad jump, shuttle run, 40 yard sprint and overhead medicine ball throw</td>
<td>20 male college-age rowers (amateur)</td>
<td>8 weeks core endurance training</td>
<td>Active group, n: 14</td>
<td>McGill core test (28, ) and Biering-Sorensen back test (16), measurement in time</td>
<td>Improved selected core endurance (P&lt;.05) for the core training group. 2 x 2 variance</td>
<td>No positive effect on athletic performance from core endurance training</td>
</tr>
</tbody>
</table>
Table 4. An acute effect and a Pilot training study

<table>
<thead>
<tr>
<th>Authors</th>
<th>Measured performance</th>
<th>Intervention Subjects</th>
<th>Intervention</th>
<th>Control group</th>
<th>Core stability test</th>
<th>Effect within group</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abt et al 2007</td>
<td>Cycling mechanics</td>
<td>15 competitive cyclists</td>
<td>A cycling ergonometer test post a core training session. Result was compared with cycling data (mechanics) from a test with no pre core training</td>
<td>No</td>
<td>Biodexsystem isokinetic torso rotation test</td>
<td>No positive effect on peak torque, total work, average power, maximal repetition work and average peak torque (P&lt;.05). Separate dependent T-tests</td>
<td>Poor core strength/stability may alter knee injury risk. No significant effect on pedal force and work</td>
</tr>
<tr>
<td>English and Howe, 2007</td>
<td>Baseball pitching speed</td>
<td>3 College baseball pitchers</td>
<td>6 weeks of Pilates training</td>
<td>No</td>
<td>Double leg lowering test (47) measurement in degrees</td>
<td>Improved core strength and stability for three subjects (P&lt;.05). Improved pitching velocity for two subjects (P&lt;.05).</td>
<td>Improved core strength and stability may affect pitching performance positively</td>
</tr>
</tbody>
</table>
3.3 Analysis of the training studies

All the studies in Table 3 and 4 used athletes of various levels as subjects except for the studies by Saeterbakken et al. 2011 (39) and Thompson et al. 2007 (44) and Tse et al. 2005 (45). An active control group who continued with their normal training was used in four studies (25, 38, 40, 43) and similar training was used for both subject groups in two studies (15, 44). In the study by Thompson et al. 2007 (44) the control group was assigned to continue their daily activities. This was also the case for one control group in the studies by Butcher et al. 2007 (10) and Kim 2010 (23). The acute effect study by Abt et al. 2007 (1) and the Pilot study by English and Howe 2007 (17) were the only studies that did not use a control group. The total number of subjects ranged from 15 to 55 subjects and the control groups ranged from seven to 15 for all the studies in Table 3.

The intervention period varied from 6 weeks for the studies by Abt et al. 2007 (1), Lust et al. 2009 (25), Saeterbakken et al. 2011 (39), Sato and Mokha 2009 (40), Stanton et al. 2004 (43) and English and Howe 2007 (17). The study by Thompson et al. 2007 (44) and Tse et al. 2005 (45) lasted 8 weeks, Butcher et al. 2007 (10) lasted 9 weeks, Cressey et al. 2007 (15) lasted 10 weeks and Kim 2010 (23) lasted 12 weeks. In a short summary, the training programs/exercises chosen for the different studies in table 2 and 3 are presented in Table 5 below.
Table 5.

