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**DEVELOPMENT AND EVALUATION OF A  
CORE TRAINING PROGRAMME IN HIGHLY  
TRAINED SWIMMERS**

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Thesis submitted in Fulfillment of the Requirements for the Degree of Doctor of  
Philosophy

Teesside University 2011

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# **DEVELOPMENT AND EVALUATION OF A CORE TRAINING PROGRAMME IN HIGHLY TRAINED SWIMMERS**

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## **Declaration**

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I certify that the substance of this thesis has not been already submitted for any degree and is not currently being submitted for any other degree or degrees. I certify that to the best of my knowledge any help received in preparing this work, and all sources used, have been acknowledged in this thesis.

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Angela E. Hibbs, M.Sc. B.Sc.

## Acknowledgements

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I would like to thank my family and friends for their unfailing strength, support and continued encouragement not only during the years that it has taken to write this thesis, but for their continued support in my academic and vocational pursuits over the years.

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I have reached the end of my Ph.D. marathon. There were times when it flowed freely and others when it felt impossible. The support and encouragement I have received from the sidelines has pushed me forward and enabled me to reach the finish line. The feelings of relief, satisfaction and wonderful sense of achievement will stay with me for the rest of my life, and for that I am forever grateful to those mentioned above.

# **DEVELOPMENT AND EVALUATION OF A CORE TRAINING PROGRAMME IN HIGHLY TRAINED SWIMMERS**

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Thesis submitted in Fulfillment of the Requirements for the Degree of Doctor of Philosophy, Teesside University 2011

## **THESIS ABSTRACT**

Core training is a popular technique for athletes and coaches concerned with improving sports performance. Achieving an appropriate level of muscular activation is a vital ingredient in a successful training programme. However, the evidence base with regard to the effectiveness of core training on improving an athlete's core ability and resultant sporting performance is limited. This thesis aims to 1) develop a core training programme for highly trained swimmers and 2) evaluate its effect on sporting performance using the Medical Research Council (MRC) framework for developing complex interventions. The thesis outlines current theories and findings in both the clinical and sporting sectors regarding core stability and core strength training and also the MRC framework. It determines the most appropriate method of measuring muscular activation of the core muscles (EMG) and establishes the reliability of the technique for assessing different exercises. Key core muscles were found to produce significantly reliable ( $P < 0.05$ ) measurements of below 25% CV and  $> 0.7$  ICC values while performing MVIC and core training exercises. Subsequently, popular low and high threshold core training exercises were analysed and muscle activation levels of 1 - 110% MVIC were identified. A new training programme was developed and tested on a group of highly trained swimmers over 6 and 12 week training intervention periods. Significant improvements ( $P < 0.05$ ) and a large likelihood of beneficial improvement during the performance tests were observed following 6 and 12 weeks of training ( $P < 0.05$ ) along with significant reductions in muscle activation (%MVIC) during the performance tests and training exercises. Conclusions from the intervention studies are used to develop a theoretical model outlining how to structure an effective core training programme for highly trained athletes. It is proposed that this model could be used by coaches and athletes to help plan, conduct and evaluate their core training to maximise the potential benefits that core training could have on sporting performance.

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## Abbreviations

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MVC – Maximal Voluntary Contraction  
MVIC – Maximal Voluntary Isometric Contraction  
CNS – Central Nervous System  
MUAP – Motor Unit Action Potential  
LBP – Lower Back Pain  
ROM – Range of Motion  
RA – Rectus Abdominis  
EO – External Oblique  
IO – Internal Oblique  
MF - Multifidus  
LD – Latissimus Dorsi  
GM – Gluteus Maximus  
GMe – Gluteus Medius  
GMi – Gluteus Minimus  
LG - Longissimus  
RF – Rectus Femoris  
TrA – Transverse Abdominal  
ES – Erector Spinae  
QL – Quadratus Lumborum  
VM – Vastus Medialis  
VL – Vastus Lateralis  
EMG - Electromyography  
sEMG – Surface Electromyography  
pkEMG – Peak Electromyography  
ARV EMG – Average Rectified Value Electromyography  
CV – Coefficient of Variation  
ICC – Intraclass Correlation Coefficient



## Overview of Thesis

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Core training is a popular technique for athletes and coaches concerned with improving sports performance. Achieving an appropriate level of muscular activation is a vital ingredient in any strengthening programme. However, the evidence base with regards to the effectiveness of this type of training on improving an individual's core ability is limited at present. Not only is there is a lack of intervention-based studies which are able to demonstrate the benefits of these exercises in terms of worthwhile improvements in sports performance but of the few that do, the levels of muscular activation during the course of the intervention are not documented.

The Medical Research Council (MRC) framework for the development and evaluation of complex interventions for randomised control trials (RCT) was used as a theoretical guide to designing the project. This involves a pre-clinical phase (Theorising), initial modelling (Phase I), subsequent exploratory (Phase II) and a main RCT (Phase III) followed by a long-term evaluation (Phase IV). The first three phases (Preclinical Phase, Phase I and Phase II) of this framework were performed in this study. The Preclinical Phase included a review of the literature relating to the effects of core training. In Phase I the theoretical background and quantitative data were combined to develop the main components of the intervention. Focus groups were conducted to collect additional qualitative data to inform the development of the intervention. Based on the findings of Phase I, the components of the intervention were modified in order to conduct the Phase II. The exploratory trial was conducted in an athletic setting using a sample of 30 highly trained swimmers.

The long-term goal of this project is to provide coaches and athletes with a model for core training which they can use to achieve the potential benefits of core training. The aims of the thesis are:

1. To develop a methodologically sound core training programme.
2. To evaluate the effect of this core training intervention over a 12-week period on highly trained swimmers.

In doing so the following objectives (listed by Chapter) will be addressed:

- Chapter 1) To review concepts and theory with regards to what is currently considered the most effective core training programme.
- Chapter 2) To establish the structural and methodological framework needed to enable the implementation of a core training programme in elite and sub-elite athletes.
- Chapter 3) To develop a repeatable measure of core muscle activity using surface electromyography during a range of core exercises.
- Chapter 4) To quantify the core musculature activity and evaluate the muscular response during a range of core exercises.
- Chapter 5) To implement a short-term swimming specific core training programme and evaluate performance outcomes in highly trained swimmers.
- Chapter 6) To modify the training protocols implemented in the short-term core training programme (as stated in Chapter 5) and evaluate performance outcomes in highly trained swimmers over a longer period.
- Chapter 7) To develop a theoretical model outlining how to structure an effective core training programme for highly trained athletes.
- Chapter 8) To provide general conclusions regarding the main findings from the previous chapter and discuss general limitations and future research areas.

The chapters have been structured to enable the findings from the previous chapter to help direct and justify the research design and implementation of the subsequent chapter. This is in accordance with the MRC framework design and enables a solid scientific process to be followed. Chapter 1 outlines the current theories and the different types of research conducted in the area to date. These findings are used to establish what factors need to be considered when collecting data in the area using these methods and establishing the importance of reliability (Chapter 2). Subsequently, Chapter 3 establishes the reliability of the EMG methods that will be implemented during the exploratory phase of the intervention (Chapters 4-7). The first three chapters form the development phase of the intervention. The intervention studies implemented in Chapters 4, 5 and 6 are subsequently justified based on the theories, findings and conclusions from the previous three chapters. A practical model that can be used to design successful intervention programmes is then outlined in Chapter 7 based on the findings and conclusions from the exploratory studies. Finally, general recommendations and areas for future research can be identified as a result of the new research that has been highlighted (Chapter 8).

## Overview of Chapters

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### **Chapter 1: Literature Review and Theory**

This review provides an overview of previous and current research evaluating core stability and core strength in both the rehabilitation and sporting sector. The Chapter outlines the current definitions of what is included in the term ‘core stability and core strength’ and tries to make a distinction between these terms. The Chapter summarises what little previous research has been performed looking at the effects of core stability and core strength training on improving sporting performance and how the different types of core training exercises activate the core musculature and subsequently, which type of exercise may result in the greatest performance improvement. The Chapter concludes by identifying the questions yet to be answered regarding core stability and core strength training and whether this type of training does have the potential to improve sporting performance.

### **Chapter 2: Planning an Intervention in an Athletic Setting based on the Medical Research Council Framework for Complex Interventions**

The first part of the Chapter identifies the methodological issues involved when designing a complex health intervention and identifies those issues relevant to the design of a core training programme in athletes. Many studies in the past have not followed a structured scientific research design and subsequently have failed to include the necessary components to be able to make proven and clear conclusions regarding their findings (e.g. poor subject selection, lack of a control group, no repeatability analysis, a lack of performance indicators). The framework for performing complex interventions as suggested by the MRC was decided upon as the most appropriate and scientifically established method to enable this thesis to quantify and establish theories regarding measuring and training the muscle activity of the core musculature. This framework was selected as it has been implemented successfully in the health sector to design complex interventions. It is argued that achieving requisite muscle activation levels is the ‘active ingredient’ for a successful core training intervention.

Subsequently, surface electromyography (sEMG) is introduced as the most pragmatic and valid technique to quantify this active ingredient. Consideration is then given to the known issues regarding the use of sEMG to quantify muscle activity, and attention is focused on the factors causing variability. The latter section focuses on the similarities and differences between performing interventions in athletic and clinical settings.

### **Chapter 3: Establishing a Repeatable Measurement of Core Musculature Activity during MVIC and Core Exercises**

This Chapter establishes that surface electromyography (sEMG) has been used to quantify muscle activity but there remains a lack of research using this method to investigate the core musculature and core stability and subsequently quantifying the repeatability of this signal. The Chapter introduces two common methods for reducing sEMG data, peak and average rectified (ARV) EMG methods. The peak value has been well reported in the literature, while the ARV value is a more recently established method of EMG data reduction and is less well reported. The aim of the study was to establish the repeatability of peak and average rectified EMG data during maximal voluntary isometric contractions (MVIC) and core training exercises. Ten male highly trained athletes performed five MVIC and five core exercises on a single day, while one female performed the same exercises but over 3 days to establish between-day repeatability of the sEMG signal. The MVIC exercises resulted in peak EMG CV of 3-33% and ARV EMG CV of 8-27% for the multiple subject design, and values of 6-57% peak EMG CV and 8-51% ARV EMG for the single subject design. The core exercises resulted in peak EMG CV of 5-28% and ARV EMG CV of 2-28% for the multiple subject design, and values of 7-66% Peak EMG and ARV EMG CV 7-54% for the single subject design. Within-day CV (0-65%) was observed to be more repeatability than between-day repeatability (7-77%). It was concluded that both peak and ARV EMG methods provide a repeatable signal for some of the analysed core muscles and MVIC and core exercises performed.

