Neuromuscular assessment of trunk muscle function in loaded, free barbell back squat: Implications for development of trunk stability in dynamic athletic activity.

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Acknowledgements

The journey began in 2010 when I decided to review the literature on core stability and trunk muscle activation in the back squat exercise. That may well have been the end of the story had Angus Hunter not arranged for me to present my findings to Journal Club at my alma mater, Exercise Science and Sport Medicine Division, University of Cape Town. Feedback from Tim Noakes, Mike and Vicki Lambert was that it was a worthwhile topic to research and I should consider doing a PhD

I embarked on a PhD by publication so that I could work through the topic; effectiveness of loaded squat in activating the trunk stabilizers, while developing research and publication skills and enhancing academic credibility.

I chose two friends, Angus Hunter and Mike Lambert, as academic supervisors and can happily say that those friendships have grown thanks to the PhD. Testimony to the quality of their academic support is the fact that I completed this journey. As an applied practitioner, who was fully immersed in that world, I needed guidance and support in every step; research design, neuromuscular electromyography, data analysis, interpretation and publication. So, thanks Angus and Mike for your support, patience and friendship.

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Abstract

Traditional core stability training was developed as a method of treating and preventing back pain. It was however, seamlessly applied to healthy and athletic populations without scientific evidence supporting its efficacy. Traditional core stability focussed on isolating and training the anatomical region between the pelvis and diaphragm, using isometric or low load exercises to enhance spinal stability. Scientific research challenged this approach for healthy function and athletic performance, resulting in a more functional anatomical definition, which included pelvic and shoulder girdles. Hence, a revised definition of dynamic trunk stability; the efficient coordination, transfer and resistance by the trunk, of force and power generated by upper and lower appendicular skeletal extremities during all human movement. This led to an integrated exercise training approach to dynamic trunk stability. Although early evidence suggested loaded compound exercises preformed upright, in particular back squat, were effective in activating and developing trunk muscles, evidence was inconclusive.

Accordingly, the aims of this PhD were to investigate neuromuscular trunk function in loaded, free barbell back squat to understand training implications for trunk stability in dynamic athletic activity. Five research studies were conducted; 4 are published and 1 is being prepared for re-submission.

The literature review revealed evidence that back squat was an effective method of activating trunk stabilzers and showed that these muscles were load sensitive (study 1). A survey of practitioners reported an understanding and appreciation of the challenge against core stability training for athletic populations. Furthermore, perceptions were aligned with growing evidence for dynamic and functional trunk stability training (study 2). A test-retest neuromuscular study established *inter*day reliability and sensitivity of electromyographical measurement of trunk muscle activity in squats (study 3). Trunk muscle activation in back squat was higher than hack squat at the same relative, but lower absolute loads (study 4). Trunk muscle activation was lower in squats and bodyweight jumps in the strong compared to weak group (study 5). Furthermore, activation of the trunk muscles increased in each 30^{o} segment of squat descent and was highest in first 30^{o} segment of ascent for all loads (study 5).

In conclusion, this series of studies confirmed acute effect of squats on trunk stabilizers and demonstrated that external load increases activation in these muscles. Parallel squat depth is important in optimizing trunk muscle activation. Finally, high levels of squat strength result in lower trunk muscle activation in loaded squats and explosive jumps.

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Clark, D. R., Lambert, M. I., & Hunter, A. M. (2012). Muscle activation in the loaded free barbell squat: a brief review. *Journal of Strength and Conditioning Research*, 26(4), 1169–1178

Paper 2

Clark, D. R., Lambert, M. I., & Hunter, A. M. (2018). Contemporary perspectives of core stability training for dynamic athletic performance: A survey of athletes, coaches, sports science and sports medicine practitioners. *Sports Medicine-Open, 4(1), 2-10.*

Paper 3

Clark, D., Lambert, M. I., & Hunter, A. M. (2016). Reliability of Trunk Muscle Electromyography in the Loaded Back Squat Exercise. *International Journal of Sports Medicine*, 37(6), 448–456.

Paper 4

Clark, D. R., Lambert, M. I., & Hunter, A. M. (2017). Trunk muscle activation in the back and hack squat at the same relative loads. *Journal of Strength and Conditioning Research*, July 12. Published ahead of Print.

Paper 5

Clark, D. R., Lambert, M. I., Grigson, C., & Hunter, A. M. (2018). Impact of training status on trunk muscle activation in back squat, squat jump and countermovement jump. *To be submitted*.

Abbreviations used in the thesis

ANOVA	analysis of variance
ARV	average rectified value (Electromyography signal)
BS	back squat
BW	body weight
CI	confidence interval
cm	centimetre
CMJ	countermovement jump
CS	core stability
CST	core stability training
CV	coefficient of variation
EMG	electromyography
ES	effect size
HS	hack squat
Hz	Hertz
ICC	intra-class correlation coefficient
iEMG	integrated electromyography
iMVF	isometric maximal voluntary force
kg	kilogram
LOA	limits of agreement
MVC	maximal voluntary contraction
MVIC	maximal voluntary isometric contraction
MRFD	maximal rate of force development
m/s	metre per second (velocity)
NWB	no weight belt
p	p value
RFD	rate of force development
RM	repetition maximum
RMS	root mean square
s	seconds

SD	standard deviation
SJ	squat jump
sEMG	surface electromyography
SM / SMmax	system mass maximum
TMA	trunk muscle activation
W	Watt

Muscle site abbreviations

AL	adductor longus
AM	adductor major
AMG	adductor magnus
BF	biceps femoris
EO	external oblique
ES	erector spinae
GMA	gluteus maximus
GME	gluteus medius
GN	gastrocnemius
LSES	lumbar sacral erector spinae
RA	rectus abdominus
RF	rectus femoris
SO	soleus
ST	semitendinosus
TA	tibialis anterior
TRA	transversus abdominus
ULES	upper lumbar erector spinae
VL	vastus lateralis
VM	vastus medialis

Study 5: Groups

SG	strong group
MG	middle group
WG	weak group

Study 5: Tertiles (Appendix 2)

E-1	1^{st} eccentric tertile (0-30^{o} knee flexion)
E-2	2^{nd} eccentric tertile (30-60^{o} knee flexion)
E-3	3^{rd} eccentric tertile (60-90^{o} knee flexion)
C-1	1^{st} concentric tertile (90-60^{o} knee flexion)
C-2	2^{nd} concentric tertile (60-30^{o} knee flexion)
C-3	3^{rd} concentric tertile (30-0^{o} knee flexion)

Introduction

Background

This PhD and a suite of research studies are the response to a question that arose in applied strength and conditioning during the early 2000s: *Is traditional core stability training appropriate for the development of trunk stability for dynamic athletic activity?* Clinical research into back pain and the role of deep and superficial trunk stabilizer muscles established the concept of core stability training (CST) in mid-1990 (Panjabi, 1992; Hodges and Richardson, 1998). The transfer and application of CST to healthy, uninjured and athletic populations spread seamlessly without apparent scientific justification (Lederman, 2010). There was however, significant commercial interest and investment (J. Willardson, 2007). In the exercise and fitness industry, renowned for gimmicks and fads, CST gained traction and spread to all sectors including strength and conditioning.

Context

Traditional approach to CST is incongruous to physical development of athletes for dynamic athletic performance for several reasons. The most obvious concern is the reductionist approach of CST, isolating and training muscular, skeletal and neural structures between the diaphragm and pelvis (Panjabi, 1992; Hodges and Richardson, 1998). In dynamic sporting activity, this anatomical region functions as an integral part of the full kinetic chain and therefore should be trained or developed within that context. The second major issue with traditional CST is the isometric nature of the exercise format. This flaunted well established exercise training principles of specificity and overload, particularly relevant for dynamic athletic, movement, characterised by any combination of high velocity, force and torque.

There has been extensive research on the topic of core stability in healthy populations and for athletic performance (Kibler, Press and Sciascia, 2006; J. M. Willardson, 2007; Hibbs *et al.*, 2008; Reed *et al.*, 2012; Martuscello *et al.*, 2013; Silfies *et al.*, 2015; Maaswinkel *et al.*, 2016; Prieske, Muehlbauer and Granacher, 2016; Wirth, Hartmann, *et al.*, 2016). The particular area of interest within the published literature was the loaded back squat and efficacy of this exercise in activating the trunk stabilizers. This exercise is specific to many sporting activities and can be overloaded safely and effectively. Most important however, is the manner in which it challenges the core or trunk in an integrated and functional way. In fact, for novice squatters on a progressive loaded squat programme, the ability to stabilize the trunk represents the limiting factor. In other words, primary adaptation in the first stage of a progressive load squat programme is trunk stability. Hence, development effective trunk stability is required in order to begin to overload lower limbs, the main purpose of squat training for athletic performance. What is unknown is how changes in squat load effect trunk muscle activation or how chronic squat strength training changes neuromuscular function of trunk stabilizers.

There is compelling evidence that trunk stability is dependent on effective coordination of all muscles of the trunk (Cholewicki and VanVliet Iv, 2002; McGill *et al.*, 2003; Akuthota and Nadler, 2004; Hibbs *et al.*, 2008; Behm *et al.*, 2010; Wirth, Hartmann, *et al.*, 2016). The trunk muscles with the largest moment arms are the erector spinae, quadratus lumborum and rectus abdominis which are responsible for stabilizing the spinal column (Cholewicki and VanVliet Iv, 2002; Behm *et al.*, 2010). The internal and external obliques and transversus abdominis develop intra-abdominal pressure, thereby stabilizing the spine specifically in the lumbar region (Cholewicki and VanVliet Iv, 2002; Behm *et al.*, 2010). McGill et al (1996) determined that surface EMG was an effective method of measuring EMG amplitude in these muscles for most tasks, including maximal voluntary contractions (McGill, Juker and Kropf, 1996). They explained that the magnitude of error increased for deep muscles such as psoas. In our review, the most common muscle sites used to measure trunk stability (Anderson and Behm, 2005; Hamlyn, Behm and Young, 2007; Nuzzo *et al.*, 2008; Bressel *et al.*, 2009; Willardson, Fontana and Bressel, 2009; Clark, Lambert and Hunter, 2012) were (Appendix 3):

- Rectus abdominis (RA: 2 cm lateral from the midline of the umbilicus)
- External oblique (EO: halfway between inferior costal margin of ribs and anterior superior iliac spine)
- Upper lumber erector spinae (ULES: 6 cm lateral to L1-L2 spinous processes)
- Lumbar sacral erector spinae (LSES: 2 cm lateral to L5-S1 spinous processes).

Hence, quadratus lumborum, multifidus, internal oblique and transversus abdominis were excluded. Two reasons put forward by these authors was diminished accuracy of surface EMG in measuring deep muscles and that the selected superficial muscles were reflective of neuromuscular activity during dynamic trunk stability (Anderson and Behm, 2005;

Hamlyn, Behm and Young, 2007; Bressel *et al.*, 2009; Schwanbeck, Chilibeck and Binsted, 2009).

There is agreement in the literature that an important factor contributing to confusion around the topic of core stability is the absence of agreed terms and definitions (Kibler, Press and Sciascia, 2006; Hibbs *et al.*, 2008; Behm *et al.*, 2010; Key, 2013; Martuscello *et al.*, 2013; Silfies *et al.*, 2015; Spencer, Wolf and Rushton, 2016; Wirth, Hartmann, *et al.*, 2016; Clark, Lambert and Hunter, 2018). The terms core stability and core strength have attracted much attention and debate (Hibbs *et al.*, 2008; Prieske *et al.*, 2016; Wirth, Hartmann, *et al.*, 2016). Hibbs et al (2008) described the aetiology of these terms and explored the concept that stability was required for everyday function and rehabilitation from lower back pain (LBP), while strength was necessary for dynamic athletic activity (Hibbs *et al.*, 2008). They concluded that there was no evidence for this separation and that core strength was central to stability (Hibbs *et al.*, 2008). Many now subscribe to a more functional definition of core stability; a dynamic process characterized by effective muscular function and neuromuscular control (Silfies *et al.*, 2015; Prieske *et al.*, 2016). Where muscular function includes both strength and endurance, while neuromuscular control refers to coordination of efferent and afferent neural pathways (Silfies *et al.*, 2015). Describing trunk stability as core strength and core stability is closely associated to the scientific endeavours to measure core strength and endurance (Hibbs *et al.*, 2008; Prieske *et al.*, 2016).