<table>
<thead>
<tr>
<th>Author</th>
<th>Weeks</th>
<th>Exercise</th>
<th>Intensity (resistance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butcher et al 2007</td>
<td>9</td>
<td>Dynamic and static floor type of exercises such as:</td>
<td>Body weight</td>
</tr>
<tr>
<td>Cressey et al 2007</td>
<td>10</td>
<td>Multi joint bar and dumbbell exercises such as: deadlift, squat, lunge and side plank</td>
<td>Submaximal weight, unstable dyna-disc for lunges. 40 second side plank</td>
</tr>
<tr>
<td>Kim 2010</td>
<td>12</td>
<td>Multi joint exercises such as: deadlift, squat, cable crunches and rotational core exercises</td>
<td>Body weight, Swiss ball and Medicine ball, cable machine</td>
</tr>
<tr>
<td>Lust et al 2009</td>
<td>6</td>
<td>Sit-up, rotational sit-up and static and dynamic back exercises</td>
<td>Body weight, Swiss ball, weight plate and elastic band</td>
</tr>
<tr>
<td>Saeterbakken et al 2011</td>
<td>6</td>
<td>Dynamic exercises with a sling such as: 1 leg squat, side plank, crunches and push up</td>
<td>Body weight and a sling (similar to TRX suspension training)</td>
</tr>
<tr>
<td>Sato and Mokha 2009</td>
<td>6</td>
<td>Dynamic and rotational Swiss ball exercises such as: crunches, Russian twist, hip bridge and back extension</td>
<td>Swiss ball</td>
</tr>
<tr>
<td>Stanton et al 2004</td>
<td>6</td>
<td>Dynamic and rotational Swiss ball exercises such as: Lunge, superman, roll-out and Russian twist</td>
<td>Swiss ball</td>
</tr>
<tr>
<td>Thompson et al 2007</td>
<td>8</td>
<td>Dynamic progression of Swiss ball exercises such as: medicine ball rotation, hip bridge and crunches. Floor exercises such as: crunches, rotational crunches and superman</td>
<td>Body weight, Swiss ball and Medicine ball</td>
</tr>
<tr>
<td>Tse et al 2005</td>
<td>8</td>
<td>Dynamic exercises such as: Sit-up, back extension and side flexion</td>
<td>Body weight</td>
</tr>
<tr>
<td>Abt et al 2007</td>
<td>6</td>
<td>Dynamic exercises such as: Medicine ball rotation, lateral weight plate bend, standing cable rotation, weight plate sit-up</td>
<td>Body weight, weight plate, Medicine ball and cable machine</td>
</tr>
<tr>
<td>English and Howe 2007</td>
<td>6</td>
<td>Dynamic and static floor exercises such as: single leg stretch, criss cross, spine twist, rolling, rowing, teaser and rolling down</td>
<td>Body weight</td>
</tr>
</tbody>
</table>

Similar core strength/stability parameters were used for the training studies as for the correlations studies in terms of definition and measurement which is presented table 6 below. The Sahrmann core stability test (25) was used by Sato and Mokha 2009 (40) and Stanton et al. 2004 (43). Side bridge strength test (26) was used by Cressey et al. 2007 (15) and Lust et al. 2009 (25). Butcher et al. 2007 (10) and English and Howe 2007 (17) used a double leg lowering test (48), Tse et al. 2005 (45) used the McGill core endurance test (28) and the Biering-Sorensen trunk test (16). These core tests have research and clinical data supporting their method and result.

The study by Kim 2010 (23), used an isometric strength test, Saeterbakken et al. 2011 (39) used an increased training program as measurement and Thompson et al. (44) used the “Fullerton senior fitness test” (38). In the acute effect study by Abt et al. 2007 (1), an isokinetic rotation test was used to determine core strength. These four test methods are hard to assess in terms of reliability and validity since it does not exist comparable methods and result.
Table 6.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type of exercise/test</th>
<th>Units</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>McGill core test</td>
<td>Static plank and back tests</td>
<td>Time to exhaustion/failure</td>
<td>Failure when the hips/core drops out of alignment</td>
</tr>
<tr>
<td>Double leg lowering</td>
<td>Lowering of the legs when one is lying down</td>
<td>Degrees of the legs when failure is researched (lower value is better)</td>
<td>Failure when there is no contact with the lower back when the legs are lowered</td>
</tr>
<tr>
<td>Plank/side plank test</td>
<td>Static plank test</td>
<td>Time to exhaustion/failure</td>
<td>Failure when the hips/core drops out of alignment</td>
</tr>
<tr>
<td>Isotonic and isometric test</td>
<td>Isotonic 1RM: squat, back extension</td>
<td>Isometric lower back strength</td>
<td>Isometric strength was measured by TKK-1270, TAKEI machine</td>
</tr>
<tr>
<td>Sahrmann core test</td>
<td>Dynamic movement in prone position when one strives to minimize the lumbar movement</td>
<td>5 gradient scale of exercises, (five being top score)</td>
<td>A clinical test of core stability of the core/hip</td>
</tr>
<tr>
<td>Fullerton senior test</td>
<td>Different exercises, not core specific</td>
<td>Execution of exercises, perfect form</td>
<td>A general fitness assessment of seniors strength, flexibility, balance and coordination</td>
</tr>
<tr>
<td>Biering-Sorensen test</td>
<td>Strength endurance of the back muscles with the use of a examining table</td>
<td>Time to exhaustion (higher value is better)</td>
<td>Failure when one cannot hold the upper body in a prone position</td>
</tr>
<tr>
<td>Bioindex isokinetic torso rotation test</td>
<td>Rotational core strength</td>
<td>Peak torque (N·m)</td>
<td>The Biodex System 3 Multi-Joint Testing and Rehabilitation System was used for the core test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total work (J)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average power (W)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peak repetition total work (J)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average peak torque (N·m) (higher value is better)</td>
<td></td>
</tr>
</tbody>
</table>

The sport performance measures used in the training studies were not the same as those used in the correlation studies in Table 1 and 2. Only the study by Butcher et al. 2007 (10) and Cressey et al. 2007 (15) investigated effects of core training on athletic performance. The other seven addressed how core training affects golf performance (23, 44), Baseball pitching (25, 17), Handball throwing (39), running kinetics and economy (40, 43), rowing (45) and cycling mechanics (1).