---

**Chapter 4: Establishing the Level of Core Musculature Activity during Core Exercises to Determine the Content of a Core Training Programme (Phase I: Modelling)**

This section describes a laboratory based study in which muscular activity is recorded by sEMG on 11 participants. The aim of this investigation was to determine the activity levels in selected core muscles for a range of core exercises. Five female subjects performed one exercise within five different types of core exercise (static, dynamic low threshold, dynamic high threshold, asymmetrical and symmetrical) and six male subjects performed sixteen core exercises covering each of the five types of exercise. The five types of movements were found to influence the levels of muscle activation recorded for both peak and ARV EMG with the dynamic high threshold exercises eliciting the highest peak EMG levels, with the asymmetrical exercises resulting in high ARV EMG levels. During the sixteen core exercises, three muscles (RA, EO and RF) were found to be consistently activated over 60% MVIC while the other five muscles (IO, MF, LG, GM and LD) were consistently activated between 10 – 60% MVIC. It was concluded that the core exercises and the eight muscles contributed to core stability and core strength to varying extents during the exercises and that each type of core exercise resulted in sufficient levels of muscle activity (to develop core stability activity 10-25%; core strength, >60%) to potentially result in core ability enhancements. Based on the findings of this data, further conclusions could be made as to what type of exercise (i.e. dynamic or static, asymmetrical or symmetrical, low- or high-load) and what training intensity (i.e. duration, repetition rate) may be needed to result in training benefits on the core musculature.

**Chapter 5: Short-term Evaluation of a Core Training Programme (Phase I: Development of an Intervention)**

This Chapter outlines the implementation of a six week exploratory core training intervention programme in the target population. This forms the second stage of Phase I within the MRC framework [10]. The introduction section seeks to bring together the evidence including the supportive findings acquired during the thesis. The aim of this study is to quantify the effect of this core training intervention programme and evaluate it in terms of performance outcomes in highly trained swimmers. Fifteen highly trained swimmers performed the core training programme three times per week for six weeks. Performance tests were conducted pre- and

post-training to establish any training adaptations. It was observed that the performance levels of the core training group improved significantly during the countermovement vertical jump test. For example, pre-training jump height increased 10% from 24.7cm±4.5cm to 27.1cm±4.9cm post-training ( $P<0.05$ , effect size 1.3) and in many of the performance tests a trend for improvement was observed. For example, 50 m swimming time was 1.4% faster with 50 m swimming time improving from 29.7s±1.54s pre-training to 29.3s±1.44s post-training, (effect size 0.8) but at a non-significant level ( $P>0.05$ ). Significant changes in the core musculature activations levels were also observed for five of the core muscles (RA, EO, MF, GM and RF) analysed in the training group during some of the core exercises ( $P<0.05$ ). The findings suggest that these changes to performance and muscle activations may be heightened over a longer training period. Modifications were recommended for a longer term exploratory trial as a potential for a positive performance effect was observed in this shorter trial.

### **Chapter 6: Long-term Evaluation of a Core Training Programme (Phase II: An Exploratory Trial)**

The Chapter outlines a twelve week intervention training programme and establishes whether the longer training period results in a greater performance enhancement than that observed following the exploratory six week intervention programme. Previous research has concluded that as experienced athletes are highly trained to begin with, training adaptations are harder to achieve, potentially requiring a longer intervention period (twelve weeks). From the positive effects on performance observed in the exploratory six week trial intervention, it was proposed that by doubling the length of intervention, the performance effects would be heightened. Ten highly trained swimmers performed the core training programme three times per week for 12 weeks while a further ten swimmers formed a control group. Multiple performance tests were conducted pre-, mid- and post-training intervention programme and were compared (along with sEMG core musculature data for all subjects) to establish any training enhancements. Three performance tests (countermovement and squat jump heights and shoulder flexion strength) showed a significant improvement in performance following six weeks of training. This increased to four performance tests (maximal forward bridge hold test) following 12 weeks of training ( $P<0.05$ ). The remaining two performance tests also reported improved performances but not significantly so, however these still reported a strong potential beneficial

or trivial effect on performance when magnitude based inferences were calculated instead of statistical significance values (50m swimming time, 85.3%; sit-up bleep test, 59.2%). Muscular activations levels were also found to be significantly altered after six weeks and to a greater extent after 12 weeks of core training for the majority of the core muscles analysed ( $P < 0.05$ ). The Chapter concludes by highlighting that core training can improve performance and alter the muscle recruitment of the core musculature in highly trained athletes when a specifically designed core training programme is administered in a scientific manner.

### **Chapter 7: Development of a Theoretical Model to Design Core Training Programmes for Highly Trained Athletes**

The Chapter outlines the main findings of the previous chapters and summarises these in a theoretical model which may have use for the athlete and coach when looking to implement core training into their programmes. Two case studies are provided to show how this model could be affected by different training backgrounds of two swimmers.

### **Chapter 8: General Conclusions**

The Chapter provides an overview of the main findings from the previous chapters and the implications of these for the athlete and coach. The general limitations that occurred during the data collection studies and how these were minimised or controlled are discussed. Finally areas of future research which would provide further valuable knowledge regarding training core stability and core strength are highlighted.

# **Chapter 1**

## **Literature Review and Theory**

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## **1.1 Introduction**

Core stability and core strength training in the rehabilitation and sporting sectors have become extremely popular in recent years with many concepts and theories being suggested to improve an individual's core ability. It is believed that this helps to overcome an existing injury or weakness to the core musculature (rehabilitation sector) or enhances sporting performance by establishing efficient core stability and core strength to maximise performance (sporting sector). This Chapter looks to discuss these concepts and theories and highlight some of the remaining unanswered and confusing research findings published to date.

### **Aim of Chapter**

To review concepts and theory with regards to what is currently considered the most effective core training protocols based on research performed in the rehabilitation and sporting sectors.

## **1.2 Definitions of Performance, Core Stability and Core Strength**

What is referred to as the core varies greatly from study to study, with only a few studies including upper and lower sections of the body (i.e. the shoulders, hips and upper leg) along with the trunk muscles [11-14]. Furthermore, many studies fail to distinguish between core stability and core strength, two concepts which are fundamentally very different. The confusion over the precise definition of core stability and core strength is largely due to the fact that what is included in these processes differs greatly depending on what context they are viewed in. For example, in the rehabilitation sector, the focus is on rehabilitation following injuries causing lower back, arm and leg pain. Performing exercises which emphasise the control of spinal loading enables the general population to be able to perform everyday (low-load) tasks. This requires less core stability and core strength than highly trained athletes in the sporting sector who have to maintain stability during highly dynamic and in many cases, highly loaded movements [15]. The anatomy involved during sporting tasks includes much more of the body (i.e. shoulders and knees), which contribute in the transfer of energy from the larger torso to the smaller extremities through the body to produce effective sporting techniques. This results in a different definition of core stability and core strength when referring to sporting individuals.

Panjabi [16] concluded that core stability is the functional integration of the passive spinal column (e.g. vertebrae, ligaments and intervertebral discs), active spinal muscles (muscles and tendons around the joints) and the CNS that work together in a manner that allows the individual to maintain the intervertebral neutral zones while performing activities of daily living. Brown [17] stated that this was done by the muscular system of the trunk providing the majority of the dynamic restraint along with passive stiffness from the vertebrae, fascia and ligaments of the spine. Kibler et al. [18] summarised core stability in a sporting environment as the ability to control the position and motion of the trunk over the pelvis to allow optimum production, transfer and control of force and motion to the terminal segment in integrated athletic activities. While Akuthota and Nadler [19] summarised core strength as the muscular control required around the lumbar spine to maintain functional stability. Faries and Greenwood [20] provide clearer suggestions as to the difference between core stability and core strength for the rehabilitation sector by suggesting that core stability refers to the ability to stabilise the spine as a result of muscle activity, with core strength referring to the ability of the musculature to produce force through contractile forces and intra-abdominal pressure. This is different to the traditional concept of strength in the sporting sector which has been suggested by Lehman [11] as the maximal force that can be generated at a specific velocity by a muscle.

Due to the different demands placed on the body during sporting activities, more complex core exercises are trained (usually highly dynamic movements with added resistance) compared to those used for training the general population (mostly static in nature) [11]. As a result, the research findings performed with LBP sufferers and the general population cannot be extended to the athletic and elite sports performer. This inability to generalise findings together with the inconsistency of definitions of the core makes the collection and application of meaningful data difficult. Consequently, findings with regard to the effect of core training remain inconclusive and contradictory. It has been suggested, however, that it is important to have sufficient strength and stability for the body to function optimally in both everyday and sporting environments [21] and that by having sufficient stability and strength, athletic performance could be enhanced [22].

For the purpose of this thesis, what is referred to as the core, core stability and core strength needs to be clearly established. The core musculature will refer to all the musculature from the neck to the knees (including shoulder stabilisation muscles and the upper leg muscles). Core stability will refer to the production of muscle stiffness by the elastic components and ligamentous structures within the muscles which aids in the ability to minimise postural sway and spinal movement during loading and force production. Core strength refers to the increase of force generation to aid movement brought about by creating active stiffness in the muscles and force production through the core muscles.

### 1.3 Functional Anatomy of the Core

Lehman [11] identified certain muscles that are important to consider when analysing core stability and core strength. These include the transverse abdominis (TrA), rectus abdominis (RA), external oblique (EO), internal oblique (IO), erector spinae (ES) and quadratus lumborum (QL) muscles (Figure 1.1). Wilson [23] also found that the gluteus medius (GMe) and gluteus minimus (GMi) muscles play an important role in core stability (in assisting in hip extension and external rotation) helping to properly position and stabilise the pelvis.

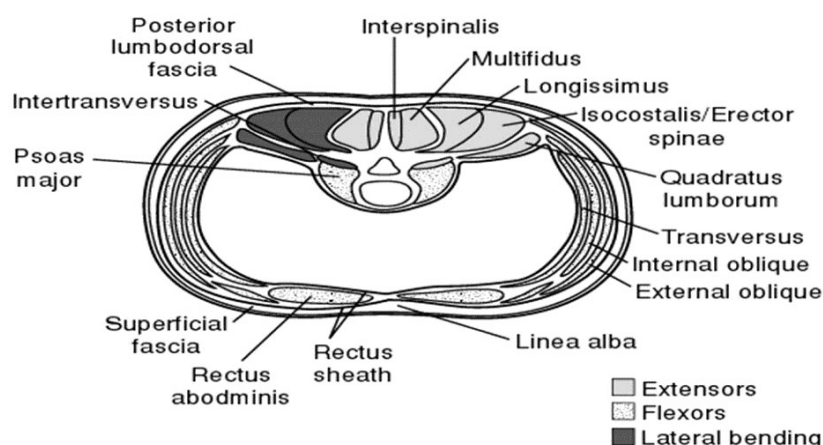


Figure 1.1. Anatomy of the core musculature. A cross-sectional view of the stabiliser and mobiliser muscles (modified from Weintraub [5]).