In a systematic review, Prieske et al (2016) found that trunk muscle strength, measured isometric and dynamically, played only a minor role in measures of fitness and athletic performance (Prieske *et al.*, 2016). Isometric tests included timed prone plank and dynamic tests, peak isokinetic torque in trunk flexion and extension (Prieske *et al.*, 2016). Regardless of the absence of an association between trunk muscle strength, fitness and performance tests, it is patently clear that these tests do not reflect complex, dynamic and multifaceted day-to-day movement or athletic activity. This highlights the folly of attempting to measure trunk stability using currently available methods and technology. Based on growing evidence in scientific literature (Prieske *et al.*, 2016; Wirth, Hartmann, *et al.*, 2016) and this glaring methodological testing error, it is clear that *trunk strength is central to trunk stability and is not directly measurable given prevailing methodology*.

Back squat (Papers 3, 4 & 5) and hack squat (Paper 4) exercises are central to research published in papers 3, 4 and 5. Free barbell back squat is a widely used exercise in programmes for sports performance, health and fitness and body building. The hack squat is more common in body building, general fitness and rehabilitation training programmes. The primary purpose of both exercises is to develop eccentric and concentric strength of the lower limb through flexion and extension of knee and hip joints and to a lesser extent ankle joint. The mechanics of free barbell back squat require that the line of force or centre of gravity in the sagittal plane remain over the base of support through the full range of movement. In the hack squat line of gravity does not need to coincide with the point where force is applied in the foot position, due to the supported trunk and fixed external load. These difference in mechanics of these two exercises obviously have implications on the neuromuscular demands of all muscles involved (Appendix 2).

Most neuromuscular research has investigated the acute responses (McCaw and Melrose, 1999; Caterisano *et al.*, 2002; Gullett *et al.*, 2009; Paoli, Marcolin and Petrone, 2009; Brandon *et al.*, 2014) and chronic adaptation (Hakkinen, 1989; Hakkinen *et al.*, 1998; Aagaard *et al.*, 2002) of prime mover muscles responsible for driving concentric load in the back squat. These muscles, the quadriceps group comprise of vastus lateralis, rectus femoris and vastus medialis. Research indicates that isometric (Carolan and Cafarelli, 1992) and isokinetic (Häkkinen *et al.*, 1998) training results in increased maximal voluntary activation of the agonists with a significant reduction in coactivation of the antagonists or muscles opposing the quadriceps, the hamstrings. There is however, little evidence for synergist or stabilizer muscle response to compound lower limb strength training. Buckthorpe and co-workers (2015) measured changes in neural activation of agonist, antagonist and stabilizer muscles after 3 weeks isometric and isointertial elbow flexion training (Buckthorpe *et al.*, 2015). Maximal dynamic strength (1RM) increased significantly more than isometric maximal voluntary force (iMVF). Agonist, antagonist and stabilizer EMG increased significantly in the follow-up 1RM test, and only in the stabilizers for iMVF test. It is highly likely that synergist adaptation to compound lower limb strength exercises, such as back squat, underpin improvements in dynamic squat strength and reported associated performance gains. Despite the obvious importance of trunk stabilizers in transferring and resisting force during the squat, there is scant neuromuscular information on trunk muscle activation response and adaptation to squat training.

Early research compared trunk muscle activation in squats to instability exercises (Anderson and Behm, 2005; Hamlyn, Behm and Young, 2007; Nuzzo *et al.*, 2008; Bressel *et al.*, 2009) and gave the first evidence that squat load directly influenced activation of these muscles. Subsequent studies compared trunk muscle activation in back and overhead squat (Aspe and Swinton, 2014) and the squat to isometric and dynamic strength exercises (Comfort, Pearson and Mather, 2011). There was a clear and obvious requirement for more information on neuromuscular trunk function in loaded, free barbell back squat.

Scope

The suite of studies in this PhD thesis straddle performance sport and applied sports science research. The main question arose in response to a strength and conditioning trend in high performance sport (PhD candidate). The research question and methods were formulated according to principles of applied sports science research through the guidance from two PhD supervisors and many of those acknowledged above (page 2). This conforms to the conceptual model proposed by Coutts (2016), where he proposes that questions innovated in high performance are investigated using robust and rigorous sports science research methods to develop and reinforce evidence based practice (Coutts, 2016).

Despite the significant rise in applied sport science research in performance sport (Coutts, 2016; Kraemer *et al.*, 2017), there is little evidence of this translating effectively to applied practice, let alone sports performance (Bishop, 2008). In response, Bishop (2008) proposed the Applied Research Model for the Sports Sciences to better facilitate translation to practice by informing initial design and conceptualization of research (Bishop, 2008). The model consists of 8 steps progressing from problem definition, concluding with implementation studies to measure the effectiveness in practice. Retrospective alignment of studies in this PhD to this model proves quite insightful. Paper 1, the review and paper 2, the survey defined and contextualized the problem into a research question fulfilling the model's criteria for step 1 and 2. The third paper established methodological reliability of neuromuscular and kinematic measures proposed for studies 4 and 5. This, along with paper 4 comparing trunk muscle activation in hack versus back squat is classified as descriptive research and is therefore aligned to step 2 of the model. The final study falls across steps 3, 4 and 5; establishing predictors of performance, experimental testing of predictors and determinants of key performance predictors. In this study, we investigate and compare a number of key performance attributes in strong versus weak squatters. The model progresses to intervention studies which would be a recommendation arising from this PhD; conduct a training study to assess the impact of improved squat strength on trunk muscle activation and dynamic trunk stability in proxy tests of athletic performance.

The starting point for this PhD was to review the scientific research literature on the topic of muscle activation in loaded back squat exercise. This is the first published paper of this thesis (Clark, Lambert and Hunter, 2012). This was important in order to determine and confirm the specific area of our research within the context of wider neuromuscular research into the back squat exercise. Furthermore, it was important to review the related neuromuscular research methods as they applied to the back squat exercise. This informed methods used in our study to establish reliability in trunk electromyography (EMG) capture in the back squat (Clark, Lambert and Hunter, 2016). It also determined kinematic tests and EMG normalization methods used in all our subsequent research (Clark, Lambert and Hunter, 2016, 2017).

Application of traditional CST was well established and appeared to withstand the growing scientific challenge. In fact there was a view that it's use in healthy and athletic populations continued to develop and spread (J. Willardson, 2007). Surveys are an effective scientific research tool used previously to assess nutrition knowledge (Torres-McGehee *et al.*, 2012) and understanding of scientific training principles in the workplace (Durell, Pujol and Barnes, 2003). The motivation for the specific area of research in the PhD arose from a clear gulf between applied practice and scientific principles and latterly, published scientific evidence. Hence, the second question was to determine *perceptions and application of core stability training in people working and participating in sport using a survey. In the publication, survey results are analysed to determine extent to which scientific research informed CST perceptions and practice.*

Our first publication, confirmed that back squat was an effective method of activating the trunk muscles and that this activation increased with increases in load (Clark, Lambert and Hunter, 2012). It was also apparent that methodology around the measurement of trunk activation in back squat, reported in the scientific literature was inconsistent and unreliable. Surface electromyography (sEMG) data capture for muscles of the trunk required a standardized approach to ensure that findings could be interpreted, compared and have an impact on practice. This review also identified inconsistencies in EMG normalization methods. *The purpose of the third study was to establish reliability and sensitivity of the measurement of trunk muscle electromyography in the loaded back squat exercise.*

We established reliability of sEMG in measuring trunk muscle activation in the back squat and demonstrated that this method was sensitive to typical load changes in this exercise. Most previous trunk muscle activation research had compared the back squat to isometric (Comfort, Pearson and Mather, 2011) or unstable exercises (Anderson and Behm, 2005; Hamlyn, Behm and Young, 2007; Nuzzo *et al.*, 2008; Bressel *et al.*, 2009). The requirement to stabilize the free barbell in the back squat is a unique and important feature of the exercise. In the one published study, there was no difference in trunk muscle activation between the more stable Smith machine squat and the free barbell squat for the rectus abdominus and erector spinae muscles (Schwanbeck, Chilibeck and Binsted, 2009). This was contrary to what we believed based on our review of the literature. *Hence, the fourth study of the PhD compared trunk muscle activation in free barbell back squat to machine supported hack squat for a range of moderate to heavy loads.*

The survey demonstrated that perceptions and practice amongst people working and participating in sport did reflect the current information in the scientific literature. The review and survey concluded that there was a requirement for more data on efficacy of commonly used exercises in activating trunk stabilizers. A further recommendation was to investigate the adaptations to long-term squat training. Specifically, how does acquired back squat strength through regular, progressive training change trunk stability in dynamic athletic activity? *Hence, the fifth and final study aimed to determine how squat training status influenced trunk muscle activation in the back squat, squat jump and countermovement jump.*

Study 1: Scientific review - muscle activation in the loaded free barbell squat

The scope of the review included all publications that reported muscle activation measured by sEMG in back squat. The review did include data for other exercises where these were compared to back squat. Studies included reported neuromuscular activation data for all muscle sites of the lower limb, hips, thighs and trunk region.

Section headings of the review paper reflect topics covered in the scientific literature. Most of these topics were areas of interest in the applied setting, where research had aimed to verify common applications and variations of back squat exercise using neuromuscular analysis. Common applications include technical squat variations such as stance width, hip rotation and squat depth and programming manipulations such as external load and instability.

A limitation of the review process and publication was the use of a systematic narrative review method rather than a systematic or meta-analysis method. The variety and breadth of the sub-topics related to muscle activation in the back squat was more suited to a systematic narrative approach. Furthermore, differences in research design and methods precluded a systematic of meta-analysis review. The selected method presented and debated findings of selected research publications. It included qualitative analysis in the discussion and quantitative analysis in tables that reported muscle sites investigated in each study (Table 1) along with study design and key findings (Table 2). The outcome however, did serve to guide and inform neuromuscular research in back squat trunk muscle activation. The review summary confirmed there was sufficient evidence that loaded barbell squats were effective in activating trunk stabilizing muscles. Recommended practical applications gave clear direction for subsequent research to determine the role of back squat in developing dynamic trunk stability.

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Study 2: A survey of contemporary perspectives of core stability training

The review confirmed that loaded barbell squat was effective in activating the trunk muscles. The next question was to determine the extent to which these developments in the scientific process and literature had entered applied thinking and practice. This was the justification and purpose of the survey, the second section of the thesis. The background section of the survey presents an in-depth review of the scientific challenge to traditional CST for healthy and athletic populations. Followed by a detailed explanation of the purpose of the survey and how questions were built around prominent themes in the scientific CST debate (Appendix 1). Furthermore, in the survey discussion, findings were analysed against the prevailing issues in the scientific literature to measure the extent to which research had influenced applied perceptions and practice.

The limitations of the survey are covered in the final paragraph of the discussion in the published paper. However, it is worth pointing out the further potential bias that may have arisen as a result of recruiting participants from the principle investigators email contacts and LinkedIn connections. This most certainly contributed to the high number of respondents from strength and conditioning.

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Sports Medicine - Open

ORIGINAL RESEARCH ARTICLE Open Access

Contemporary perspectives of core stability training for dynamic athletic performance: a survey of athletes, coaches, sports science and sports medicine practitioners

David R. Clark[1*], Michael I. Lambert[2] and Angus M. Hunter[3]

Abstract

Background: Core stability training has grown in popularity over 25 years, initially for back pain prevention or therapy. Subsequently, it developed as a mode of exercise training for health, fitness and sport. The scientific basis for traditional core stability exercise has recently been questioned and challenged, especially in relation to dynamic athletic performance. Reviews have called for clarity on what constitutes anatomy and function of the core, especially in healthy and uninjured people. Clinical research suggests that traditional core stability training is inappropriate for development of fitness for heath and sports performance. However, commonly used methods of measuring core stability in research do not reflect functional nature of core stability in uninjured, healthy and athletic populations. Recent reviews have proposed a more dynamic, whole body approach to training core stabilization, and research has begun to measure and report efficacy of these modes training. The purpose of this study was to assess extent to which these developments have informed people currently working and participating in sport.

Methods: An online survey questionnaire was developed around common themes on core stability training as defined in the current scientific literature and circulated to a sample population of people working and participating in sport. Survey results were assessed against key elements of the current scientific debate.

Results: Perceptions on anatomy and function of the core were gathered from a representative cohort of athletes, coaches, sports science and sports medicine practitioners ($n = 241$), along with their views on effectiveness of various current and traditional exercise training modes. Most popular method of testing and measuring core function was subjective assessment through observation (43%), while a quarter (22%) believed there was no effective method of measurement. Perceptions of people in sport reflect the scientific debate, and practitioners have adopted a more functional approach to core stability training. There was strong support for loaded, compound exercises performed upright, compared to moderate support for traditional core stability exercises. Half of the participants (50%) in the survey, however, still support a traditional isolation core stability training.

Conclusion: Perceptions in applied practice on core stability training for dynamic athletic performance are aligned to a large extent to the scientific literature.