3.4 Effect and conclusion

The two studies by Kim 2010 (23) and Thompson et al. 2010 (44) that studied golf performance both showed a positive effect from the intervention. The positive result could be related to the subject groups, the professional and elderly golfers due the specific training of the oblique’s (rotational exercises) and the fact that an elderly sedentary subject group had much room for significant statistical improvement.

Saeterbakken et al. 2011 (39) and English and Howe 2007 (17) found that pitching was improved after core training that could also be related to the research used in the studies,
complex exercises for the whole body. This may have a positive effect on the kinetic chain during throwing action. Sato and Mokha 2009 (40) found indications of a positive effect on middle distance running from improved core strength by the use of Swiss ball training. The positive result could be related to the use of some recreational subjects who have potential for significant improvement.

No difference between the intervention and control group were the result in the study by Cressey et al. 2007 (15) and Lust et al. 2009 (25). These studies also concluded no improvement of the core training compared to regular strength training for upper and lower body with multi joint exercises (15). This was also the case in the study by Butcher et al. 2007 (10), but in this study there were three groups with different result between them. The result in the three studies by Stanton et al. 2004 (43), Tse et al. 2005 (45) and Abt et al. 2007 (1) was negative in terms of the effect from core training on sport performance such as running economy, different athletic strength and conditioning variables and cycling ergonometric performance (power and torque variables).

This could probably be explained by the nature of the sports for these studies since the core muscles most likely are not prime inducers of strength and power for running, rowing and cycling. The study by Abt et al. 2007 investigated acute effects of core training which may also be hard to find a positive result from (1). Another limiting factor for the training studies was the average training period of 8 weeks. Was it to short in order for a physiological training effect?
4. Discussion

There are several problems with trying to come up with a general conclusion from the studies analysed in this paper. First of all, there does not exist a consensus in the literature of the very definition of core stability and strength (5, 18, 22, 24, 36, 37). This is not only due to the fact that different approaches exist regarding the definition of the “core” but is also related to the fact that different studies has focused on strength or stability with different test and training methods (24). The relationship between these two definitions, strength and stability is widely debated (18, 24) as the two interacts since one needs both strength and the endurance in the core musculature in order to the carry out their primary function which can be described in the following way (21):

“The “core musculature” can be defined generally as the 29 pairs of muscles that support the lumbo-pelvic-hip complex in order to stabilize the spine, pelvis, and kinetic chain during functional movements” (18).

To make things even more complicated, the core muscles are likely to behave in a situation dependent fashion during various sport motion, just as other prime moving muscles (24, 37). Different sport performances will therefore request different demands of the core muscles in terms the type of contraction (concentric, eccentric or isometric) and overall control from the central nervous system depending on the sport skill (37).

The correlation studies in Table 1 all used athletes as subjects which might have played a significant role in terms of the results. The already highly skilled and well trained athletes may have responded differently to the core endurance tests and the sport performance tests compared to a recreational/sedentary population. This relates to the fact that athletes most likely have high experience and good result in the “athletic performance” tests (sprints, jumping, and different strength tests) and the possible lack of core strength/stability may therefore not be significant in the result data after a statistic analysis.
Regarding the measurement and evaluation of core strength/stability in the correlation studies, this was done mainly through core endurance tests with a measurement in time (28, 29) as can be seen in Table 2. The result were interpreted that a higher score (elapsed time) of static strength endurance was seen as proof for a high level of core stability (28, 29). The problem when it comes to evaluating these result relates to the fact that the measured sport performances in the studies (23, 31, 32, 41, 46) were of anaerobic, power and explosive nature. This might have contributed significantly to the lack of correlation due to the fact that one was using the wrong type of core test. A more sport specific core test (power/anaerobic) will most likely give a different result.

In fact, it was only one correlation study that showed a positive relationship between a high level of core strength (high score in the core test used in the specific study) and sport performance, the golf study by Wells and colleges (46). The positive correlation between some of the tested golf shots performance (driver, 5 iron various shortgame shots) and core endurance measured by the side plank, is most likely related to the fact that the subjects were of a high level of competitive amateur golf. They therefore had adapted in a sport specific way with a high strength level in the obliques, which are one of the prime movers in the side plank test (46, 37).

It might be that the side plank is a very sport specific way to train and test golf shot performance since these muscles are most likely prime movers in a Driver and 5 iron and some short game shot. The result for the correlation studies should not be taken as general results since only athletes took part in the studies (23, 31, 32, 41, 46). However, since the method used for the studies in Table 1 were fairly similar (30-32, 40, 46) and so were the result, one has an indication that high core endurance (28, 29) may not be linked to improved power and anaerobic sport performance.