The contribution of these abdominal muscles to stability is related to their ability to produce flexion, lateral flexion, rotation movements and control external forces that cause extension, flexion and rotation to the spine [24, 25]. Comerford and Mottram [26] emphasize the importance of the RA muscle and believe that this muscle has a high recruitment threshold and is important in bracing the spine for high-load activities such as pushing or lifting heavy loads. The QL and MF muscles have a lower threshold of recruitment and mostly contribute to posture and stability [12]. The relative contribution and precise roles of these muscles to core stability and core strength is not clear and future research needs to be performed to establish these links [19]. For example, McGill [12] observed that the psoas muscle (the largest muscle in the lower lumbar spine) [27] is not involved in providing core stability, whereas Gibbons [27] reported that this muscle does have a stability role through axial compression and suggested that it was involved with lateral flexion, rotation and extension as well as hip flexion.

Core stability and core strength are required primarily to protect the lumbar spine from excessive loading and rotational movements which could lead to injury of the spine. Akuthota and Nadler [19] broke the processes that contribute to the stabilisation of the lumbar spine down into seven components:

1. Osseous and ligamentous structures: These structures are responsible for the passive stiffness that is imparted onto the lumbar spine. Any injury to these structures involving the tissue may cause functional instability of the spine. Excessive loading to the area may cause weak muscular control, leading to the disc no longer being able to provide optimal passive stiffness or stability [28]
2. Thoracolumbar fascia: This area provides a link between the lower and upper limb and works as a 'retinacular strap' of the muscles of the lumbar spine due to their orientation around the spine and acts as an activated proprioceptor [19]. The thoracolumbar fascia is built up of three layers; anterior, middle and posterior layers. The posterior layer has the most important role in supporting the lumbar spine and abdominal musculature.

3. Paraspinals: This component consists of the lumbar extensor muscles, which includes two major groups; the erector spinae and local muscles such as rotators and multifidus. The erector spinae muscles (longissimus and iliocostalis) are primarily thoracic muscles which have long moment arms that are ideal for lumbar spine extension [29]. The local muscles act as position sensors for the spinal segment and work as segmental stabilisers [30].

4. Quadratus Lumborum: This is a large, thin, quadrangular muscle that has direct insertions to the lumbar spine and is a major stabiliser of the spine [12]. Akuthota and Nadler [19] state that it consists of three major components; the internal oblique, external oblique and longitudinal fascicles (these have received much less attention than the transverse abdominal muscle). The external oblique muscle acts eccentrically in lumbar extension and lumbar torsion [19]. Akuthota and Nadler [19] reported that many fitness programmes fail to target and work the external oblique, so resulting in an imbalance. Exercises such as isometric or eccentric trunk twists can be performed to strengthen this muscle and aid in stability and strength.

5. Abdominals: These muscles are the most reported and investigated of the trunk muscles and serve as a vital component of the core and to its stability [31]. The abdominal muscle fibres run horizontally around the abdomen and consist of a number of individual muscles (for example, the RA; this forms part of the anterior abdominal wall and contributes to flexion of the lumbar spine). The abdominals have been shown to be active prior to limb movement in healthy individuals [32] which implies that these muscles are used as a preparatory stabiliser for the spine.

6. Hip girdle musculature: The hip girdle area has a significant role within the kinetic chain in transferring force from the lower extremities to the pelvis and spine [33]. Studies using people with LBP have identified poor endurance and delayed firing of the hip extensor (gluteus maximus) and abductor (gluteus medius) muscles, implying that these muscles also have a role in spinal stability [34, 35].

7. Diaphragm and pelvic floor: The diaphragm and pelvic floor muscles play a role in spinal stability. Studies have identified that inspiration and expiration during breathing

and the subsequent movement of the diaphragm has an important effect on achieving stability of the spine [36] (as contraction of the diaphragm increases intra-abdominal pressure which subsequently increases stability of the surrounding area which is then imparted on to the lumbar spine).

Leetun et al [15] reported that hip muscle activation significantly influences the ability of the body to generate force in the upper leg muscles and it has been identified that hip muscle activation is important to achieve core stability and/or core strength [37]. The hip muscle activation therefore leads to the knee being a victim of poor core stability, as the upper leg muscles have a large impact on the knee when trying to generate force from the upper leg muscles down through the knees to the floor [15]. Subsequently when researching the contribution and function of the core during movements, it is important to include multiple joints in the definition of the core; for example, everything from the neck to the knees, especially during dynamic sporting movements. Elphinston [14] investigated the gluteus maximus (GM) muscle and its contribution to spinal stability. The GM muscle has an essential role in hip extension and also in hip control [38]. A weak GM muscle therefore has an influence on the alignment of the lower knee and ankle which results in greater medial and rotational movement leading to an increase in stress and strain on the joints, predisposing to a greater injury risk [14]. A weak GM muscle also has a resultant effect on the opposing side LD muscle to compensate and try to maintain the tension in the fascia by alternative methods [14]. More research needs to be performed on the effect of poor core stability on the neck and knee muscles and joints and their performance during sporting movements and exercises [18].

One of the main core muscles to be researched in the past is the transverse abdominal muscle (TrA) [24, 39, 40]. As a result there are many reviews published regarding the contribution of this muscle to core stability [24]. In contrast other muscles are less well understood. Due to this, the TrA muscle will not form a large part of the current thesis as other important unanswered questions remain on the other core muscles and their involvement in core stability. However due to its importance to core stability, an understanding of this muscle is recommended. The TrA muscle arises from the iliac crest, lower six ribs and the lateral raphe of the thoracolumbar fascia and passes

medially to the linea alba [38]. McGill [41] suggested that the TrA has limited ability to move the trunk, but due to its horizontal fibre orientation, when it is contracted it leads to a reduction of the abdominal circumference and is responsible for the increase in tension in the thoracolumbar fascia and intra-abdominal pressure. Comerford and Mottram [42] support this view by concluding that the TrA muscle is used to control the intersegmental displacement of the lumbar vertebrae and is not involved in the movement of the spine. Due to the muscles ability to control the abdominal contents [43], it contributes to respiration by increasing expiratory air flow rate [44], decreasing end expiratory lung volume [45] and defends the length of the diaphragm [46] all of which help in controlling intra-abdominal pressure.

A number of models have been published that try to describe the core musculature and the complex integration of the processes that work together to bring about core stability. For example, Richardson et al. [47] described the core as a box with the abdominals anteriorly, paraspinals and gluteals posteriorly, the diaphragm superiorly and the pelvic floor and hip girdle musculature inferiorly. Bergmark [25] suggested a model for the core muscles that identified these as ‘local’ and ‘global’ muscles (depending on their role in establishing stability) and helped classify the different contributions of the trunk muscles to spinal stability (Figure 1.2). Bergmark’s model [25], identified ‘local’ muscles as those with attachments to the lumbar vertebrae and hence influenced inter-segmental control (e.g. TrA) and ‘global’ muscles, as those with attachments to the hips and pelvis and so influence spinal orientation and control the external forces on the spine (e.g. GM). It is important that both systems (local and global) are integrated to establish normal movement function. For example, if only the global mobiliser muscles are trained, a muscular imbalance occurs as they ‘take over’ the local stabiliser muscles role, resulting in restricted and compensatory movement patterns that are less efficient [48]. Stabilising muscles are responsible for posture holding and distributing and absorbing force in the body, whereas mobilising muscles contribute to rapid movement, force and power [25] due to their multi-joint positioning and large moment arms. All of these processes are important to train whether in the rehabilitation or sporting sector as they all contribute to performing movements safely and correctly.

Similar to Bergmark's 'box model' of the core, Comerford [42] suggests that the core is best represented as a double walled cylinder consisting of the lower and upper back, abdomen and chest (the trunk) (Figure 1.2). Comerford [42] also suggests that the pelvic and shoulder girdles must be included in any analysis of the core musculature. This is due to the shoulder girdle (the scapula) providing the linkage between the arm and trunk and the pelvis as the link between the legs and the trunk.

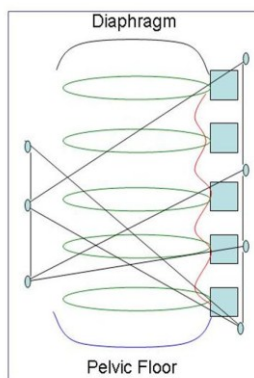


Figure 1.2. Schematic representation of the core musculature (modified from Comerford [1]). The dark squares represent the spinal vertebra, circular areas represent the abdominal muscles and diagonal lines represent the global mobiliser muscles with the red area representing the local stabiliser muscle location.

Stephenson and Swank [49] concluded that the core of the body is responsible for the transmission of force between the upper and lower halves of the body. This is supported by Tse et al. [50] who suggested that the core musculature includes the muscles in the trunk and pelvis.

### 1.3.1 Functional Anatomy of the Core during Sport

Roetert [51] reported that core stability and balance are critical for good performance in almost all sports and activities. This is due to the three dimensional nature of many sporting movements which demands that athletes must have good strength in the hip and trunk muscles to provide effective core stability. Roetert [51] suggested that some sports require good balance, some force production, others body symmetry, but all of these in turn require a stable core. Research suggests that a lack of core strength and stability can manifest itself in inefficient sports techniques and predisposes that athlete



to injury [52]. LBP is a common problem in any sport that requires significant twisting motions and repetitive flexion and extension [53-55].

An individual's core stability and core strength are vital when an individual's centre of gravity is moved outside the base of support (e.g. during many sporting movements). The individual subsequently needs to make postural adjustments to prevent a loss of balance and to reposition the centre of gravity back within the base of support [56]. This is achieved by using muscles in the core musculature to stabilise the lumbar spine and enable joint movement to take place [57]. The acceleration or deceleration of body segments during sports performance is determined by the ability of the core musculature to control the upper and lower extremities [58]. Therefore the core can be considered as the kinetic link between the lower and upper extremities and is vital in effective force transfer through the body [59] [18]. It does this by providing a rigid mass which the forces can easily travel through and not get absorbed by excessive and unnecessary movement of the lumbar spine and trunk [60] which also leads to a greater injury risk [76]. Willardson [59] suggested that de-conditioned core muscles would not be as effective in transferring forces through the body, resulting in greater compensatory stress on muscles, joints and connective tissues which would in turn increase the athletes injury risk. The effectiveness of core stability exercises for treating and preventing lower and upper extremity injuries has been widely observed in the rehabilitation literature [27, 232, 279]. However, much less research has been performed in the sporting sector, with minimal research performed looking at the effectiveness of core training programmes in enhancing healthy athletes core ability and subsequently enhancing their sporting performance [8].