Keywords: Core, Stability, Dynamic, Trunk, Athletic, Performance, Loaded, Functional, Compound, Exercise

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Key points

- Core stability training for healthy and athletic populations has recently been questioned and challenged in scientific literature. The narrow definition of both the anatomy, spinal region between pelvis and diaphragm, and the method of training the core through the isolation of muscles in this region does not relate to full body core function that characterises dynamic athletic performance.
- The survey reveals that this is reflected in opinions of people working and participating in sport. Half of the participants identified the area between and including the pelvic and shoulder girdles as the core. Majority supported functional loaded exercises such farmer's walk (87%) and barbell squats (84%) as effective exercises for the development of core stability.
- Despite the support for a more functional approach, selected traditional core stability training methods do retain a certain amount of support; isometric plank exercise (56%) and unstable stability ball exercises (41%). Many respondents (42%) felt that core function should be measured subjectively through observation of sporting and or exercise performance.
- Trunk is the preferred name of the anatomical region for almost half (45%) the participants while 35% supported the term core.

Background

The absence of a universally accepted definition of core stability (CS) is well noted in the scientific literature [1–8]. A number of these publications have proposed a definition, focussing either on function, anatomical constituents of the core or both. Several reviews have questioned and challenged core stability training (CST) for prevention and treatment of back pain [9–11] and for improvement of function and performance in healthy and athletic populations [1, 5–7, 12–14]. There is a view [1, 7] that CST in its current form evolved from clinical research [15] in the 1990s. The application of a clinical exercise approach in healthy and athletic populations has been criticised, primarily on the basis that teaching an isolated muscle pattern in uninjured athletes is unfounded [6, 10, 16]. Despite this, CST as an intervention spread to all exercise disciplines across clinical, fitness and sports performance settings with significant commercial interest and support [14].

Most review articles on this topic recognised that the application of traditional CST in healthy and athletic groups lack scientific justification [3, 7, 14, 17]. This resulted in a body of research investigating CST in healthy populations [18–22] along with aforementioned review articles [1, 6, 7, 12–14]. Reviewers have noted that research cannot progress this topic effectively until there is a standardised agreement on the anatomical structure and function of the core [1, 6, 7]. A further limitation reported by most reviewers is the absence of a valid and reliable test of core function [1, 12]. As a result most research on the topic is methodologically limited [12, 13] and therefore ineffective in confirming or challenging the concept and practice of CST for health and performance. A case has been made in the literature for a more functional definition of anatomy of the core, applicable to healthy and athletic populations [1, 8]. Similarly, it is proposed that the description of core function is revised to encompass normal healthy and athletic human movement [8].

Several comprehensive reviews over the last decade have examined the research on the effectiveness of various CST methods for athletic performance [1, 6, 7, 12–14]. Reviews covered the variations in CST including instability training, trunk rotation exercises, functional training and exercise intensity. Martuscello et al. proposed a five core exercise classification system based on their review of the research [6]. The categories were traditional core exercise (sit-ups), core stability exercises (isometric plank), ball or device exercises (stability ball), free weight exercise (squat and deadlift) and noncore free weight exercise (upper body). In a recent study conducted in an applied performance sport setting, Spencer et al. proposed a comprehensive spinal exercise classification [2]. The classification incorporated static and dynamic exercises that were either functional or non-functional according to spinal displacement across four physical outcomes: mobility, motor control, work capacity and strength. Both studies [2, 6] clarify the range and nature of core stability exercises used in the literature and practice; however, there is concern that many core stability intervention studies are diluted by other exercises and activities preventing a clear assessment of impact of CST [7, 12, 13]. Furthermore, in athletic populations, a reductionist approach or selective activation to improve integrated function is unsubstantiated [1, 2, 7, 12].

The proposed protection against injury and improved athletic performance from CST has been the subject of many research studies and review papers. Silfies et al. concluded that following a review of 11 studies, there was limited evidence to support the use of CST to prevent upper extremity injury and improve athletic performance [3]. The authors questioned whether performance in core stability tests reflected physical or athletic capability and level of conditioning, rather than solely core stabilization. Tests included the isometric front and side bridge, single-leg raise [10], star excursion test [11] and closed kinetic chain upper extremity stability test [12]. A systematic review conducted by Prieske et al. [12] concluded that CST compared with no training or regular sports-specific training does improve trunk muscle strength measured predominantly by isometric plank. However, increases in trunk muscle strength only had a small effect on physical fitness and athletic performance measures in trained individuals. CST compared to alternative physical training methods in trained individuals had little impact on trunk muscle strength, physical fitness and athletic performance measures. Both studies strongly suggest that high levels of general fitness are associated with better performance in CS tests and therefore a lower risk of injury and better athletic performance test scores [3, 12].

Separating the core into smaller local and larger global muscles has little bearing on core stability for dynamic movement in healthy people. In Lederman's [10] words, this is an anatomical classification with no functional relevance. The role the core plays in stabilising the body is dynamic and responsive to many postural challenges that occur in normal movement and complex, reactive environment of sport [14]. The concepts of core strength and core stability have been reviewed the literature [1, 5, 23]. Whether these are separate attributes [5] or whether core strength is required for core stability [23] remain unresolved questions [1]. In this context, core stability is an integrated, functional motor task [7, 24] and training should reflect this according to movement patterns [14, 24], forces [7, 24] and torque and velocity [8, 24].

A limitation identified by Prieske et al. [12] was the lack of validity of tests used in most of the research. Trunk muscle strength in most studies was measured by timed isometric test (prone bridge) which, firstly, does not reflect force and velocity of movement of dynamic athletic activity [12]. Secondly, CST programmes in many of the studies incorporated prone plank or similar isometric exercises in the exercise intervention, which rendered timed isometric prone plank an inappropriate test of trunk muscle strength in these cases. Most reviews conclude there is not a valid method of measuring the effect of CST on trunk muscle strength within the context of improving dynamic athletic performance [1, 13, 14, 17, 25, 26]. As a result, many researchers have resorted to using conventional performance tests such as countermovement jump and sprint tests [12, 13, 27].

The first three levels of Martuscello's [6] core exercise classification system appear to contravene the established overload training principle [28] when applied to an athletic population. Traditional low load core exercises, minimal range or isometric core stability exercises and ball/device exercises are all characterised by low force, low velocity and restricted range of movement. Hence, these do not represent training overload in preparation for activities that characterise most sports and athletic events. Researchers have begun to investigate trunk muscle activation in a number of dynamic, loaded free weight exercises to determine their suitability for the development of dynamic trunk strength and stability [29–37]. Surface electromyography methodology shows there is good evidence that loaded exercises performed in a standing position are an effective method of overloading the trunk stabilization system in a dynamic manner. While several reviewers recognise this development [6, 7, 14], it is best summarised by Wirth et al. (2016), '… we recommend the use of classical strength-training exercises as these provide the necessary stimuli to induce the desired adaptations.'

The flawed foundations of CST for dynamic athletic performance have been exposed in the scientific literature. Research is underway to better understand the most effective training methods for the development of trunk stability. The aim of this survey is to assess the current perspectives of CST in the applied sports setting to determine how well scientific literature informs these opinions. Our hypothesis is that opinions of those who work and participate in sport will reflect scientific debate on key core stability training topics.

Methods

The online survey questionnaire (Additional file 1) was developed around common themes on core stability as defined in the current scientific literature. The online survey was created and distributed using Bristol Online Survey (BOS) tool (Tower Hill, Bristol, UK). The questionnaire comprised four sections: anatomy of the core, function of the core, methods of measuring core function and methods of training the core. The survey concluded with general questions about the application of core strength training for dynamic athletic performance.

The survey question on the anatomy of the core is based on definitions in the literature. We used the definition of local and global stabilization of intersegmental spine proposed by Bergmark (1989) [38]; the passive spinal column, active spinal muscles and neural control unit as described by Panjabi [39]; axial skeleton between pelvic and shoulder girdle including rib cage, spinal column and associated muscle and nerves proposed by Behm et al. [8]; and lumbo-pelvic hip complex according to Faries and Greenwood [23]. Categories of exercises and selection criteria for CST used in the survey question were drawn from published studies that investigated muscle activation using these manipulations. The question around core strength and core stability were based on reviews of this topic [1, 7].

A pilot survey was conducted using the postgraduate sports studies group ($n = 20$) at the University of Stirling. The questionnaire was modified according to feedback from the pilot survey. Approval for the study was granted by the local research ethics committee in accordance with the Helsinki Declaration (2013) [40].

Participants

The survey was circulated using two methods: shared with the principal authors' 700 LinkedIn connections and sent by email to 220 qualifying contacts. All recipients were asked to share the survey with all their contacts that met the criteria of working or participating in sport.

Statistical analysis

The data analysis was descriptive and frequency was presented in the tables as number and percentage (n (%)). Data presented in Figs. 1, 2, 3 and 4 were analysed using Kruskal-Wallis test to assess support for each statement on 5-point Likert scale. Data presented as mean and 95% CI. Five-point scale is as follows: 1 = strongly agree or very effective and 5 = strongly disagree or not effective at all. Significant differences were further analysed using Dunn's multiple comparison post hoc test. Priori alpha level of significance was set at $p < 0.05$.

Results

Participants

The online survey was completed by 241 respondents from a range of disciplines involved in sport (Table 1). The highest return by employment group was received from strength and conditioning coaches (S&CC; 47%) followed by athletes and players (A&P; 17%) and sport medicine practitioners and physiotherapists (SM&P; 17%). A quarter of the cohort were involved in sport at university or school level (27%). A similar number (33%) were working in professional sport, either with full-time professional athletes (21%), or elite funded athletes in institutes of sport (12%). Volunteers working in recreational sport made up 15% while 9% were semi-professional in part-time paid roles.

Responses to all questions were analysed for all respondents ($n = 241$) and for each of the five demographic groups. There were no differences between group responses and total cohort, so data are presented and discussed for the total cohort.

The majority (87%) were qualified to degree level or higher, 40% had masters or MSc degrees and 12% had doctoral degrees. Most respondents (73%) reported to have a discipline specific professional qualification. Respondents reported to have been working in their specific discipline for an average of 8 years (range 0–36 years).

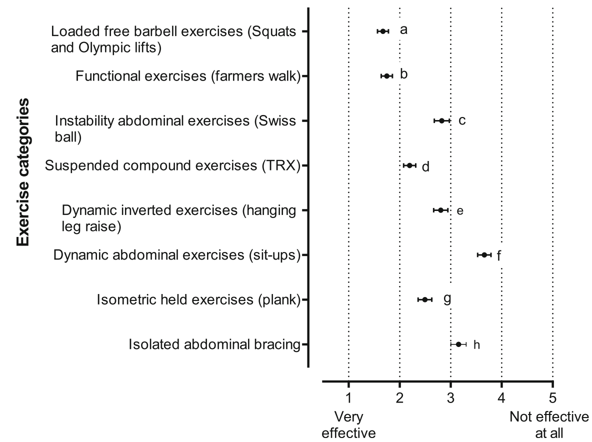

Fig. 2 Responses to a series of questions on the effectiveness of selected categories of exercise in developing core stability for dynamic athletic performance. Data are reported as mean level of effectiveness with 95% CI. 1 = very effective, 5 = not effective at all. Significant differences $p < 0.001$: a vs c, d, e, f, g and h; b vs c, d, e, f, g and h; c vs d and f; d vs e, f and h; e vs f; f vs g and h; g vs h. CI: confidence interval

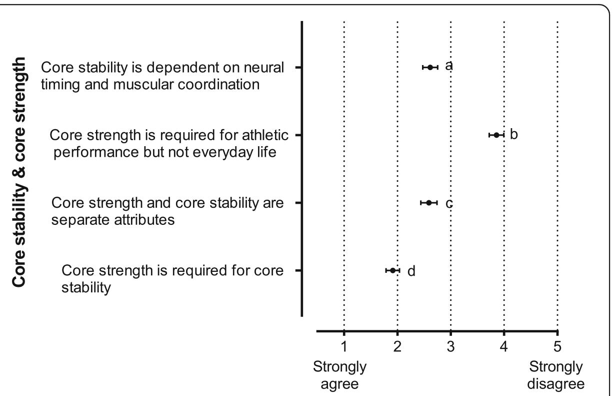

Fig. 1 Reported support for a series of statements relating to core stability and core strength. Data are reported as mean level of agreement with 95% CI. 1 = strongly agree, 5 = strongly disagree. Significant differences $p < 0.001$: a vs b, a vs d, b vs d and c vs d. CI: confidence interval