The 11 training studies in Table 2 and 3 showed a much more diverse result compared to the correlation studies. Once again different core/back endurance tests were used such as Biering-Sorensen (16), McGill (29), side plank (28) and the two clinical tests, the Sahrmann (26) and the Fullerton Senior Fitness test (37). The different definitions used for the concept of core
strength and stability were linked to these tests methods of a clinical character. As stated above regarding the correlation studies, these test and evaluation methods seem poorly chosen since they were not adapted to the specific sports studied.

The mixed result from the training studies may once again be related to the used subject groups and their initial training level. This could for example explain Butcher et al. 2007 (10) and Cressey et al. 2007 (15) who found no improvements from core training on different athletic variables that were similar to the ones used in the training studies in Table 1 for an athletic population. It is reasonable to assume that an athletic subject group do not have the margin for improvement as none athletic that will be noticeable in a statistical analysis. The opposite could on the other hand explain the positive result in the study by Thompson et al. 2007 when an elderly population showed an overall improved golf shot performance after a training program that included core training (44).

Three studies showed a clear no result from core training on sport performance, cycling (1), running (43) and rowing (45). The reason for the lack of correlation between cycling, running and rowing performance and core stability may be related to the nature of these sport actions since the core muscles most likely are not prime inducers of strength and power for cycling, rowing and running but may contribute to overall fatigue during testing (9, 12). This is most likely the reason for the negative result in the acute study by Abt el. 2007 since the cycling test was preceded by a core training session (1). It is also hard to evaluate the results in this study in a wider perspective since it was an acute training study with a specific core measurement using an isokinetic Bioindex rotation test followed by a core endurance plank test after an ergonomic cycling test because there exist no comparable data or method (1).

The results in the study by Stanton et al. 2004 (43), where there was a negative relationship between treadmill running and core training contradicts the positive result in the study by Sato and Mokha 2009 (40). There might be several reasons for this, the method, track versus treadmill running or the core training regime that differed in the two studies. The most likely reason for the contradictive result is related to the limited subjects used in these studies, 14 in the study by Mokha 2009 (40) and 8 in the study by Stanton et al. 2004 (43). The subject
selection may also explain the negative results in the rowing study by Tse et al. 2005 (45). The amateur athletic subjects improved their core test result but this does not seem to have had any positive transfer effect on the rowing since it is not likely that the core muscle contribute as prime mover during rowing (45).

The positive results from the training studies in Table 2 and 3 was of throwing character, handball velocity (38), pitching velocity (17) and improved pitching accuracy (25). As stated above there could be an explanation related to the subjects used but it could also be the case that the core/hip musculature have a key role when it comes to throwing kinetics (22). Different forms of core training may enhance rotational and throwing performance when the prime moving core muscles in these sport actions are being trained (22, 35). This may also explain the positive result for the two golf studies (23, 44, 50) and the positive correlation found by Wells et al. in their golf study (46).

4.1 Future studies

There is a need for more sport specific core test protocols and measurements regarding power/explosive/anaerobic sports compared to many of the endurance type used today (26, 28, 29). Examples of new approaches and ideas regarding core training exist today (49, 51) in the Strength and Conditioning field and will hopefully influences sport science in order to develop a new and better core test (50). Examples of new studies that take a different approach with interesting result are for example the ones by Stuart McGill. In one study he looked on core strength during different Strongman events and rather surprisingly found the highest muscle tension during the suite case lift (50). In another study by McGill, a single case study with former UFC welterweight champion George St. Pierre, high rotational force was tested and developed by isometric core endurance training with use of a slamball. A tool similar to a light medicine ball with a rope (50). These are examples of studies one can build on when developing new more specific core tests in the future.
Regarding correlation and training studies, more research studies are required with specific athlete or nonathletic populations to confirm or disprove associations between sport specific core tests and specific sport performance (37). One would also like to see future studies that include control groups. In order to compare data, future studies should use similar sport performance parameters used in the studies up to date such as; sprints, vertical jump, power clean, bench press and squat (30-32, 41). Since these exercises are very common in strength and conditioning regardless of the specific nature of physical demanding sports (4), the result would be more comparable and lead to new knowledge and guidance for coaches and athletes.

5. Conclusion

There was no common view upon how core strength / core stability should be measured. Most studies did not show a positive correlation between sport performance and core strength/stability measurements. Only one correlation study had a positive association between core strength regarding golf shot performance. The training studies found that core training improved throwing (pitching and handball throwing) and golf shot performance. However current research does not support that core training enhances performance in explosive sports such as jumping and running.
References


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