Battinelli [61] and Watson's [62] definition of performance and the important factors that constitute this (genetics and environmental influences) and the trainability of these factors (muscle strength, joint mobility and the muscles capacity to do work) implies that an individual's core stability and core strength ability should have an effect on the subsequent performance of the individual. However, despite this strong theoretical link, there remains a lack of published research findings to support this proposal. One study that highlights the importance of core training and the impact on sporting performance was conducted by Abt et al [63]. Abt et al. [63] investigated the effect of

core stability on the mechanics of cycling. They observed that following a fatiguing core stability session, the lower extremity mechanics (mainly the knee joint alignment), core endurance and core strength were all reduced. Therefore, based on this study and others [24, 104, 121], it could be suggested that a strong core stability and core strength are required to maintain an efficient posture to enable force production and optimal technique and that it is important to train both of these processes to optimise sporting performance [19].

Previous studies [64, 65] have shown that an increase of only 1 - 3% of muscle tension or up to 25% of the maximum voluntary contraction (MVC) of a muscle is required to significantly increase the stiffness around the spine. This stiffness provides the required stability to sufficiently overcome external perturbation in the spinal region (Figure 1.3). As shown in Figure 1.3, only a small amount of muscle activation initially results in a large stability response. This is consistent up to approximately 25% MVC where the stiffness of the muscle is near maximal. Therefore relatively low maximal forces are required in a muscle to provide sufficient muscle stiffness to result in muscle and core stability. Muscle stiffness is produced by the visco-elastic properties of a muscle and the actin-myosin cross bridges that bring about contraction in a muscle. Muscle stiffness is brought about by a combination of intrinsic and reflex mediated muscle stiffness. Both types are trained by performing strength training (intrinsic stiffness) and motor control training (reflex stiffness).

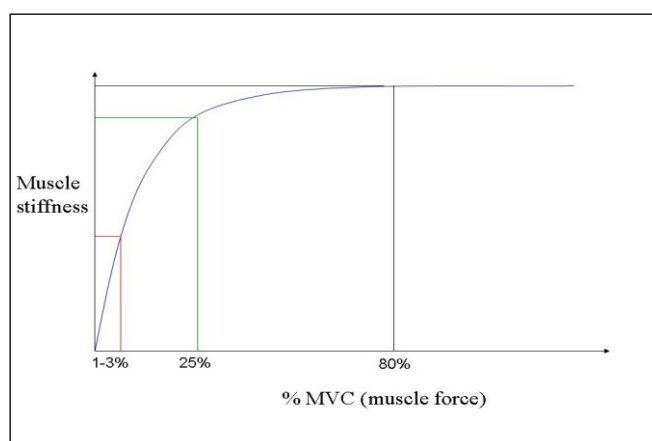


Figure 1.3. The relationship between muscle stiffness and muscle force (modified from Comerford [1]).

Hodges [24] suggests that the CNS controls segmental stability and orientation of the spine independently by recruiting the core musculature. This is implemented using a feed-forward activation mechanism. The need for a feed-forward response from a muscle occurs when the body moves a limb, the body configuration is altered and reactive forces are placed on the body that are equal in magnitude but in the opposite direction to that of the movement [66]. Pre-activation of the muscles by the CNS prepares for these reactive forces on the body prior to limb movement [67]. For example, Comerford and Mottram [48] conclude that there is an increased risk of injury to the back if the TrA muscles are not consciously activated prior to performing anything remotely strenuous. A lack of this feed-forward mechanism has been shown in LBP sufferers [68].

Hodges and Richardson [69] performed a series of tests which involved the TrA and superficial muscles in movements that were and were not planned and subjects responded to a stimuli. The TrA response time was constant but the superficial muscles response time varied, thus supporting the suggestions that the TrA performs a general, stabilising role to the core, with the superficial muscles having a more precise role in specific limb movement. Hodges and Richardson [39, 58] found that the TrA muscle was consistently the first muscle to be activated prior to limb movement (when rapid unilateral arm and leg movements were performed). This was supported by Hodges et al. [67] who used a kinematic movement system to analyse body movement prior to trunk movements being carried out. They found that prior to rapid bilateral shoulder movements there was a small but consistent motion of the spine in the opposite direction to the movement, therefore supporting the view that the CNS activates muscles prior to movement to ‘dampen’ the forces (rather than being rigid). Hodges [24] also concluded that the different influence of preparation for limb movement on the activation of the trunk muscles suggests that the CNS deals with segmental stability of the spine in a variety of ways. This has a significant implication on how the TrA and the other abdominal muscles are trained. For example, Hodges [24] concluded that the TrA muscle is controlled independently of the other trunk muscles and should be trained separately from the other muscles at a continuous low level activation.

Hodges [24] suggested that different movements in a range of directions place varying forces on the body and therefore results in changes in the direction of the forces acting on the spine. This variety of forces results in different activation patterns of the trunk muscles depending on the limb movement being performed. For example, the ES muscle is active significantly earlier during shoulder flexion than shoulder abduction or extension and a converse relationship is observed for the flexing abdominal muscles [39, 58, 70]. However, it has been found that the TrA muscle is active consistently, irrespective of the force direction [24] supporting the view that this muscle plays a vital role in overall spinal stability, irrespective of the type of movement being performed.

Comerford's [48] core stability model identifies local and global muscles and the concept of stabiliser and mobiliser muscles. Stabilising muscles are responsible for posture holding and the distributing and absorbing of force in the body[48]. In contrast, mobilising muscles (due to their multi-joint positioning and large moment arms) contribute to the increased movement, force and/or power of the limbs [25]. This helps to identify three categories in which the muscles can be placed depending on their functional role [48]; local stability role (increases segmental stiffness, controls excessive intersegmental movement and controls low-load challenges), global stability role (provides stability across joints) and global mobility role (produces movement and controls high-load challenges).

The different types of core stability and core strength exercises that are commonly performed in core training programmes involve many different types of exercises, such as; static, dynamic, symmetrical, asymmetrical, with and without external resistance and using stable and unstable bases. These different types of exercises result in different demands and subsequent muscle activation levels of the core musculature [222, 232, 233], with some activating the muscles to a higher extent than others [16, 92, 220]. Which type of exercise is most effective in improving an individual's core stability and core strength depends on the resultant muscle activation level and which ones are most sport-specific to sporting performance [71]. This has important implications for subsequent training programmes, as ideally, an individual should perform exercises that produce the same muscle activation each time and elicits the same level of muscle activation as in training. An exercise that sometimes produces a

high activation and other times a low activation would not be as effective as one that produces high muscle activity each time that it is performed. Therefore it is important to establish the muscle activation repeatability of such exercises on the major core muscles involved during these exercises, something which is yet to be established to any extent in the published literature but something which this thesis hopes to begin to answer.

### **1.3.2 Functional Anatomy of the Core during Swimming**

The freestyle swimming stroke is the main swimming technique using in training sessions [72]. It is therefore appropriate that this study focuses on this technique (reviews of the other swimming strokes can be found in previous literature [6, 73-76]). The freestyle swimming technique is made up of both arm (provides the main propulsive force, ~90%) and leg (controls the body position in the water) cycles which need to be timed to maximise the effectiveness of the swimming stroke [6].

During the freestyle swimming stroke, the legs perform a repetitive movement which involves hip flexion and extension, knee flexion and extension and ankle plantar and dorsi flexion [77] along with rotational movements of the shoulders and hips. These kicking movements are brought about by the muscle activation of the prime movers and global mobiliser muscles of the thigh (rectus femoris and gluteus) and calf (gastrocnemius and tibialis anterior) muscles which need to be timed to result in an optimal and effective production of power through the legs to result in an effective swimming technique (i.e. body roll, hand pull-through and arm recovery) [78]. Local stabiliser muscles (i.e. paraspinal muscles) are also recruited to help stiffen the core region and protect the spine during the rotational movements [77].

Souza [79] summarised the freestyle swimming stroke into three phases; catch, pull and recovery. Rouard et al. [80] provides a comprehensive summary of each of the three phases during the freestyle swimming stroke and readers are recommended there for further detail. During these three phases, Coulson [6] suggests that there are five phases to the arm cycle during the freestyle swimming stroke; recovery, entry and catch, out sweep, in sweep and press. Pink et al. [73] identified that global mobiliser muscles such as; the upper trapezius, rhomboids, serratus anterior, pectoralis major,

latissimus dorsi and deltoid muscles are all involved in the arm cycle. This is supported by Rouard et al. [80] who suggest that the flexor carpi ulnaris and the latissimus dorsi muscles are the main active muscles during the freestyle swimming stroke. Many swimming coaches and researchers have outlined the optimal freestyle swimming stroke technique to optimise performance [6, 81-83]. This optimal stroke reduces drag, maximises energy transfer through the body and subsequently results in an efficient technique to move the body through the water utilising as little energy as possible to postpone fatigue [73]. Coulson [6] concluded that an efficient swimming stroke will significantly reduce wasted energy output through less drag in the water and a cleaner execution of the hand and arm entry during the recovery phases.

Fig [22] suggested that the orientation and positioning of the core muscles assist in overcoming the demands of swimming which requires rotation between the hips and shoulders. This is due to the core being most effective in generating power when creating rotation between the hips and the shoulders due to the diagonal nature of the muscles in the core, working together as a unit known as the Serape effect [13]. Santana [13] suggested that the serape effect is the result of four pairs of muscles interacting; the rhomboids, the serratus anterior and the external and internal oblique muscles. Fig [22] concluded that this movement occurs mostly in the freestyle and backstroke swimming techniques and improving the ability to generate this rotation will ultimately increase the power and speed of the swimming stroke.

Pollard and Fernandez [78] suggest that the body roll seen during the freestyle swimming stroke (where the upper body rolls through 160 degrees) is an important part of maintaining an efficient swimming stroke (as the roll enables the arm and hand to pull through the water and decreases the drag through the water by reducing the cross sectional area of the body pushing through the water) [84]. The roll of the body is a result of the activation of the paraspinal and core muscles such as the abdominal muscles [84]. Research has identified that one of the main differences between elite and recreational swimmers is the lack of body roll in non-elite swimmers which is a result of a lack of strength in the core musculature to effectively produce this roll action [77].