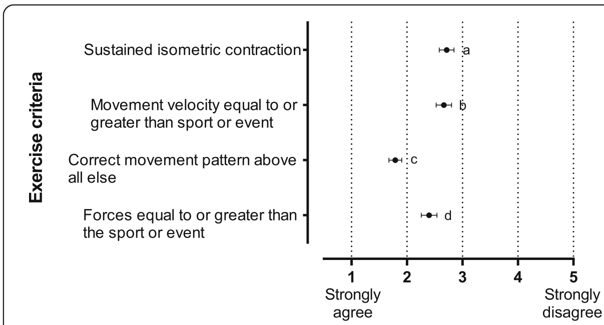

Fig. 3 Responses to which criteria should inform exercise selection for the development of core stability for dynamic athletic performance. Data are reported as mean level of agreement with 95% CI. 1 = strongly agree, 5 = strongly disagree. Significant differences $p < 0.05$: a vs c, a vs d, b vs c, b vs d and c vs d. CI: confidence interval

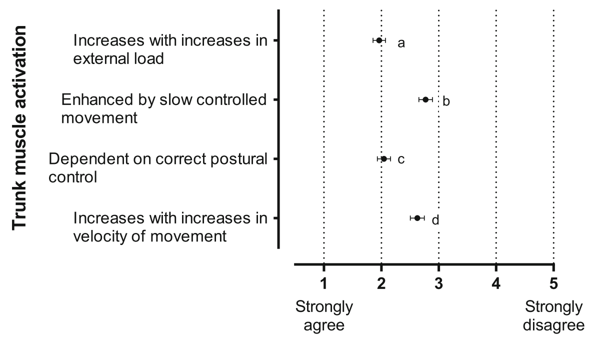

Fig. 4 Responses to a series of statements relating to ground-based loaded free barbell exercises and trunk muscle activation. Data are reported as mean level of agreement with 95% CI. 1 = strongly agree, 5 = strongly disagree. Significant differences $p < 0.001$: a vs b, a vs d, b vs c, c vs d. CI: confidence interval

Anatomy and name of the core

In response to the question on the anatomical region that comprised the core, half of the respondents (50%) identified the region between and including the pelvic and shoulder girdles and associated muscles and nerves (Table 2). Approximately, a quarter of respondents (27%) identified the region between the diaphragm and pelvic floor and associated muscles and nerves as the core, while for 18%, this was the lumbar spine, pelvis, hip joints and related muscles and nerves. Interestingly, more participants (45%) felt that the region should be called the trunk while 35% supported the term core and 18% preferred torso.

Methods of measuring core function

Respondents were asked to identify the most effective method of measuring core stability in a healthy, uninjured person. Almost a quarter (22%) reported that there was no effective method to test core stability. A number (43%) of the respondents proposed subjective assessment of core stability through observation. Of these, 17% suggested observation of sport-specific movement or exercise technique and 26%, observation of ground-based loaded barbell exercises. Objective assessments were proposed by 32% and included the timed isometric plank (19%), functional movement screen (9%) and isometric trunk bracing with biofeedback (4%).

Core function and core stability training

Core stability and core strength (Fig. 1)

The majority believed that core strength is required for stability (mean 1.9, 95% CI 1.8–2.0, $p < 0.001$) and far fewer agreed that these were separate attributes (mean 2.6, 95% CI 2.4–2.7, $p < 0.001$) (Fig. 1). Most participants disagreed with the statement that core strength was required for athletic performance, but not everyday life (mean 3.9, 95% CI 3.7–4.0, $p < 0.001$).

The effectiveness of certain exercise categories on CST (Fig. 2)

The exercise categories deemed most effective in developing core stability for dynamic athletic performance were (Fig. 2) squats and Olympic lifts (mean 1.7, 95% CI, 1.6–1.8, $p < 0.001$) and farmers walk (mean 1.7, 95% CI

Table 1 (A) Employment and (B) education information presented for all respondents (total and group)

	Total	S&CC	A&P	SM&P	SP&B	SC
All respondents	241	114 (47)	42 (17)	41 (17)	24 (10)	20 (8)
A.						
Academic, university or school sport role	*66 (27)*	29 (12)	10 (4)	*11 (5)*	*10 (4)*	*6 (2)*
Professional: full-time paid position, full-time paid athletes	50 (21)	*37 (15)*	0 (0)	9 (4)	3 (1)	1 (0)
Volunteer, recreational club sport	35 (15)	4 (2)	*21 (9)*	6 (2)	2 (1)	2 (1)
Elite professional: full-time paid position, funded, amateur athletes (Institute)	30 (12)	15 (6)	1 (0)	4 (2)	7 (3)	3 (1)
Elite non-professional, part-time, regional or national athletes	30 (12)	16 (7)	5 (2)	7 (3)	0 (0)	2 (1)
Semi-professional: paid part-time position	22 (9)	9 (4)	2 (1)	3 (1)	2 (1)	*6 (2)*
Other	8 (3)	4 (2)	3 (1)	1 (0)	0 (0)	0 (0)
B.						
MSc/Masters	*96 (40)*	*51 (21)*	7 (3)	*20 (8)*	*13 (5)*	5 (2)
Degree/Hons	84 (35)	41 (17)	*17 (7)*	9 (4)	7 (3)	*10 (4)*
PhD	28 (12)	10 (4)	2 (1)	10 (4)	4 (2)	2 (1)
Diploma	27 (11)	9 (4)	13 (5)	2 (1)	0 (0)	3 (1)
Other	6 (2)	3 (1)	3 (1)	0 (0)	0 (0)	0 (0)

Data presented as number and percentage (n (%)) of all respondents. Italics represent the highest response for the column
S&CC strength and conditioning coaches, *A&P* athletes and players, *SM&P* sports medicine practitioners and physiotherapists, *SP&B* sports physiologists and biomechanists, *SC* sports coaches

Table 2 Responses to the question of what (A) anatomic region makes up the core and (B) which term best describes this anatomical region

	Total
A.	
The spine and the associated muscles and nerves	5 (2)
The lumbar spine, pelvic and hip joints and associated muscles and nerves	43 (18)
The region between and including the pelvic and shoulder girdles and associated muscles and nerves	*120 (50)*
The region between and diaphragm and pelvic floor and associated muscles and nerves	65 (27)
Other	8 (3)
B.	
Torso	43 (18)
Trunk	*108 (45)*
Core	85 (35)
Upper limb	0 (0)
Other	5 (2)

Data presented as number and percentage (*n* (%)) of all respondents. Italics represent the highest response

1.6–1.9, $p < 0.001$). Conversely, support was moderate to low for traditional core stability exercises, namely suspended compound exercises (mean 2.2, 95% CI 2.1–2.3, $p < 0.001$), isometric plank (mean 2.5, 95% CI, 2.4–2.6, $p < 0.001$), hanging leg raise (mean 2.8, 95% CI 2.7–2.9, $p < 0.001$) and instability abdominal exercises (mean 2.8, 95% CI 2.7–3.0, $p < 0.001$). Participants identified two exercise categories that were more ineffective than effective; abdominal bracing (mean 3.2, 95% CI, 3.0–3.3, $p < 0.001$) and sit-ups (mean 3.7, 95% CI, 3.5–3.8, $p < 0.001$).

The exercise selection criteria for effective CST (Fig. 3)

Correct movement pattern (mean 1.8, 95% CI 1.7–1.9, $p < 0.001$) was identified as most important exercise selection criteria for development of core stability for dynamic athletic performance (Fig. 3). Exercises characterised by forces that were equal to or greater than the force in the sport or event, were supported by 60% of the cohort (mean 2.4, 95% CI 2.3–2.5, $p < 0.05$). Most were either undecided or disagreed on the importance of velocity of movement (mean 2.6, 95% CI 2.5–2.8, $p < 0.05$) and sustained isometric contraction (mean 2.7, 95% CI 2.6–2.8, $p < 0.05$) in core stability exercises for athletic performance.

Ground-based free barbell exercises and trunk muscle activation (Fig. 4)

Most participants agreed that increases in external load in standing barbell exercises would increase trunk muscle activation (mean 2.0, 95% CI 1.9–2.1, $p < 0.001$) (Fig. 4). Equally important in this form of resistance training was correct postural control (mean 2.0, 95% CI 1.9–2.2, $p < 0.001$). Slow controlled movement (mean 2.8, 95% CI 2.7–2.9, $p < 0.001$) and increases in velocity (mean 2.6, 95% CI 2.5–2. 8, $p < 0.001$) of strength training exercises were not seen as important in eliciting trunk muscle activation in ground-based free barbell exercises.

Finally, results for the general questions on the application of core stability exercises are presented on Table 3. Most participants (85%) felt that it was appropriate to include specific exercises to train core stability in healthy, uninjured individuals. Less than half (45%) felt that it was effective to exercise the core stabilisers in isolation, while a majority (65%) agreed that core stability is developed during normal progressive exercise training.

Discussion

Core stability training for healthy and athletic populations has been scrutinised and challenged in recent years in scientific literature [6, 7, 10, 13, 41–43]. Descriptions of the core by anatomic structures are entirely dependent on the chosen definition of core function [1]. The original narrow definition presented in early research focussed on the spinal region between the diaphragm and pelvis [44]. This approach identified muscular and neural dysfunction associated with back pain. Hence, core function was isolated to this region and proposed training intervention isolated the involved muscles. This approach did not transfer to healthy individuals and athletes where core function is obviously at the centre of dynamic movement characterised by force and velocity through the length of the body [10]. Core stability described by Fletcher (2016), '…is the kinetic

Table 3 Answer to a series of questions about the application of core stability

		Total
Do you think it is necessary to include specific exercises to train core stability in a healthy, uninjured athlete's exercise programme?	Yes	*206 (85)*
	No	30 (12)
	Do not know	5 (1)
Do you think it is possible to isolate and train the core stabilization system?	Yes	*120 (50)*
	No	82 (34)
	Do not know	39 (16)
Do you think it is effective to isolate and train the core stabilization system?	Yes	89 (37)
	No	*108 (45)*
	Do not know	44 (18)
Do you think that the core stability is automatically developed during normal, progressive exercise training?	Yes	*157 (65)*
	No	67 (28)
	Do not know	17 (7)

Data presented as number and percentage (n (%)) of all respondents. Italics represent the highest response for each question link transferring torques between the upper and lower extremities in sporting actions' [45]. Consequently, constituent anatomy of the core is described in the literature to reflect, i.e. region between and including pelvic and shoulder girdles and associated skeleton, muscles and nerves [1, 8]. Our survey results suggest this shift has permeated applied sports setting; half of the respondents agreed with this definition of the core while a quarter identified with the original description, i.e. structures between diaphragm and pelvic floor including muscles and nerves.

Surveys have been used effectively to assess nutrition knowledge [46] and understanding of scientific training principles [47] in the workplace. Response rate to our survey ($n = 241$) was good in comparison to similar surveys which gathered information from both athletes (Wade et al., $n = 57$) [48] and people working in sport (Taylor et al., $n = 28$) [49], (Durell et al., $n = 137$) [47] and (Torres-McGehee et al., $n = 579$) [46]. Furthermore, the representative quality of our cohort is reflected by the spread of respondents, with 33% in full-time professional positions, either working with professional athletes (21%) or full-time Institute of sport athletes (12%). A quarter (27%) were involved in sport in an academic setting, either school or university and a quarter (27%) were in non-professional roles, either volunteering (15%) or part-time (12%). The majority were qualified to degree level (87%) and half had postgraduate degrees (52%). Most had an industry-specific qualification and on average were well experienced (mean 8 years) in their discipline. The cohort is therefore representative of people working and participating in sport. Furthermore, they were reasonably well informed, indicating survey results that represent unbiased perceptions of the wider population.

Our survey investigated perceptions around core stability and core strength (Fig. 1). The majority believed that core strength is required for stability and far fewer agreed that these were separate attributes. In a comprehensive review Hibbs et al. [1] concluded that these two terms had yet to be clearly defined, in fact they failed to identify any characteristics that differentiated exercises for core strength and core stability. These researchers reviewed studies that investigated core stability in response to loaded resistance exercises and traditional core stability exercises. A later systematic review proposed a five-level core exercise classification system that progressed from traditional core exercises to noncore free weight exercises [6]. Interestingly the fourth classification level was free weight exercises defined as 'dynamic, externally loaded, intent to activate lower body and core muscles'. Both these reviews suggest that the concept of strength in the term core strength relates to the overarching nature of the exercise, rather than the impact on or adaptation in the core stabilization system.

While core strength and core stability may well be viewed by some in our survey as separate entities, this has yet to be demonstrated scientifically [1]. The selection of exercises used to develop core stability for healthy function can range from low load, minimal range of movement, abdominal bracing exercises to dynamic, loaded resistance exercises [6]. Research has not been able to identify and describe adaptations that occur in muscles responsible for stabilising the core as a consequence of different exercise modes [1, 12]. It is recognised though that effective core stability is the control of movement, including high force and high velocity movement, generated by interaction between axial and appendicular skeletons [5, 7, 8]. Most survey responses disagreed with the statement that core strength was required for athletic performance, but not everyday life. This demonstrated alignment with the principle that core stability underpins both healthy function and dynamic athletic performance. In effect core strength and core stability are synonyms and are used accordingly in the literature [1, 5, 23]. This is reflected in the survey question seeking to determine whether core stability and strength are separate attributes. Responses were mixed with just over half (57%) in agreement and the rest either undecided (16%) or in disagreement (27%).

In our survey questions that assessed support for exercise categories most effective in developing core stability for dynamic athletic performance, there was clearly more support for functional, loaded exercises (Fig. 2). Squats and Olympic lifts and farmers walk that engage the full kinetic chain. Conversely support was moderate to low for traditional, non-functional core stability exercises, namely suspended compound exercises, isometric plank, hanging leg raise, and instability abdominal exercises. Two exercise categories, namely abdominal bracing and sit-ups, were regarded as ineffective rather than effective, The survey results therefore reflect the many reviews that highlighted a lack of evidence to support traditional CST for healthy individuals and recommended loaded, dynamic exercises that engage the full kinetic chain [1, 6, 7, 12–14, 45].

Correct movement pattern was identified as most important exercise selection criteria for development of core stability for dynamic athletic performance (Fig. 3). Exercises characterised by forces that were equal to or greater than force in the sport or event, were supported by 60% of the cohort. Most were either undecided or disagreed on whether velocity of movement and sustained isometric contraction were important in core stability exercises for athletic performance. Kibler et al. (2006) accurately describes the exercise criteria for effective CST: 'integrated activation of multiple segments' providing 'force generation' that produces 'interactive movement' characterised by 'proximal stability and distal mobility' [5]. Core stability development is therefore integral to all dynamic exercise training and sports specific movement, while quality of training effect is determined by specificity of movement, forces and velocity.

There is growing evidence in the literature that external load in free barbell exercises performed in a standing position is related to muscle activation of trunk stabilisers [29, 30, 33, 34, 37, 50]. Impact of this stimulus on core stability in dynamic athletic performance is more difficult to demonstrate. In a recent systematic review, Prieske et al. (2016) reported a large effect for CST on trunk muscle strength measured by timed isometric plank, compared to no or only regular sports training [12]. When compared to alternative training, such as whole-body strength training, CST had a small sized effect on trunk muscle strength. CST had a small sized effect on muscle strength (e.g. Squat 1RM), a medium sized effect on muscle power (e.g. countermovement jump) and a small sized effect on athletic performance (e.g. 5000 m run time). They concluded that CST for healthy individuals, in the absence of any other fitness training, would increase trunk muscle strength. However, when combined with other training, such as whole-body strength training, CST is not effective. They also propose that increases in trunk muscle strength from CST, has limited effect on physical fitness and athlete performance in trained individuals. Findings from the survey indicate that this information has begun to inform applied practice (Fig. 4). Most agreed that increases in external load in standing barbell exercises would increase trunk muscle activation. Equally important in this form of resistance training was correct postural control.

The survey included a series of questions (yes/no/do not know) investigating perceptions on the application of CST for dynamic athletic performance (Table 3). Most (85%) of the cohort felt it necessary to include specific exercises to train core stability in healthy, uninjured athletes. With reference to traditional CST, two questions were asked; whether it was possible to isolate and train the core stabilization system, and whether this approach was effective. Half of the group believed that this was possible, 34% felt not and the rest were undecided (16%). The isolated training approach was regarded as not effective by 45%, and 37% were supportive. Prieske's review highlighted growing evidence that specific, traditional CST is ineffective in healthy individual and athletes [12]. They also that reported that regular sports training and commonly used supplementary training, such as whole-body strength training, presents superior stimuli, that adhere to the overload training principle [28], for development of core stability in this population. Most survey respondents (65%) concurred with this by agreeing that core stability is developed through normal, progressive exercise training. The perception in applied practice conflicts with scientific literature with regards effectiveness of traditional core stability exercises for athletic performance. The majority (85%) of survey respondents believed that specific exercises were required to train core stability and half supported the use of exercises that isolated trunk stabilisers.

A limitation of the survey was the method of recruiting participants through email and direct messaging on an online professional community platform (LinkedIn). Emails and notifications may have been filtered to spam or junk folders and not reached intended participants. Participants were directed to an online survey, which may have served as a deterrent. Despite this, the number and quality of participants was good in comparison to similar surveys. A further limitation may well have been the inconsistency of prevailing terminology around the topic of CST and broader area of exercise and fitness. Steps were taken to adhere to the most commonly used terms from the scientific literature in the survey.

Conclusion

The survey has provided evidence that a revised, more functional definition of core function and constituent anatomy described in the literature is starting to be used in the practical setting. Almost half (45%) of the respondents preferred trunk as the name for this anatomical region over core (35%). The absence of a valid objective method of measuring core function (22%) means that the most effective way is through observation (43%) of exercise and athletic movement. A quarter (26%) proposed subjective assessment of movement in upright loaded resistance exercises as the most effective method of measuring core function. This coincides with the strong shift in perceptions towards more functional approach to core stability training for dynamic athletic performance. Loaded exercises in an upright position, such as barbell squat and farmers walk, were viewed as effective training methods as proposed in the literature [7, 8, 14]. Core stability as an integrated, functional motor task [7], with training reflecting this according to movement patterns [14], forces [7], torque and velocity [8], appear to be guiding practice in the workplace according to the survey. These findings along with strong support for developing core stability through normal progressive exercise training, means we found in favour of our hypothesis. Some support remained for traditional CST through specific exercises (85%) and the isolation approach (50%). Our findings lead to the following recommendations: Research to continue into efficacy of activating trunk stabilisers through selected sport specific and supplementary training modalities, including compound, loaded strength exercises. Continue to investigate the transfer of training induced trunk muscle activation to functional performance, specifically functional stability.

Additional file

Additional file 1: Core Stability Survey. (PDF 103 kb)

Abbreviations

1RM: 1 Repetition maximum; CST: Core stability training; MSc: Master of Science; S&CC: Strength and conditioning coaches; A&P: Athletes and players; SM&P: Sport medicine practitioners and physiotherapists; SP&B: Sport physiologists and Biomechanists; SC: Sport coaches

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Availability of data and materials

Appendix will include the survey questionnaire, and survey master results document will be made available and labelled Additional file 1.

Authors' contributions

DC conceived and designed survey with assistance from JT (Acknowledgements) and ML. DC managed the data collection, survey circulation, data collation, analysis and interpretation. Final analysis and interpretation for publication was done by DC with assistance from ML and AH. All authors read and approved the final manuscript.

Ethics approval and consent to participate

Approval for the study was granted by the local research ethics committee in accordance with the Helsinki Declaration (2013) [40].

Consent for publication

Survey instructions informed participants of the details of the research study, completion and submission implied consent.

Competing interests

David Clark, Mike Lambert and Angus Hunter declare that they have no competing interests.

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Study 3: Determine reliability of trunk muscle electromyography in the squat exercise

The survey findings confirmed a connection between perceptions and practices in the applied setting and key aspects of trunk stability in scientific literature. The survey found good support for more functional, integrated anatomical definition of the trunk and consequently, exercise selection for developing trunk stability. There was clear support for compound loaded exercises and a recognition of the role of force, velocity and correct technical movement in exercise training for trunk stability. However, strong support remained for traditional CST training including the isolation approach.

There are two possible explanations for this ambivalence; firstly, this may reflect time taken for scientific research to fully effect change in applied setting and secondly, illustrates absence of valid and verifiable research based exercise guidelines to comprehensively replace traditional CST. The recommendations from the survey were to continue to investigate and demonstrate efficacy of loaded, upright compound exercises in activating trunk stabilizers and to demonstrate transfer of this training stimulus to athletic function and performance.

The review study recognised variability in research tools used in published research on trunk muscle activation in back squat. EMG data analysis and presentation included integrated EMG, where raw EMG signal was reported, and normalized EMG. Two methods of normalization were reported; EMG in test effort is normalized to EMG during a maximal voluntary isometric contraction (MVIC) or normalized to a pre-identified signal during a dynamic, submaximal test effort.

Previous work from our laboratory demonstrated that submaximal, dynamic EMG normalization methods were more reliable and sensitive than normalizing to maximal isometric EMG methods (Balshaw and Hunter, 2012). This was found for vastus lateralis and biceps femoris activation in the back squat at moderate (65 & 75% 1RM) and heavy (85 & 95% 1RM) loads. Prior to that, dynamic, submaximal normalization of lower limb muscle EMG was found to be more effective than MVIC method in cycling (Albertus-Kajee *et al.*, 2010) and running (Albertus-Kajee *et al.*, 2011). Dankaerts et al (2004) reported greater within and between day reliability for dynamic submaximal EMG normalization than MVIC for trunk muscles in healthy and back pain patients (Dankaerts *et al.*, 2004).

In an extensive review of EMG normalization procedures, Burden (2010) determined that accuracy MVC forces and torques were dependant on training status and could therefore be 20-40% less than absolute maximal values (Burden, 2010). Hence, using MVC generated EMG as the denominator in the normalization process may not represent a relative consistent anchor for submaximal EMG analysis for a mixed group of participants. Furthermore, they concluded that normalizing to mean EMG captured in submaximal dynamic execution of the task under investigation is suitable for within trial analysis, but not between trails where electrodes are re-applied. Kinematic stability and consistency of the back squat technique within and between participants can be controlled through standardising range of movement or squat depth and using the same relative external load. As a result, and based on evidence supporting dynamic, submaximal EMG normalization we selected to normalize EMG for the 3 neuromuscular studies to mean concentric EMG at 65% 1RM back squat. This meant the within each muscle group mean eccentric and concentric EMG at 75, 85 and 95% 1RM was normalized to the mean concentric EMG at 65% 1RM

There was also variability in methods of determining back squat test loads, which may have undermined reliability and value of findings. Particularly after having established that trunk muscle activation is sensitive to load increments. Comparing activation in response to absolute loads does not account for individual differences in strength levels. This is overcome by using relative test loads calculated from individual maximal strength test scores corrected for body mass. Furthermore, there were no reports on the reliability and repeatability of measuring trunk muscle activation by sEMG in the back squat.

Based on the review we established a standard methodology for all subsequent studies. Selected muscle sites were based on previous published research (Anderson and Behm, 2005; Hamlyn, Behm and Young, 2007) and guidelines from the SENIAM (Surface Electromyography for non-Invasive Assessment of Muscle) (Hermens *et al.*, 1999) (Appendix 3). The detailed review of the literature leading to the selection of these muscle sites is presented in the introduction of the thesis. Synchronised linear encoder signal was used to determine mean root mean square (RMS) processed EMG or muscle activation data for eccentric and concentric phases of the squat (Appendix 4).

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Study 4: Comparison of trunk muscle activation in back and hack squat

The most obvious characteristic of loaded free barbell squat is the requirement of the trunk, as an integral part of the kinetic chain, to stabilize the load through the full range of movement. Many previous studies investigating core stability compared stable squats to those performed on an unstable surface. Findings indicated that instability compromised force and power production in the squat without necessarily increasing trunk muscle activation. Furthermore, previous research had shown no difference in trunk muscle activation between the more stable Smith machine squat and free barbell squat at the same relative load (Schwanbeck, Chilibeck and Binsted, 2009). Hence, comparison of the free barbell squat to a more supported version, the hack squat, would facilitate the evaluation of the challenge on trunk stabilizers posed by the free barbell (Appendix 2). The use of equivalent relative loads meant that the absolute load in hack squat would be greater than back squat, suggesting higher lower limb activation in hack squat versus back squat.

In the neuromuscular trials of study 4, back and hack squat test order was fixed. This may be seen as a limitation according to strict scientific research design suggesting random test order. Similarly, in study 5, squat and countermovement jump tests preceded loaded back squats in all neuromuscular tests. In both cases this was done to prevent postactivation potentiation (PAP), defined as 'transient increase in muscle contractile performance after previous contractile activity' (Sale, 2002). Sale (2002) proposed that prior heavy load efforts increase activation low frequency portion of the force / frequency curve (Sale, 2002). Hence, performing hack squat trials at the same relative, but higher absolute loads prior to the back squat trials would arguably increase activation in subsequent back squat performance. Furthermore, it is well established that prior heavy squat efforts increase countermovement jump performance (Mitchell and Sale, 2011; Esformes and Bampouras, 2013). Consequently, in study 4 and 5 test order was fixed for all neuromuscular trails to ensure that hack squat preceded back squat, squat test loads were incremental and body weight jumps preceded squat trials.

The purpose of the fourth study was to compare trunk muscle activation in the free barbell back squat to the machine hack squat at 4 equivalent, moderate to heavy loads.