The main injuries seen in swimmers are to the shoulder (i.e. rotator cuff tears and tendonitis) and back (i.e. posterior facet irritation and spondylolisthesis) muscles [82]. Gauvin [82] stated that shoulder injuries alone were experienced by 50% of swimmers. Shoulder stability has been shown to be essential in reducing injuries and performing an efficient swimming technique [18]. Kibler [85] suggested that shoulder injuries are reduced by targeting core stability first and then shoulder stabilisation. For example, it may be that by increasing the ‘body roll’ during the swimming stroke, this would reduce the arm abduction needed which would result in less stress on the rotator cuff muscles of the shoulder, subsequently reducing the potential injury risk to this joint. Furthermore, lower back muscles (such as the MF muscle) have been shown to be trainable to improve stabilisation and strength by the use of core stability exercises [30]. If suitable core stability and strength can be achieved by the swimmer, the forces (as a result of the excessive twisting and rotation of the shoulders, lower back and upper legs) will be reduced and therefore decrease the likelihood of an injury [13].

Gauvin [82] suggests that injury occurrence in swimming is declining due to the improved understanding regarding the biomechanics of swimming, injury prevention and treatment of swimming injuries. Gauvin [82] suggests that the increase in numbers of swimmers performing core strength and endurance training may be a significant factor in this recent injury reduction. It may also go some way to understanding the continual improvement in swimming times observed in many major international swimming championships recently [86].

An increase in core stability enables more power to be generated in rotation between the hips and shoulders as less energy is lost in the kinetic chain between these limbs [6]. Increased movement of the trunk increases the drag and turbulence created reducing the efficiency and speed of the swimmer (Figure 1.4) [13]. Souza [79] suggested that an individual’s injury risk is increased when asymmetrical body roll or unilateral breathing is present as these result in a compensatory crossover pull-through on the side with less roll. This has led to body position, balance and core strength being trained in swimmers. As a result, one of the recommended coaching techniques for the freestyle swimming stroke emphasises an early catch, straight pull-through and early exit of the water with the arms [77]. This results in an equal body rotation (45

degrees each side) and balance and encourages good core stability and core strength [83]. Therefore good core strength and stability can be an important part of injury-free swimming and subsequently lead to a more effective technique and improved swimming performance [82].

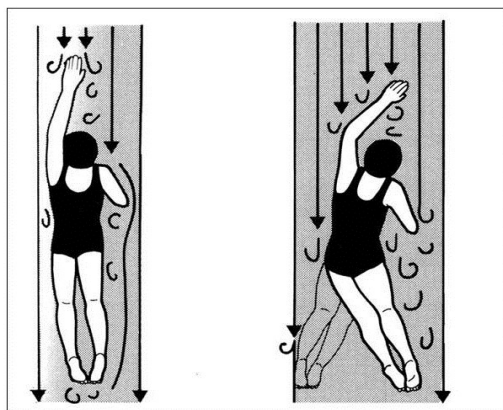


Figure 1.4. The importance of core stability when swimming to decrease drag and turbulence (modified from Coulson [6]).

#### 1.4 Types of Core Training

Training core stability and core strength has been promoted for a number of supposed benefits to the body; for example, as an injury prevention regimen, a form of rehabilitation for lumbar and musculoskeletal injuries [60] and as a sporting performance enhancing programme [19]. Core strengthening has become a major trend within the rehabilitation sector [87]. Rehabilitation programmes include processes that combine lumbar strengthening, motor control training and other regimens which aid individuals in regaining normal body movements following trauma to the body structures. Research has shown that a number of methods can enhance neuromuscular control and joint stability [88-90]. These include; contraction exercises, balance training, perturbation (proprioceptive) training, plyometric (jump) exercises (plyometric training which emphasises the loading of joints and muscles eccentrically before the unloading concentric activity) and sport specific skill training [11]. Many physiotherapy programmes use exercises that challenge proprioception using equipment such as; wobble boards, roller boards, and swiss balls [90]. Comerford [42] suggests that core stability training includes exercises that vary from imperceptible activation of the deep abdominal muscles to lifting weights overhead whilst balancing



on a swiss ball.

In many strength training programmes, it is common for only the global mobiliser muscles to be trained, and subsequently a muscular imbalance occurs (due to these muscles ‘taking over’ the stabiliser muscles role) which results in restricted and compensatory movement patterns that are less efficient [1]. It is important that both systems (local and global) are integrated to establish efficient and normal movement function [25].

Increasing muscle stiffness is an important role of the local stabiliser muscle group. Hodges [24] suggested that the contribution of the superficial stabilising trunk muscles, such as, RA, EO, IO and the ES to trunk orientation and posture are more straight forward than the TrA muscle. Cresswell [91] observed, during dynamic resistance exercises (when lying on ones side) RA, EO and IO muscle activation occurring at the end of trunk extension, which acts to decelerate the trunk. Comerford and Mottran [26] outlined the importance of the RA muscle and suggest that this muscle is important in bracing the spine for high-load activities such as pushing or lifting heavy loads and has a high recruitment threshold. The oblique muscles (EO and IO) have a lower threshold of recruitment and mostly contribute to posture and stability. Therefore, Comerford and Mottram [26] conclude that if one wants to improve core stability, it is these muscles (EO and IO) which need to be targeted and emphasised in training. Cresswell [91] also observed pre-activation of these muscles prior to trunk movement, suggesting that the CNS also controls the oblique muscles (similar to the TrA muscle) to overcome the challenges of controlling orientation and the centre of mass changes as a result of limb movement.

#### **1.4.1 Types of Core Training in Relation to Sport**

When looking to train the core muscles and target core stability or strength, there are many forms of exercises that have been used to try and achieve performance benefits. Performing these exercises is believed to result in changes to systems such as; local and global muscle motor control and traditional strengthening of the core and limb muscles [1]. In order to train core stability and core strength it is important to perform both low-load and high-load threshold training [1]. This integrated training approach

is outlined in Figure 1.5. Due to the different processes and training methods of the core musculature (e.g. low- and high-load training), Comerford [48] established further definitions to summarise the processes involved when analysing the core musculature and suggested when these processes should be trained using low- and high-load training methods. For example, motor control stability could be targeted by performing low threshold exercises while core strengthening results from high threshold (high-load) exercises which recruit the muscles to a greater extent. This highlights the importance of performing both low and high threshold core training to potentially result in core stability and core strength benefits. Definitions of these training factors are outlined below;

*Motor Control Stability*; low threshold stability where the CNS modulates the efficient integration and low threshold recruitment of local and global muscle systems

*Core Strength Training*; high threshold or overload training of the global stabiliser muscle system and leads to hypertrophy as an adaptation to overload training

*Systematic Strength Training*; traditional high threshold or overload strength training of the global mobiliser muscle system

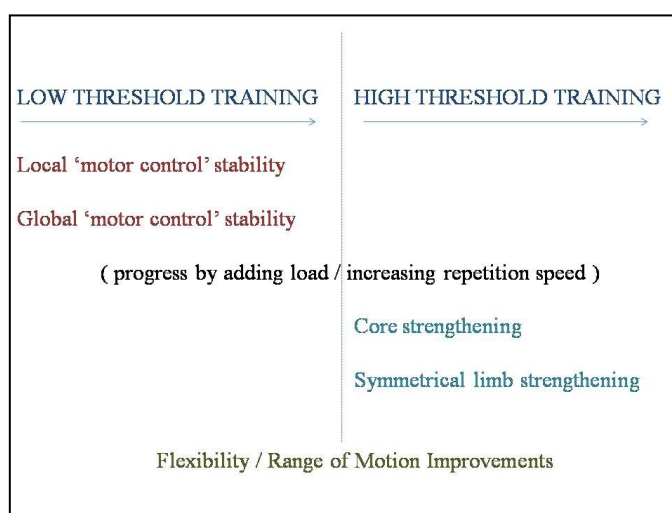


Figure 1.5. Training adaptations following low and high threshold training methods (modified from Comerford [1]).

An understanding of the differences between the types of training is vital to have an understanding of the characteristics that are important to include in an individual's core stability programme, for example, activation threshold level, muscle emphasis, position and direction of muscle loading and type of muscle contraction involved [48]. Training programmes attempting to correct weak links in an individual's core ability include strategies that regain control of the site and direction of the deficiency at the appropriate threshold of training. It is proposed that the core musculature does this by; increasing joint range and muscle extensibility, improving joint stability, enhancing muscle performance and optimising movement function [92]

Due to the different functional roles of the muscles (local and global and stabiliser and mobiliser roles) a range of training exercises for these muscles needs to be employed to improve the muscles ability to function. Various low and high-load exercises should be performed to challenge the core musculature in all directions and ranges of movement to develop total core stability [25]. For example, a range of movements that target the hip flexors and back extensors (i.e. the abdominal and glutei muscles) that include flexion exercises (e.g. curl-ups, leg raising and squats with rotation), extension exercises (e.g. targets hip extensors and hamstrings) and rotational exercises [93] of varying intensities could be performed. Research stating whether there are any benefits of specific core stability or core strength exercises in activating the core muscles is limited and conflicting due to the wide variety of data collection methods, exercise techniques and range of subjects used during studies. However it has been established that there is not one single exercise that activates and challenges all of the core muscles [60], therefore a combination of exercises is required to result in core stability and strength enhancements in an individual [94, 95]. The choice of exercise is important as the magnitude of the muscle activation (low or high-load) and the recruitment pattern of the motor units determines whether core stability or core strength is developed.

Low-load and high-load training involves different types of movements, for example, low-load training involves less demanding, posture related exercises which focus on muscle recruitment, whereas high-load training can involve exercises such as overhead weighted squats and hanging leg raises, which place a greater stress on the core musculature and promotes core strength development [96]. As a result of training,

different physiological adaptations occur within the muscles, potentially resulting in an improved strength or recruitment of the muscles. These adaptations are hugely dependent on the length and type of core training programme that is being implemented [49, 71, 97, 98].

In most elite athletes training programmes, power, strength, endurance and flexibility are all emphasised [99]. This is based on the relationship between force, power and stability and that by strengthening the core and limbs it is believed to benefit overall sporting performance. However, most of these training programmes fail to include low-load motor control training which has been identified as an essential part of core strength training and improving core stability [1]. It is proposed that initial core strengthening programmes should enable people to become aware of motor patterns and allow them to learn to recruit muscles in isolation [93]. Programmes can then progress to functional positions and activities (Table 1.1) [19]. Vezina and Hubble-Kozey [100] suggested that core training programmes should focus on emphasising proper sequencing of muscle activation, coactivating synergistic muscles and restoring muscle strength and endurance to key trunk stabilisers. Akuthota and Nadler [19] suggested that re-learning the motor control of inhibited muscles may be more important than strengthening in patients with LBP. In this case it may be that improvements in performance are as a result of improved neural co-ordination and recruitment rather than specific improvements in core strength or stability. Careful performance measures are required in studies to identify which of these is ultimately trained following intervention programmes.