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Study 5: Impact of back squat training status on trunk muscle activation in squats and jump tests

We established reliability and sensitivity of sEMG measurement of trunk muscle activation in back squat and demonstrated acute effect of moderate to heavy loads. Comparisons between back and hack squat confirmed that free barbell version placed higher demands on trunk stabilizers than more supported hack squat. The only previous research suggested no difference in trunk muscle activation between 8RM in free barbell back squat and Smith machine squat (Schwanbeck, Chilibeck and Binsted, 2009).

Two questions remained; how does trunk muscle activation change through the full range of squat movement for different loads and secondly how does regular progressive squat training impact on trunk muscle activation in the squat jump (SJ), countermovement jump (CMJ) and back squat? To answer the first question, we used a synchronised electro-mechanical knee goniometer (Appendix 5) to enable the analysis of RMS data in three segments or tertiles for each phase of the squat (Appendix 6). In the second question, we compared trunk muscle activation in participants with different squat training status and strength while performing loaded squats and bodyweight jumps.

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Thesis Conclusion

Thesis summary

The first study, the literature review confirmed that *trunk muscle activation increased with squat load and was greater in the concentric phase compared to the descent*. Furthermore, the review revealed the need to *establish reliability and sensitivity of surface EMG in measuring back squat trunk muscle activation* (Clark, Lambert and Hunter, 2012).

The survey found *that the majority of respondents were aligned to the more integrated definition of core anatomy and function, and hence supported a functional approach to exercise selection for developing trunk stability.* Despite this clear alignment with the scientific literature, *several participants remained in support of an isolated approach for the development of core stability.*

In the third study, we *demonstrated acceptable interday reliability and sensitivity of sEMG in measuring trunk muscle activation in barbell loaded back squat*. Importantly, we confirmed that in a well trained group, *activation increased significantly in response to increases in load equivalent to 10 percent of squat 1RM.* This increase occurred in all four trunk muscles (RA, EO, LSES and ULES) in the eccentric phase and all muscles (EO, LSES and ULES) apart from RA in concentric phase.

In the fourth study, *we demonstrated that despite significantly higher external loads in the hack squat, trunk muscle activation was greater in free barbell back squat at equivalent relative loads.* We determined that the back squat kinematic characteristics explaining these differences were*; greater range of movement, faster descent and the requirement to control the unsupported external load through the full movement, engaging the entire kinetic chain.*

The most important and novel finding in the final study was that *trunk muscle activation was lower in participants who were stronger in the squat compared to weaker subjects.* This was found for all three loads (65, 75 and 95% SM) in the eccentric phase and only the heaviest load (95% SM) in concentric phase. The second novel finding was that this *lower EMG response in the stronger group translated to all three phases of the SJ and CMJ but was only significant in concentric and flight phase.* This reduced activation in the strong group was also associated with significantly higher jump performances compared to the weak group. *In summary, adaptation to progressive squat training results in more efficient trunk stability in squat strength tasks and dynamic, bodyweight jump performance.* The final study demonstrated that *trunk muscle activation increased significantly in each 30^o segment of descent and reached the highest level in the first 30^o segment of ascent for all test loads. Hence, highest trunk muscle activation occurred in the two lowest 30^o segments of the parallel squat movement.*

Research design

In the 3 neuromuscular studies we used cross-sectional design to observe a single group (Study 3 and 4) and compare different groups, strong, middle and weak (Study 5), at a single time point. This is an observational approach where we did not intervene and influence participant status. As a result, the study 5 findings require ratification in a training study in order to facilitate further effective translation to applied practice. Specifically, a well structured randomized controlled trial (RCT) measuring effects of increased squat strength on trunk stability while performing dynamic athletic actions (Hecksteden *et al.*, 2018). The study should be conducted on a representative and large enough cohort of participants to ensure appropriate statistical power (Hopkins, Schabort and Hawley, 2001). Current applied training guidelines for development of trunk stability in healthy and athletic participants lack scientific foundation. Our findings partly fill this void by addressing the fact; loaded compound exercises are an effective method of developing dynamic trunk stability. Further investigation and clarification through effective RCT's are required to challenge and replace the many un-scientific core stability training practices.

Reliability and comparison studies on a small number of participants using multiple comparisons have been questioned. In study 3 & 4, we had a relatively small number of participants and analysed a fairly large number of data points, including kinematic and RMS measures. Hopkins et al (2001), in a review suggested that reliability of tests relating to physical performance were acceptable in a lower number cohort where the group is homogenous in the key area of competence (Hopkins, Schabort and Hawley, 2001). In these two studies, the 10 participants were competent in the barbell back squat evidenced by a mean relative 1RM of 165% body mass. Given that barbell back squat was the exercise being studied, we concluded that our cohort size represented an acceptable number for the analyses that we performed. Nevertheless, we performed sample size calculation at 90% power using G*Power effect size difference (F test ANOVA RM) from RMS (ULES) from 75-95% SM from back squat reported in study 4. This confirmed that a minimum sample size of 8 is required when performing 3 repeated measurements.

In study 5 we had a total group of 50 participants, who demonstrated normal distribution for relative BS 1RM according to D'Agostino & Pearson normality test (alpha=*0.05*). This resulted in two groups of 17 (weak and middle groups) and one of 16 (strong group). Using the same effect size RMS as above but applied in a different G*Power model (F test ANOVA RM) using 3 independent groups at 90% power, we calculated that a minimum of 12 participants per group were required. Given we used substantially more than 12 in each group we are therefore confident that type I and type II errors were avoided.

Electromyography

The use of surface EMG to measure muscle activity has been used for over two centuries and the refinement of procedures have improved accuracy and reliability. Electrode placement for effective measurement of trunk muscle EMG has been researched resulting in published guidelines (Hermens *et al.*, 2000; Huebner *et al.*, 2014). Normalization of trunk stabilizer EMG data captured in dynamic exercise has been extensively researched and discussed at length earlier in this thesis (Introduction and Introduction to Paper 3). The neuromuscular studies began with an investigation that demonstrated acceptable reliability and sensitivity for our method of analysis of trunk muscle activation in the back squat. Specifically, the research studies 4 and 5 were designed to ensure neuromuscular data was captured in a single test session, thereby avoiding re-application of electrodes and associated loss of accuracy. While there are recorded limitations associated with surface EMG assessment of muscle function and specifically in trunk stabilizers, it remains the most effective method of measuring this in loaded dynamic exercise. The accuracy of our finding, that increases in squat load produced greater trunk muscle activation in all muscles tested, improved over the 3 neuromuscular studies. This strongly suggests that this is a valid and reliable finding. This consolidates previous studies which reported trunk muscle load effect for the squat using diverse methodology as reported in our review (Clark, Lambert and Hunter, 2012).

Surface EMG measurement of rectus abdominus activation response to load increases in the dynamic back squat has proven inconsistent (Hamlyn, Behm and Young, 2007).

Huebner et al (2014) investigated surface EMG amplitude in 5 trunk muscles for 4 different electrode placement positions and found RA EMG amplitude varied the most, regardless of electrode position (Huebner *et al.*, 2014). We argued (study 3) that the variance in RA sEMG measurement may result from folds in the skin adjacent to RA during deep flexion of the hip. In study 3 we reported unacceptable absolute reliability (CV%) but fair relative reliability (ICC) for RA RMS and found a tendency for load effect in this muscle (Clark, Lambert and Hunter, 2016). In the second neuromuscular study we found a significant load effect for RA for all loads in both phases of the back and hack squat (Clark, Lambert and Hunter, 2017). We repeated this finding in the final study (n-50) where RMS in RA increased by 18 and 45% in the eccentric and concentric phase respectively, in response to 20% increase in external load. It appears that through improved and consistent electrode placement, better management of clothing and artefact, we were able to capture RA sEMG more accurately as we progressed through the 3 neuromuscular studies. Importantly this confirmed that RA activation is sensitive to increases in squat load.

EMG measurement on one side of the body is an established method for bilateral standing and jumping exercises performed in sagittal where the load is carried in the midline (Seroussi and Pope, 1987; Sihvonen, Partanen and Hanninen, 1988; Vakos *et al.*, 1994). Bilateral symmetry of EMG signal has been demonstrated in this category of movement, which means that EMG captured on the right-hand side accurately reflects bilateral trunk muscle activation in this category of exercise.

Kinematics

In the three neuromuscular studies, we used a linear transducer (Celesco, PT5A, California, USA) to measure barbell displacement and in study 5, jump kinematics. This is a highly effective method for analysis of squat kinematics where participants remain on the ground, with flat feet throughout the movement. Furthermore, there is evidence that analysis of jumps by linear transducer is valid and reliable in comparison to force platform tests (Harris *et al.*, 2010; Hansen, Cronin and Newton, 2011). Linear transducer data can determine the start and end of the squat and separate eccentric and concentric phases accurately. However, when identifying phases of jumps where participants leave the ground in the flight phase, this technology has limitations. The end of the concentric phase determined by linear transducer is the point where concentric displacement matches the start position or upright standing. Therefore, flight phase starts once displacement proceeds beyond this point. The start of the flight phase in kinematic analysis of jumps using a force plate would be at 'toe off' after full plantar flexion (Linthorne, 2001). This means that in study 5, the segment from flat foot upright standing to toe off is included in flight phase, despite still being in contact with the ground. What has not been reported, in the authors view, is relative contribution of this plantar flexion segment of the concentric phase to force application and jump performance.

In study 5 we found that trunk muscle activation was significantly higher in concentric phase compared to eccentric phase and importantly remained at the same level during flight phase. The question therefore arises, does the ground contact portion (plantar flexion) included in the flight phase influence this activation? Farris at al (2016), in an *in vivo* analysis of plantar flexor muscle-tendon interaction during vertical jumping, concluded that this muscle group makes their greatest contribution in early to middle portion of the concentric phase (Farris *et al.*, 2016). The authors suggest this is primarily to stabilize and facilitate power generated by knee extensors. They concluded there was no evidence that stored elastic energy in the plantar flexors contributed to force production in the final stage of concentric phase prior to toe off. Our interpretation therefore, is that high muscle activation in the flight phase is to stabilize the trunk for effective performance and in preparation for landing. This is supported by our finding that in the strong squat group activation in both concentric, and specifically the flight phase, was significantly lower than in the weak group.

In studies 3 and 4 we found that eccentric displacement decreased significantly with each 10% increase in load, while concentric displacement remained unchanged for all loads. The absence of knee and hip angle measurements in these two studies meant that we were not able to explain this with any certainty. We presented two possible explanations; increases in load resulted in subconscious proprioceptive inhibition preventing full knee and or hip flexion to avoid the final, most challenging segment of the parallel squat. We also suggested spinal shrinkage due to incremental compressive forces might be a factor. Wisleder et al (2001) found spine shrinkage of -3.9 ± 1.2 mm resulting from spinal bending, rotation and pure compression in response to a load equal to body mass (Wisleder *et al.*, 2001). We found a mean reduction in displacement of 56 mm (Range 22-86 mm) for loads equivalent to 77, 100, 127 and 150% body mass. Even at loads greater than body mass, it is unlikely that spine shrinkage would account in full for this reduction in eccentric displacement. Hence, we propose that reduced displacement is the result of lower squat start position due to spine compression and protective inhibition preventing full depth squats at heavier loads. Our explanation for the absence of a reduction in concentric displacement in studies 3 and 4 remains applicable. The instruction to complete this phase as explosively as possible means that velocity increases as mechanical load is overcome, and peaks in the final stage of hip and knee extension. This means that the final height of displacement exceeds the (compressed) start point, which is clearly visible when observing moderate to heavy load squats performed explosively.

Impact: Applied strength and conditioning

The back squat is an established method of developing lower limb for performance in sports where strength, power, acceleration and speed are important (Seitz *et al.*, 2014). There is also a growing appreciation of the role of trunk stability in effective function of the kinetic chain in dynamic athletic performance. Specifically, the role of the trunk anatomical region in resisting, coordinating, transferring and optimizing forces, torques and power generated by the limbs within the full, integrated kinetic chain. However, there is little scientific evidence on how this should be trained in a healthy and athletic population.

Trunk stability for sports performance is integrated within the full kinetic chain and therefore must tolerate force, torque and velocities characteristic of such movement. Logically therefore, a training intervention to develop trunk stability must adhere to two key training principles, specificity and overload. To be specific, exercises should be dynamic and similar to the movement for which trunk stability is required. Overload is achieved by executing selected movements under conditions of greater force, torque or velocity of movement.

The findings of this suite of studies confirm that loaded free barbell squat is effective in activating the trunk stabilizers. Importantly, this stimulus is integrated within a compound, whole body movement, which addresses the first limitation of traditional CST, specificity. Our research has confirmed that loaded back squats represent a training overload for the trunk stabilizers, thereby addressing the second limitation of traditional CST. While there has been progress in scientific challenge to traditional core stability, research has failed to give clear direction on the most effective training methods to develop dynamic trunk stability for athletic performance. Our research provides that direction with scientific evidence;

- *Trunk stabilizers are sensitive to typical training load manipulation in the back squat.*
- *Trunk muscle activation is highest in the final 30^o of squat descent to parallel and first 30^o of ascent regardless of load.*
- *Adaptations to loaded back squat training improve efficacy of trunk stability mechanisms under load.*
- *Trunk muscle adaptations to loaded squat training transfer to powerful, dynamic bodyweight jumps, characteristic of many sports.*

The loaded parallel back squat can be viewed with confidence as an effective method of activating and training the trunk stabilizers. Squat training with loads ranging from 65 to 95% of 1 repetition maximum will activate trunk stabilizers effectively. This will increase dynamic trunk stability required to withstand increasing loads in the squat and over time will do this more efficiently, at lower levels of trunk muscle activation. Furthermore, training to parallel depth or lower will optimize activation during training and develop stability in the deepest, most challenging phase of squat descent and ascent.

The development of squat strength through continuous, progressive training will transfer to SJ and CMJ performance (Wirth, Keiner, *et al.*, 2016). We showed that squat strength was also associated with lower trunk muscle activation in concentric and flight phase of SJ and CMJ. Therefore, squat training adaptation results in greater jump performance at lower levels of activation of the trunk stabilizers. Arguably, this adaptation to squat training will transfer to a range of dynamic athletic actions.

Recommendations for strength training programmes for development of strength, power and performance in athletic activities:

- Include the loaded free barbell back squat at progressive loads ranging from 65 to 95% 1RM for the development of trunk stability.
- Ensure correct and safe technique, specifically squatting to a minimum of parallel depth.

Use the following criteria to monitor progress in the development of trunk stability:

- In *compound loaded exercises*, observe and monitor the ability to *adhere to correct technique under load and progression of load*. Specifically, the capacity to manage load through the trunk; *evidenced by monitoring the ability to keep the path of the load over the base of support through the full range of movement.*
- In *technical sporting movements*, observe and monitor the ability to *execute technical movements at high force, velocity and torque effectively and correctly in situ*.
- In both of the above contexts, *monitor and assess acute change within a training session in response to fatigue to assess short-term endurance*.
- In both of the above contexts, *monitor and record development across a longitudinal training period to assess progress and chronic adaptation.*

Impact: Future research

Reviews on the application of CST for sports performance and proxies thereof report a number of commons research flaws (Reed *et al.*, 2012; Silfies *et al.*, 2015; Prieske, Muehlbauer and Granacher, 2016; Wirth, Hartmann, *et al.*, 2016), which should guide and inform future research. There is agreement that absence of a valid test of core stability has undermined progress in scientific understanding of core stability training effects (Hibbs *et al.*, 2008; Prieske, Muehlbauer and Granacher, 2016). Isolating and measuring trunk muscle strength as a component of trunk stability is in itself flawed (Okada, Huxel and Nesser, 2010). Furthermore, current reliance on tests that resemble common exercises used in CST means that results are biased in favour of CST. Complex neuromuscular interactions that underpin dynamic trunk stability cannot be described by a single measure of strength, especially strength measured by an isometric test. Current scientific methodology is not capable of isolating and measuring these factors within athletic activity to inform training manipulations. Nor is methodology available to measure acute exercise response or chronic training adaptations in selected trunk stability exercise interventions. *Which means that testing proxies of sports performance is currently the most effective method of assessing transfer of trunk stability training interventions.*

Our novel findings that improved trunk stability developed through loaded barbell squat training make a significant contribution to:

1. Increased load carrying capacity in loaded barbell squat by enhancing stability at more efficient levels of trunk muscle activation.

2. Increased body weight jump performance by increasing trunk stability at more efficient levels of trunk activation.

The importance of these findings for applied strength and conditioning practice have been described above. With reference to the first point, there would be value in better understanding how other commonly used loaded compound exercises, engage and develop the trunk stabilizers. Perhaps more meaningful and interesting, relating to point 2, is how do the adaptations to loaded squat training translate to trunk stability in other dynamic athletic activities? Research recommendations:

- Subject the *key findings of this research to further investigation in a randomized controlled training study.*
- Investigate *acute response and adaptation* of trunk muscles to exercise and training with *compound loaded exercises, including deadlift and Olympic weightlifting exercises.*
- Based on the principle that squat training impacts positively on stabilizer adaptation, *determine the impact of progressive squat training on neck strength as a protection against concussion*.
- Impact of *enhanced trunk stability from progressive squat training on dynamic trunk stability in performance of common sporting activities* such as; sprinting, cycling, reactive agility in racquet sports, canoe paddling and rowing.

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Appendices

Appendix 1-Survey questionnaire

Appendix 2-Back and hack squat

Appendix 3-Electrode placement

Appendix 4-Eccenric and concentric phases

Appendix 5-Kinematic set-up

Appendix 6-Eccentric and concentric tertiles

Core Stability (copy)

Page 1: Page 1

There have been a number of recent reviews highlighting the lack of consensus around the topic of core stability. There is however agreement that core stability is important in everyday life and dynamic sporting activity. The confusion lies in the most effective manner of developing and measuring core stability.

This motivated me to embark on a PhD a few years ago looking at neuromuscular function of the trunk in the loaded squat in the hope of shedding some light on this approach for developing core stability.

An obvious related question is: How do people working in sport view core stability and its development for dynamic athletic performance?

I appreciate your time in completing this short survey (<15 min) which will focus on ***core stability for dynamic athletic performance***.

Page 2

Section 1: Demographics

1. What is your ***Primary*** discipline? ✱ *Required*

- Sports Medicine Practitioner
- Sports Physiotherapist
- Masseur / Soft Tissue Therapist
- Strength and Conditioning Coach
- Sports Physiologist
- Sports Psychologist
- Performance Nutritionist
- Biomechanist
- Performance Analyst
- Sports Coach
- Athlete / Player
- Sports management
- Other

1.a. If you selected Other, please specify:

2. What area of sport are you involved in? ✱ *Required*

- Professional, full-time paid position working with full-time paid atheletes
- Semi-professional, paid part-time position
- Elite professional, full-time paid position working with funded and amateur athletes

(Institute)

- Elite non-professional, part-time working with regional or national selected athletes
- Volunteer in recreational club sport
- Academic, university or school sport role
- Other

2.a. If you selected Other, please specify:

3. Please indicate below which describes most accurately where you do most of your work. ✱ *Required*

- Team sport
- Individual athletes
- Combination of team and individual athletes

4. What is your highest academic qualification? ✱ *Required*

- PhD
- MSc or Masters
- Degree or Honours degree
- Diploma
- Other

4.a. If you selected Other, please specify:

4.b. Do you have a professional qualification linked to your discipline? ✱ *Required*

- Yes
- No

4.c. How many years have you been working in your current discipline? ✱ *Required*

Section 2: Core Stability

5. Which statement below **do you think** best describes what constitutes ***the core*** most accurately? ✱ *Required*

- The spine and the associated muscles and nerves
- The lumbar spine, pelvic and hip joints and associated muscles and nerves
- The region between and including the pelvic and shoulder girdles and associated muscles and nerves
- The region between and diaphragm and pelvic floor and associated muscles and nerves
- Other

5.a. If you selected Other, please specify:

6. What term do you believe best describes the anatomical region that this survey is dealing with? ✱ *Required*

- Torso

- Trunk
- Core
- Upper limb
- Other

6.a. If you selected Other, please specify:

7. Please rate how strongly you agree or disagree with the following statements.

	✱ *Required*				
	1 Strongly agree	2 Agree	3 Neither agree nor disagree	4 Disagree	5 Strongly disagree
Core strength is required for core stability	○	○	○	○	○
Core strength and core stability are separate attributes	○	○	○	○	○
Core strength is required for dynamic athletic performance but not everyday life	○	○	○	○	○
Core stability is dependent on neural timing and muscular coordination rather than core strength	○	○	○	○	○

8. Do you believe that trunk muscle activation measured by ***surface electromyography*** is ***reflective of performance*** of the core stabilization system? ✱ *Required*

- Yes
- No
- Don't know

9. Please rate the following ***categories of exercise*** on their ***effectiveness*** in developing core stability ***for dynamic athletic performance***?

	✱ Required				
	1 Very effective	2	3	4	5 Not effective at all
Isolated abdominal bracing					
Isometric held exercises such the plank					
Dynamic abdominal exercises such as sit-ups					
Dynamic inverted exercises such as hanging leg raise					
Suspended compound exercises using systems such as the TRX					
Instability abdominal exercises performed on a Swiss ball					
Functional exercises such as farmers walk					
Loaded free barbell exercises such as Squats and Olympic lifts					

10. Please rate how strongly you agree or disagree with the following statements as they relate to determining ***exercise selection*** for the development of core stability for ***dynamic athletic performance***.

✱ Required

	1 Strongly agree	2 Agree	3 Neither agree nor disagree	4 Disagree	5 Strongly Disagree
The exercise must subject the athlete to forces equal to or greater than expected in the sport or event	○	○	○	○	○
The exercise must emphasize correct movement pattern above all else	○	○	○	○	○
The exercise must subject the athlete to velocity of movement equal to or greater than expected in the sport or event.	○	○	○	○	○
The exercise must develop capacity for sustained isometric contraction	○	○	○	○	○

11. Please rate how strongly you agree or diagree with the following statements as they relate specifically to ***ground based loaded free barbell exercises*** (Squats and Olympic weightlifting exercises).

	✱ *Required*				
	1 Strongly agree	2 Agree	3 Neither agree nor disagree	4 Disagree	5 Strongly disagree
Trunk muscle activation will increase with increases in velocity of movement.	○	○	○	○	○
Trunk muscle activation is dependent on correct postural control	○	○	○	○	○

Trunk muscle activation is enhanced by slow controlled movement	○	○	○	○	○
Trunk muscle activation will increase with increases in external load	○	○	○	○	○

12. What is the most effective method of measuring core stability in a healthy, un-injured person? ✱ *Required*

13. Do you think it is necessary to include specific exercises to train core stability in a healthy, uninjured ***non athlete's*** exercise programme? ✱ *Required*

- Yes
- No
- Don't know

14. Do you think it is necessary to include specific exercises to train core stability in a healthy, uninjured ***athlete's*** exercise programme? ✱ *Required*

- Yes
- No
- Don't know

15. Do you think that the development of core stability can ***prevent back pain***? ✱ *Required*

- Yes
- No
- Don't know

16. Do you think that certain ***lower limb overuse injuries*** are caused by ***poor or under developed*** core stability? ✱ *Required*

- Yes
- No
- Don't know

17. Do you think it is ***possible*** to isolate and train the core stabilization system? ✱ *Required*

- Yes
- No
- Don't know

18. Do you think it is ***effective*** to isolate and train the core stabilization system? ✱ *Required*

- Yes
- No
- Don't know

19. Do you think that the core stability is ***automaticall***y developed during normal, ***progressive*** exercise training? ✱ *Required*

- ◯ Yes
- ◯ No
- ◯ Don't know

Page 3

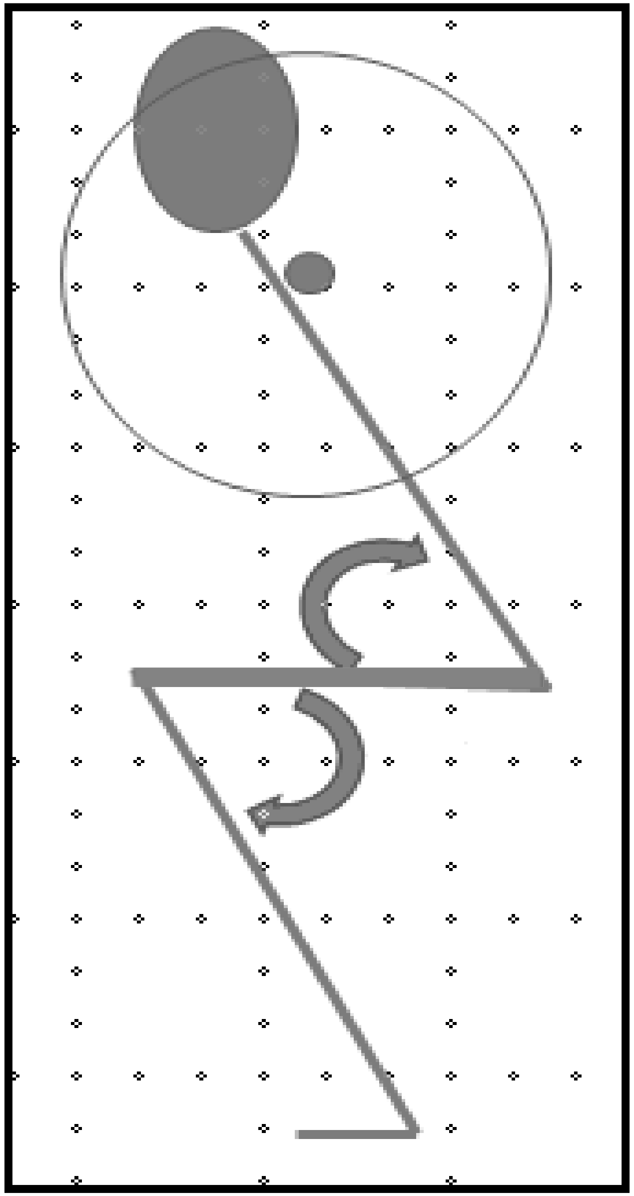
Thank you for completing the survey.