Many training programmes focus on the high intensity (high force, end-range joint and muscle stretching), strength-biased muscle training which can lead to a contribution to injuries [92]. It is important to incorporate low-load motor control stability training as well [1] (see Table 1.1). By neglecting the local muscles, the force produced by the global muscles will be too great for the local muscles to control and result in greater injury risk [20].

Table 1.1. Guidelines for training the core components. Based on Comerford [1]).		
Core Strengthening (Trunk)	Motor Control Stability (Global)	Motor Control Stability (Local)
Fatiguing high load exercises	Non fatiguing low load exercises	Non fatiguing low load exercises
Asymmetrical and symmetrical limb loading	Asymmetrical limb loading	Train in different postures
Rotation challenge	Trunk not move out of neutral (isometric)	Trunk does not move out of neutral
Emphasis rotation control at trunk	Emphasis rotation control at trunk	Allow global stabiliser co-activation
Discourage global mobiliser dominance	Short range hold for postural control	Discourage global dominance
Encourage core rigidity	Discourage core rigidity	Discourage core rigidity

Stephenson and Swank [49] suggested that to develop a strong and stable spine, one needs stability, flexibility and strength training of the core in all three planes of motion. They stated some basic requirements of a core strength programme; flexibility of the abdominal and lower back, hip extensor and flexor muscles, the need to perform exercises in an unstable environment and that the exercises performed are isometric and dynamic (develops tension and stabilisation of the spine). For strength training, they stressed the importance of the principles of overloading and functionality when training the core muscles.

Functional progression of exercises is one of the most important components of a core strengthening programme [19]. Comerford [48] suggests that in the clinical setting, it is usually believed that a linear framework should be followed for training programmes; for example, stability training starts with local motor control training (build spinal stability and strength and muscle coordination) [42] and progresses through global motor control to core strengthening and finally to high-load traditional muscle strengthening (dynamic movements while maintaining the good core stability) [99]. However, Comerford [48] believes that there is no evidence to support this linear framework and that each individual needs to have their own specific programme that progresses for their individual needs. The exercises performed in the training

programme must progress from training isolated muscles and basic core exercises to training as an integrated unit (dynamic multi-limb movements) to facilitate functional activity [49]. Exercises can be progressed and made more complex by for example starting from non-neutral positions which further challenges the core musculature [19]. However, it is essential for individuals with instability or recovering from an injury that stretching and advanced exercises are used with caution, as this places greater stress on the area where there is lack of current support [12].

Lehman [11] emphasises that periodisation is important in any training programme. This periodisation concept changes the programme variables (volume, speed of movement, exercises performed, and intensity) and the main emphasis of training over a set period of time. This trains the different muscular characteristics (i.e. hypertrophy, absolute strength, and power) giving an all round training effect for the athlete. The process is based on the idea that the body continually adapts to changes in stimulus and habituates to a constant stimulus [101]. The periodisation periods can be long (months) or short term (weeks) which are then followed by a maintenance phase [102].

The overloading principle is a common principle used in many training programmes and is required to bring about a performance effect [99]. However, it is important that the individual is not overloaded too much (hence it is essential that a pre-intervention assessment is performed before any intervention or training programme takes place). McGill [29] suggested that this principle of overloading may predispose individuals to injuries. For example, traditional sit ups increase the compression loads on the lumbar spine [103] and pelvic tilts increase spinal loading. Alongside this these exercises can be argued to be non-functional to everyday movements [29]. Therefore it is important that any core training programme is properly established and monitored for each individual.

Depending on what the outcome goal is for the core training programme, the emphasis of the training programme will focus on improving one or more of the following aspects of core ability; muscle stability, strength, endurance or power. Many researchers have concluded that to achieve enhanced core ability, core strength is more important than core stability [11, 71], while others have suggested that training core

endurance is the priority [95, 102, 104]. What is agreed is that there are different processes which contribute to achieving a strong core (stability, strength, endurance and power) and that it is important to focus training on each of these components to prevent weaknesses developing within the core musculature [19, 105].

It may be that for elite athletes, core endurance is more important than core strength [104]. The ability to maintain posture for example is essential in many sporting techniques to enable an efficient performance. It may be that only lower levels of muscle contraction are required (to maintain a body position) but for long periods of time. Lehman [11] suggests that due to only requiring a minimal level of muscle contraction to stabilise the spine (<25% MVC, Figure 1.5) core endurance may be more important than core strength and subsequently identifies exercises such as; the curl-up, bird-dog, side and front bridge support and the weighted squat to develop core muscle endurance. These exercises challenge all of the anterior, lateral and posterior trunk muscles and sufficiently stress the muscles but do not exceed the thresholds for compression and shear loading which may predispose the body to injuries. This is supported by McGill [12, 56] who suggests that core endurance is more important to stability than core strength. Similarly, Faries and Greenwood [20] suggest that endurance should be trained before strength (therefore focusing on establishing the correct motor control systems prior to increasing the body's strength). They also suggest that endurance training focuses on low-load, longer (30 - 45 seconds), less demanding exercises, while strength exercises are based on high-load, low repetition exercises. For example, Lehman [11] encourages the use of the weighted squat as a high-load exercise. He suggests that this is an excellent example for a core training exercise as the entire anterior, lateral and posterior core muscles as well as the shoulder stabilisation muscles are active thus ensuring that the spine does not buckle.

Lehman [11] outlined strength as the maximal force that a muscle can generate at a specific velocity and suggests using resistance training to increase strength. Six or less repetitions per sets equals approximately 80% of an athlete's one repetition maximum (the maximum amount of weight an individual can lift in a single repetition for a given exercise) [61] which is the current recommendation for building strength from the National Strength and Conditioning Association (NSCA) [106]. Lehman [11] outlined

a core training programme in which exercises are performed two times per week on separate days where strength and power exercises are not performed with weights being increased with observed improvements in core strength and endurance. It has been widely observed that following a period of resistance training, power, strength and / or endurance can be improved due to muscle adaptations resulting from the stress placed on the muscles [107]. These adaptations include metabolic and morphological changes [108]. Morphological changes include improvements in motor unit recruitment, firing rate and synchronisation [109]. Metabolic changes include alterations in the protein synthesis which account for the motor unit adaptations [107]. These changes involve an increase in the key enzymes in the mitochondrial electron transport chain and an increase in mitochondrial protein concentration [107]. Muscle hypertrophy is also well reported following high training stimulus [108] and results from subcellular changes within the trained muscle (more and thicker actin and myosin protein filaments, more myofibrils, sarcoplasm and connective tissue surrounding the muscle fibres) [110]. It is believed that morphological adaptations occur as a result of lower threshold training (muscle activation levels of 1-60% MVIC) with metabolic adaptations also occurring for activations of >20% [107]. Muscle hypertrophy adaptations result from the higher activations and high threshold training demands which stress the muscles to a greater extent (>60% MVIC) [108].

Lehman [11] defined power as the rate of work or the product of force and velocity of the movement. Power production is improved by heavy resistance training (resistance; >80% one repetition maximum) and explosive exercises (weight 30 - 60% one repetition maximum and accelerate maximally) [101, 111], for example, the power clean or clean and jerk and the squat jump with additional weights. These exercises increase the explosiveness of an athlete by increasing the force developed at a high velocity. It is still important that any training performed is specific to the actual sport the athlete performs as strength gains are specific to the velocity that the athlete trains [71, 112]. Therefore this type of core training would only be recommended for certain sports individuals where power is essential.

The different emphasis that core training programmes can take to target principles of core stability and core strength have been highlighted above, all of which theoretically



could lead to improvements in an individual's core ability. What effect, if any, the training programme has on actual performance of the required movement depends on how transferable the improvements in core stability or core strength are to the actual performance movement. There are a huge amount of training programmes available on the internet and in books that provide core training programmes for all types of individuals from the elderly and injured to world class athletes. However many of these have not been assessed for their effectiveness in targeting the required muscles to the necessary activation levels to result in the optimal performance enhancement. What is well established is that certain factors of the training programmes affect how effective they are, for example, type of movements (i.e. static or dynamic) [12], the speed that the exercises are performed at [58], amount of added weight resistance [57] and the duration the training programme [101].

#### **1.4.2 Types of Core Training in Relation to Swimmers**

Scovazzo [113] suggests that muscles can be activated to 15 - 20% MVC before they are susceptible to fatigue. Swimming research has found that many of the muscles involved in the arm cycle during the freestyle swimming stroke are activated above this level[80] and therefore are fatigued when swimming which puts these muscles at a greater risk of injury. Due to this, the stabilisation and strength of the joints around the shoulder and trunk is essential [85]. Santana [13] identified a number of exercises that can be performed to strengthen the muscles involved in the swimming stroke, for example traditional strength lifts such as; squats, bench press and pull-ups along with exercises that provide loading, resistance and body rotation.

Gauvin [82] suggests that a standard strengthening programme for swimmers should consist of isolated and combined limb movements, dynamic exercises and strength and endurance training exercises which should be performed in sets to fatigue or ten sets of ten repetitions to optimally train the small stabilising and endurance muscles. This is supported by McGill [56] who suggests that spinal stability training should emphasis endurance rather than strength. Traditional methods of core training for swimmers include the use of stretch cords and swim benches which both stimulate the arm action of swimming (and incorporates the diagonal kinetic chain between the shoulders and hips which generates the effective rotational power during the swimming stroke) [22].

Juker et al. [103] found that during a twisting exercise the EO muscle was activated to 52% MVC which highlights the importance of this muscle during this type of exercise. Other training methods include resistance machines and free weights involving multi-joint movements. A core training programme should be included alongside the pool-based swimming training program and should be designed to incorporate periodisation periods to allow for neuromuscular adaptations [114]. Goldby et al. [115] suggests that between three and six months is required to adapt the body following the identification of a weakness in technique or following an injury.

In swimming, traditional methods and exercises that are used to train the core stability and core strength of swimmers include those that use equipment such as, swim benches and stretch cords [116, 117]. However neither of these specifically involves the core musculature. Resistance machines and free weights are also used [118, 119], but these exercises are usually only in one plane of motion and use only one joint movements, so are not representative of the sporting movement. It has been clearly identified that it is important to involve movements that are sport specific. For swimming, this would involve exercises having a focus on loading the full length of the body (chest, shoulders and back, hip and leg strength) [82].