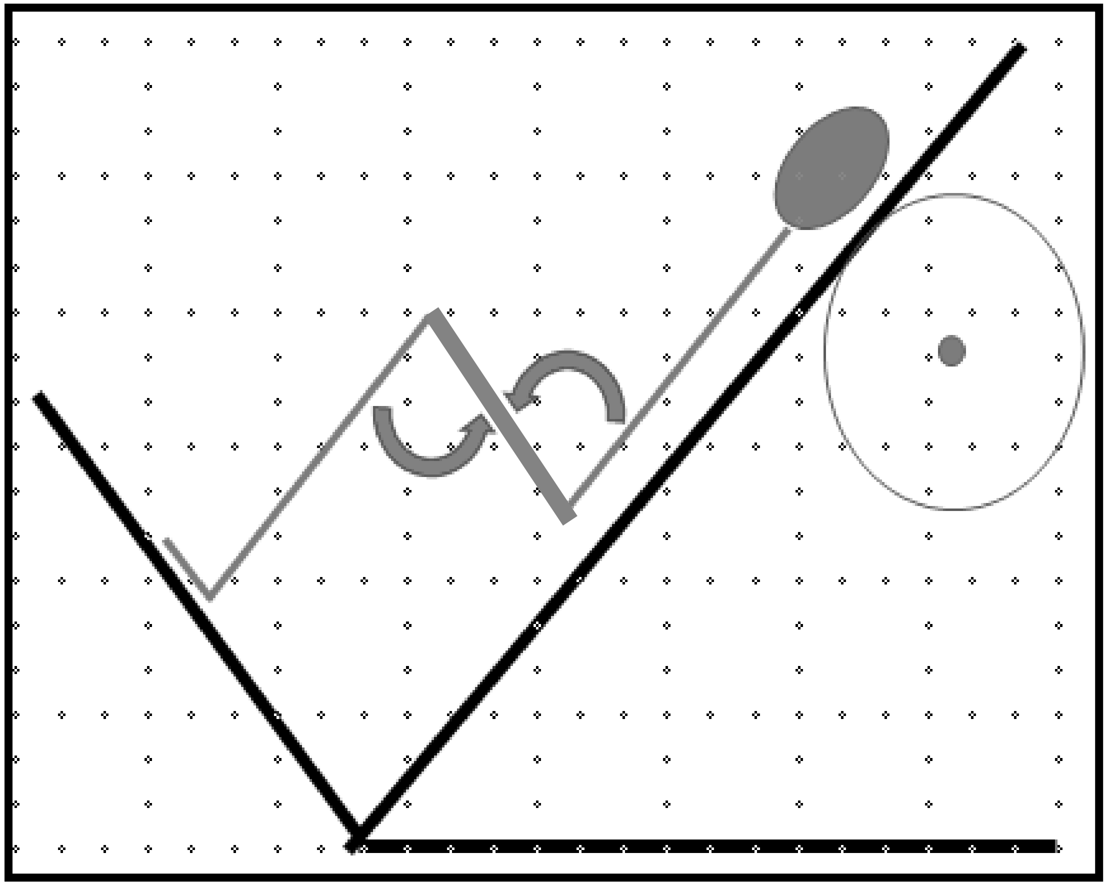
Appendix 2

Back squat and hack squat set-up

Appendix 2

Back squat and hack schematic





Muscle Sites:

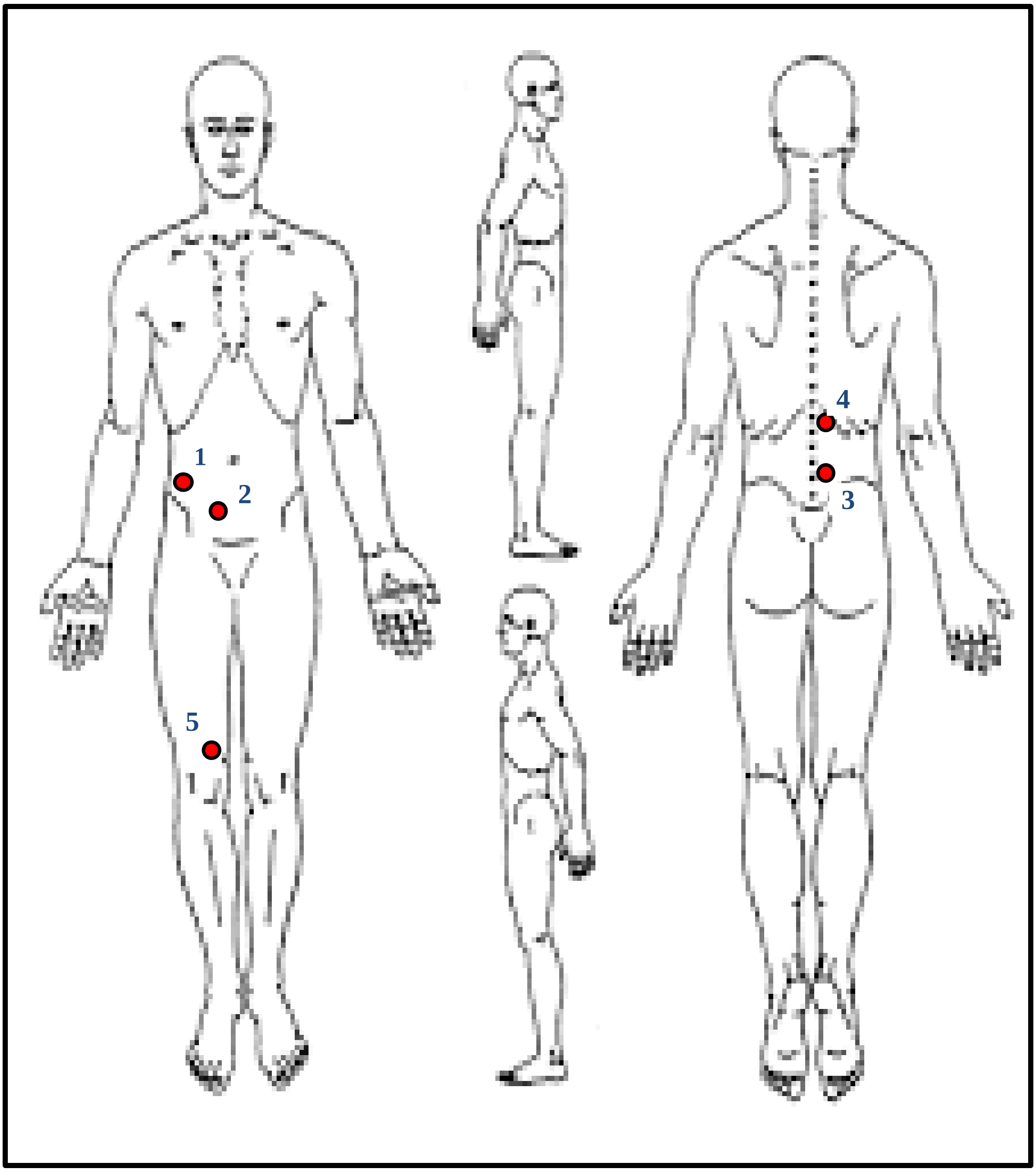
1 – Exernal oblique (EO)

2 – Rectus abdominus (RA)

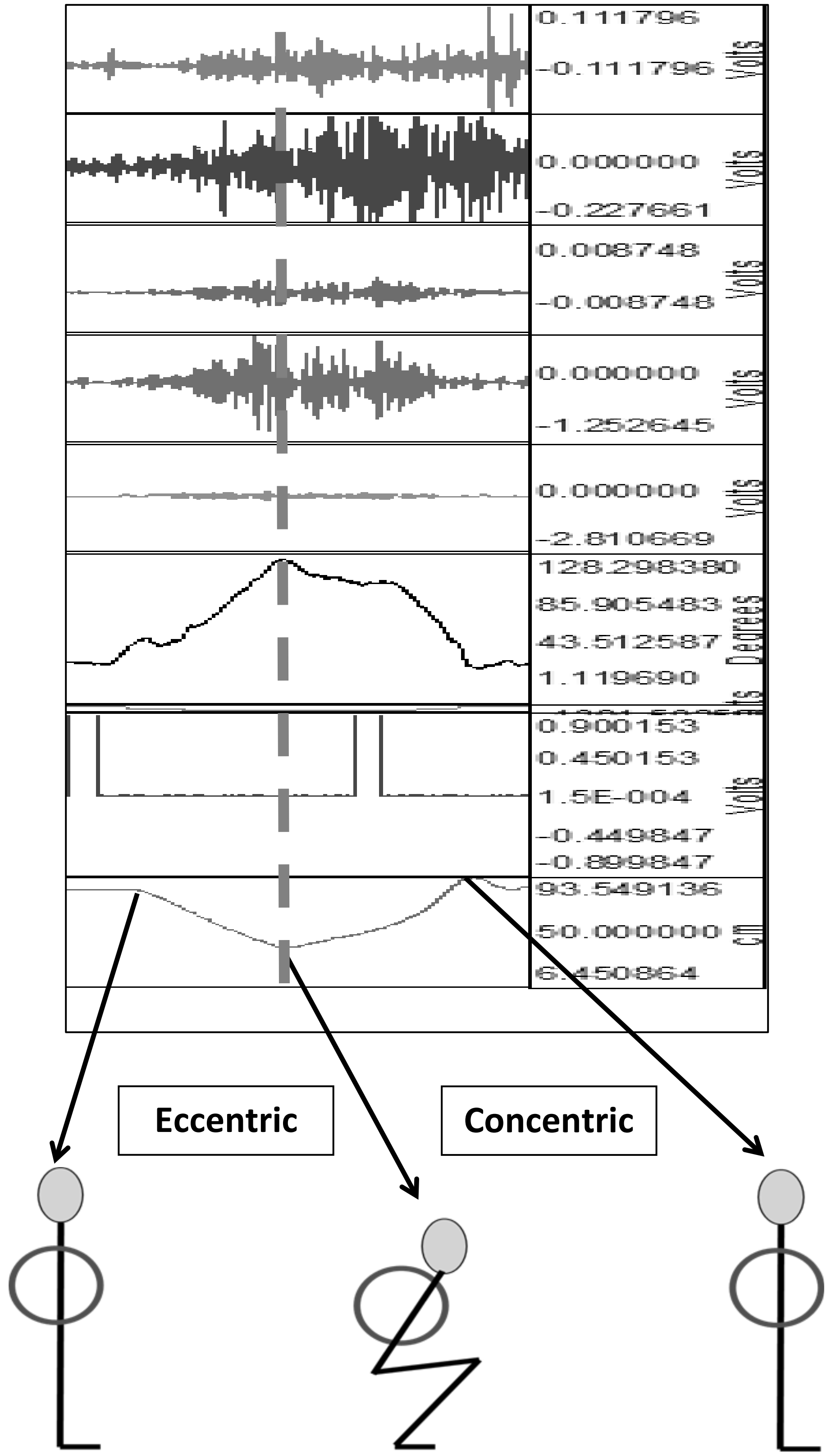
3 – Lumbar sacral erector spinae (LSES)

4 – Upper lumbar acral erector spinae (ULES)

5 – Vastus lateralis (VL)



Appendix 4



Eccentric and concentric phase determined from displacement (cm) measured by linear encoder used to identify mean EMG for each phase.

Appendix 5

Kinematic set-up: Back squat

Linear encoder:

- Measures barbell displacement (cm)
- Determine eccentric and concentric phases of the back and hack squat and jumps
- Determine flight time for jumps

BioNomadix 2 Ch. EMG transmitter:

- Each transmits high resolution sEMG signal at a rate of 2000Hz from two muscle sites to the Biopac MP150 receiver unit

Electromechanical goniometer:

- Measure knee flexion in eccentric phase and extension in concentric phase.
- Signal used to determine three 30^{o} tertiles in each phase; eccentric and concentric.

Eccentric Phase Divided into Tertiles (30º)

Concentric Phase Divided into Tertiles (30º)