### **1.5 Techniques for Measuring Muscle Activity**

Electromyography (EMG) is a technique for evaluating and recording the electrical activity produced by skeletal muscles [120]. The technique measures the electrical potential generated by muscle cells when they are recruited and contracted. Typical EMG potentials range from  $<50 \mu\text{V}$  up to 20 – 30 mV depending on the muscle being analysed [4]. The electrical potentials are generated when motor units (motor neuron and the muscle fibres it innervates) are activated which releases an impulse (action potential) that travels along the motor neuron to the muscle via the neuromuscular junction (where the nerve and muscle connect) [121]. The impulse then generates the action potential in the muscle fibres of that motor unit (creating a motor unit action potential, MUAP) [122]. Multiple motor units that are activated then formulate the measured EMG signal [120]. Different methods of EMG data collection are possible with fine-wire electrodes and surface electrodes being the most common methods [121]. Surface EMG (sEMG) is used for recording muscular activity from superficial

muscles, whereas intramuscular (needle) or fine-wire electrodes are used for deeper positioned muscles or localised muscle activity data analysis [121].

To perform fine-wire EMG analysis, a needle electrode containing two fine-wire electrodes is inserted through the skin into the muscle tissue. The use of fine-wire electrodes when performing EMG analysis does reduce the likelihood of experiencing cross talk between muscles [122], however this method also has its limitations especially when performing dynamic movements. Fine-wire EMG analysis has many ethical issues, for example, the procedure is very invasive and can cause discomfort during and after the movements have been performed. The accurate placement of the needle electrodes also needs guidance using ultrasound to get the placement in the muscle correct. This requires expert knowledge and experience in both ultrasound and fine-wire EMG analysis [68]. As a result, the use of surface EMG electrodes is commonly used instead to monitor the general activation of the muscle rather than localised muscle fibres (as with needle electrodes).

Researches investigating the core musculature that have used EMG analysis have predominantly used surface EMG to collect the muscle activation data [90, 97, 100, 123, 124]. Surface electromyography is a technique used to measure muscle activity non-invasively using surface electrodes placed on the skin overlying the muscle [120]. sEMG has been used extensively in the literature to analysis a variety of muscle characteristics during body movements, such as onset timings of muscles [67], muscle activity amplitude [100] and effects of fatigue on muscle activity [50]. However the limitations of sEMG have been well reported in the literature [120-123] and include the issues of cross-talk (signal interference from other muscles) which makes it difficult to identify the origin of the electrical signal when two or more muscles that lie in close proximity to each other are active simultaneously [121]. However, theoretical models developed by Fuglevand et al. [125] and Winter et al. [126] indicate that very little cross talk occurs from muscles when performing sEMG. Both studies indicate that up to 90% of the EMG signal is picked up within 10 – 12 mm of the surface electrodes when electrode spacing of 20 – 25 mm is used. Therefore it can be suggested that sEMG is appropriate for the data collection on superficial muscles [126]. sEMG is a good representation of the whole muscles level of activation and it has been reported

that the reliability of the sEMG signal is better than analysing muscle activity using intra-muscular electrodes [74, 127-130]. This may be due to the complex nature of placing intra-musculature electrodes in the muscle [68, 90, 124]. Therefore if sEMG can be used accurately to measure muscle activity during these exercises, the ethical issues and added complexity associated with fine-wire EMG data collection can be removed from the study. Therefore it is essential that sEMG data collection procedures are tested to make sure they result in repeatable data.

### **1.5.1 Techniques for Measuring Muscle Activity in Relation to Swimming**

sEMG has been used in the past to investigate the muscle activation during different swimming strokes [7, 72-74, 113, 131]. These have focused on muscle timings, activation and effect of injury on muscle activation. From previous research, Clarys and Cabri [77] suggest that 44 muscles have a major involvement in the freestyle swimming technique with all skeletal muscles (over 600 muscles) involved to some extent [7]. The timing of the muscle contractions during the swimming stroke is essential for an efficient stroke [77]. Ikai et al. [75] were the first to study muscle activations during swimming and reported the activation of 15 muscles in university and Olympic level swimmers. Ikai et al. [75] stressed the importance of the mobiliser muscles during the freestyle swimming stroke especially the latissimus dorsi, deltoideus and teres major muscles. Lewillie [76] concluded that the EMG activation is determined mostly by the swimming stroke rather than the swimmer and that highly skilled swimmers are able to reproduce a similar pattern of activation during the swimming stroke. Nuber et al. [74] provides a detailed overview of the activation of the arm muscles during the freestyle swimming stroke (with different muscles showing a range of activation levels during the different phases of the stroke) highlighting the importance of the timing of these contractions and showing that different muscles are more dominant at different phases of the swimming cycle.

Clarys [72] investigated 25 superficial muscles involved in the freestyle swimming technique and reported the extent of the muscle activation during the swimming stroke. They reported that most of the muscles (20 out of 25) had two contraction peaks during the gliding, pull and push phases, with a relaxation period during the recovery phase. The latissimus dorsi was activated for the largest part of the swimming cycle (92%)

(also supported by Dalla Pria Bankoff and Vitti) [131] followed by the rectus abdominis inferior (91%) and superior (83%) (Figure 1.6). The gluteus maximus (superior) was active for 80% with the external oblique muscle active for 28% and the rectus femoris muscle for 22%. This highlights the importance of the core muscles during the swimming cycle as well as the arm and shoulder muscles.

Rouard et al. [80] investigated the upper extremity muscles when swimming using the freestyle swimming technique to exhaustion. They identified maximum integrated EMG values that averaged between 40 and 70% during the swimming stroke with certain phases resulting in activations of up to 90% (for example, biceps brachii during the insweep phase of the stroke). They observed that the insweep, or pull phase of the stroke resulted in the greatest muscle activation of the arm muscles, with the later pull / outswEEP phase resulting in the highest maximal force and hand velocity. Rouard et al. [80] also identified that the stabiliser muscles during certain phases of the stroke (such as the triceps brachii during the insweep phase) increased in activation as fatigue increased. They suggested this was due to the heightened demand for joint stability as the prime movers fatigued.

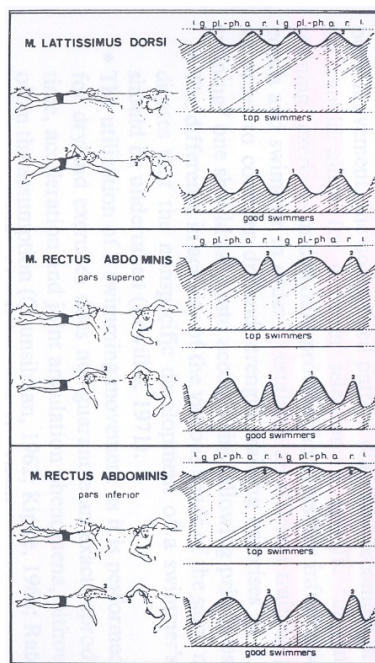


Figure 1.6. The muscle activity of two major contributors (latissimus dorsi and rectus abdominus) to core stability during the freestyle swimming stroke (modified from Clarys [7]).

Due to the important activation of the core muscles during the freestyle swimming stroke observed in previous research [77, 80] it can be suggested that core stability and core strength are factors that could help improve swimming technique. By having good core stability and strength this could enable the efficient transfer of forces through the body to propel the body through the water and reduce the injury risk to the swimmer by establishing an efficient muscle recruitment process [82]. The lack of depth of research on muscle activation levels of the core musculature (especially the core stabiliser muscles) during swimming prevents more knowledge being available regarding the demands on these muscles during the swimming stroke and establishing whether training these processes could improve subsequent swimming performance.

In conclusion, the freestyle swimming technique has been researched using EMG, with the technique broken down into phases and the major muscle groups and roles clearly defined, with the arm and leg muscles receiving the main focus. The core musculature has received less interest, possibly due to the more complex nature of gathering this information. As a result the exact contribution that these muscles provide during the swimming cycle is limited along with any firm conclusions regarding what impact improving swimmers core stability and core strength has on actual swimming performance. The current thesis will attempt to establish some of these unanswered questions by collecting and analysing data collected during core training exercises in swimmers and establishing and evaluating a comprehensive core training programme implemented over a number of weeks.

### **1.5.2 Techniques for Measuring Muscle Activity in Relation to Core Exercises**

Axler and McGill [94] used sEMG to investigate 12 abdominal exercises and attempted to quantify the muscle activation of selected muscles during these exercises and establish a challenge to cost indice for each exercise in regards to the spinal loading. They observed that the full sit-up generated the highest compressive forces on the spine, with the hanging leg raise producing the highest abdominal muscle activation. Axler and McGill [94] concluded that there is not one exercise that can be used to optimally train all of the abdominal muscles and minimise spinal loading. Therefore which exercises should be used in a training program depends on the individuals

athletic ability, for example an exercise that may be advantageous for one person may be harmful for another if they have back problems or a weaker core stability and strength to begin with [94].

Certain core stability and core strength exercises are more effective in activating the chosen core muscles than others [94]. Research on this is limited and is conflicting due to the wide variety of data collection methods, exercises techniques and subjects used for analysis. Although it is commonly accepted that there is not one single exercise that activates all of the core muscles [56, 94]. As such, a combination of exercises is required to result in overall core stability and strength enhancements in an individual [29, 94]. McGill [12] has suggested that to train the QL and the EO muscles, the ideal exercise is the side bridge, as this minimises lumbar spine loading but still activates the muscles to 50% of MVC. For activating and training the RA and TrA muscles, the curl-up exercises have been found to be optimal [95]. Back extensor exercises usually involve high spinal loading and care needs to be taken when performing these exercises [93]. The single leg extension exercise and the birddog exercises have been found to minimise this spinal loading while maximising back extensor muscle activation (18% MVC and 27% - 45% MVC respectively) [12]. This previous research highlights the varying levels of activation of the core musculature during different types of core exercises and emphasises the importance of establishing these recruitment levels to be able to design an optimal training intervention programme.

Urquhart et al. [124] analysed the postural activity of the TrA muscle and summarised the effect of different body positions on the subsequent muscle activity. The TrA muscle is made up of a number of different regions and Urquhart et al. [124] concluded that there are regional differences within the TrA in the postural responses with limb movement. Activity was recorded when sitting and when relaxed supine during end range isometric hold tests. It was found that the TrA was consistently active throughout the test, however the upper region showed an opposite activation to the lower and middle fascicles and that the onset of EMG in the upper region was later than that of the middle and lower regions. The response was also found to differ depending on body position, with recruitment delayed in sitting compared to standing. These results reflect the variation in the contribution of the abdominal muscle regions

to the stability of the trunk and highlight the indepth analysis that can be obtained when EMG analysis is used on the core musculature.

Surface EMG data has the potential to quantify muscle activity pre- and post-training to establish training adaptations and can highlight which components of the core are successfully being targeted and activated to a greater extent than those components that are not. By establishing this knowledge, training programmes can be adapted and designed to be as effective as possible to help the sports performer reach their full potential. This is an area that has largely gone unreported in many sports, yet could provide invaluable information for coaches, athletes and sport scientists alike. For example, Hamlyn et al. [132] found that there was significantly greater sEMG activity of the lower (MF) and the upper (LG) erector spinae muscles during a 80% 1RM (one repetition maximum lift) squat and deadlift when compared with traditional low threshold unstable core stability exercises such as the birddog or superman [12] exercises and supports previous research that has found lower muscle activation during unstable exercises [133]. Hamlyn et al. [132] suggest that the greater sEMG activity during the squat of the erector spinae muscles is due to the individual's positional changes to handle the compressive forces on the spine and overcome the destabilising torques of the swaying body and suspended resistance overhead. This is supported by research that has found lower erector spinae muscles (MF) to be highly active as a stabiliser during the squat movement [134] and research by Hamlyn et al. [132] who suggest that the upper erector spinae muscles (LG) are involved primarily with providing the stiffness to the spine to help generate forces which control the range of motion [135].

The benefits of using both fine-wire and surface electrodes to measure the core muscular activation during complex exercises such as those performed during core training programmes have been outlined in this Chapter. It is clear that the use of fine-wire electrodes when performing EMG analysis during highly dynamic and challenging body movements does have ethical issues to consider. Therefore surface electrodes have generally been preferred in the past [120]. Ainscough-Potts et al. [40] stated that fine-wire EMG is an invasive procedure and that there has been a development towards using other techniques to establish muscle recruitment levels.



Real time ultrasound scanning techniques have become more popular in recent years for measurements of abdominal muscle activity [136]. Ultrasound imaging has been used to analyse muscle recruitment as changes in the muscles thickness is believed to be related to muscle recruitment [137].

Ultrasound technology and imaging has been used since the 1980's for rehabilitation purposes [138]. Studies have shown that it is a safe, cost-effective and accessible method for visualising and measuring the deep muscles of the trunk [138-140]. Using this type of measurement enables for real-time images of muscles to be observed. Clinical studies [136, 140] have shown that ultrasound measurements and technology provides a method to obtain both valid and reliable data of muscles sizes and can be an indicator of muscle activity (using static quantitative measurements of muscle width, length, depth, cross-sectional area or volume) [138].

Hodges et al. [141] investigated the ability to measure muscle activity using ultrasound methods. They measured the architectural parameters (pennation angles, fascicle lengths and muscle thickness) of several muscles including the tibialis anterior, bicep brachi, brachialis, transverse abdominals, internal oblique and external oblique abdominal muscles. Isometric contractions from 0 - 100% MVC were performed and EMG surface and fine-wire electrodes were used. The authors found that the architectural parameters changed markedly with contractions up to 30% but there was little changed after this. Hodges et al. [141] therefore concluded that ultrasound imaging can only be used to detect low levels of muscle activity and cannot discriminate between moderate and strong contractions.

Hodges et al. [141] did report that the ultrasound measures did reliably detect changes in EMG of as little as 4% (biceps thickness), 5% (brachialis) and 9% (tibialis) MVC. Generally they found that it was less sensitive to changes in abdominal muscle activity, but that it was possible to detect contractions of 12% MVC in the TrA and 22% MVC in the IO muscle (this maybe due to the deep positioning of these muscles in the body). Ainscough-Potts et al. [40] also used ultrasound imaging to analysis the core muscles of the body and they provide a detailed methodology for their ultrasound data collection and highlighted the wide range of muscle thickness of the transverse abdominal muscle in the normal population. This difference may be slightly reduced in

the athletic population but will still vary between sports and this may have a significant effect on how data should be collected on this muscle when comparing data between subjects. Ultrasound measurements also do not take into account a number of factors, for example, the amount of change in the abdominal wall thickness during a contraction does not necessarily represent the intensity or amount of actual muscle activity [141]. This may be due to the impact of other surrounding structures around the muscle, for example, protrusion of the abdominal contents due to breathing [141]. The two-dimensional nature of the analysis also poses some issues, for example, when muscles contract they alter their architecture in three dimensions not two, therefore the change in muscle size may not reflect the absolute change [138]. Due to the above issues, it is essential that researchers using this method have a detailed knowledge of both the anatomy of the abdominal region and ultrasound technology prior to any data analysis. Due to the complexity of the technology, it takes time to develop the skills and knowledge required to achieve the collection of reliable and valid data and subsequently be able to accurately interpret the measurements when using ultrasound technology.

Despite the limitations highlighted above, findings from many studies support the use of the non-invasive technique to measure abdominal muscle thickness and estimate relative muscle activity and most studies performed using ultrasound imaging show that it is a reliable and valid method of assessing core muscle activity [137]. However expert training and a significant amount of experience using the equipment is required to enable valid and reliable data to be collected, a skill that not many researchers have. Therefore methods such as sEMG have been used much more frequently in the past to collect the same data with the same reliability and accuracy [137], as a result this method is going to be the main data collection method used in the current thesis.

Ultrasound technology has been used as a non-invasive method of measuring abdominal muscle activity [137, 138]. However since this is a relatively new method of analysis, it is not known whether it can provide a valid measure of changes in motor control of these muscles. Whittaker [138] states that with ultrasound analysis, there is still debate on issues such as scope of practice, its specific role in the rehabilitation process and its limitations. Some studies have tried to investigate the reliability of

using ultrasound measurements, for example, Ferreira et al. [137] observed similar findings when ultrasound results were compared with those from EMG analysis. They [137] used ultrasound and EMG methods and compared these findings within ten healthy subjects and ten LBP sufferers. The TrA, EO and IO muscles were analysed and it was concluded that the participants with LBP had significantly smaller increase in thickness in the TrA muscle with isometric leg exercises with similar conclusions resulting from the EMG data analysis.

Ainscough-Potts et al. [40] used ultrasound analysis to investigate the response of the TrA and IO muscles to different postures. Thirty subjects performed basic exercises when sitting in a chair, on a gym ball and when one leg was raised off the floor. The subjects (when asked to raise one foot off the floor) had a significant increase in thickness for both the TrA and the IO. This demonstrates that these muscles are automatically targeted by the body to maintain stability when the base of support is decreased significantly and implies that there is a general trend for the muscles to increase in thickness and activity as stability of the body decreases. Therefore, as it was proposed by Richardson et al. [47], to increase the activity of the IO and TrA muscles, one method of doing this is to decrease the stability of the base of support during specific core exercises.

Akuthota and Nadler [19] suggest that an understanding of the precise role of the individual muscles contributions to core stability and core strength is limited and future research needs to be performed to establish these mechanisms more clearly. Akuthota and Nadler [19] suggest that improving core stability and core strength is a way of preventing injuries and a way to enhance athletic performance. However more research is needed to formally identify these links and establish how the core muscles are trained to bring about a performance enhancement.

### **1.6 Physiological Adaptations to Core Training**

Physiologically, core strength and stability training leads to a greater maximal power and more effective use of the muscles of the shoulders, arms and legs [11]. This theoretically results in a better body balance and a lower risk of injury, leading to additional effects on performance, such as speed, agility, power and aerobic endurance

[50]. Neural adaptations from core training include; more efficient neural recruitment patterns, faster nervous system activation, improved synchronisation of motor units and a lowering of neural inhibitory reflexes [142]. It is believed that high-load training alters the muscle structure, whereas low-load training improves the CNS's ability to control muscle co-ordination and therefore the effectiveness of the movement [48]. Subsequently by training with low- and high-load exercises (within a well-structured and functional training programme) improvements should be attained in all the contributing processes to core stability and core strength [49] which (it is reasoned) will in turn benefit sporting performance.

High threshold and strength training is believed to result in hypertrophy of the muscles (structural change) and neural adaptations (of the motor units in the muscles) [132, 143, 144]. This then benefits performance by increasing the possible force generation, CNS facilitation, improved intrinsic muscle stiffness and tissue mobilisation [142]. However it is essential that the local muscles are also targeted by the training and that low-load threshold training is performed to bring about local muscle benefits and not lead to an imbalance in muscle recruitment (as this may subsequently lead to a movement dysfunction and potential injuries) [42]. Spinal instability and injuries to muscles (e.g. the core) and joints (e.g. knee and hips) sustained during movements are associated with insufficient strength and endurance of the trunk stabilising muscles and inappropriate recruitment of the trunk and abdominal muscles [100]. It is important that any core stability weakness is identified and corrected as this significantly increases an individual's muscle and joint injury risk [145].

Hodges and Richardson [146] performed a number of movements at different speeds. They suggested that if the limb movement speed or acceleration is slow, the resultant forces on the body are smaller. They measured feed-forward activation (pre-movement muscle activation) of the TrA during rapid movements and slower speeds and found no TrA feed-forward activation during the slower speeds. Cresswell and Thorstensson [147] found that the TrA activity was greatest with the fastest movement speeds when subjects performed a lifting task at different velocities. Cresswell [91] observed bursts of TrA activity when there were periods of high acceleration and deceleration of the trunk during flexion and extension tasks. These results suggest that the TrA maximal

activity is closely related to periods of maximal stress and so supports the theory that the TrA plays an essential role in stabilising the spine [24].

High-load or fast activities recruit the fast motor units in the muscles when performing a movement optimally and these activities utilise the larger global multi-joint muscles that provide a mobility role [42]. Slow motor units of the muscle are utilised during low threshold recruitment in postural sway and movements involved with unloaded limbs [42]. It is therefore important for optimum motor control to train both the fast and slow motor units in a muscle to optimise core stability and core strength. Subsequently the rate at which an exercise is performed has an influence on the muscle activation recorded [94]. Higher muscle forces will be seen if an exercise is performed at a faster rate as higher accelerations are required of the limbs. Similar suggestions can be made for exercises that have large ranges of motion and those that have added muscular load by using resistance bands or weights. Therefore care needs to be taken when performing these exercises to allow for these variations and subsequently the rate that the exercise is performed at needs to be controlled.

The degree of movement has been observed to have an effect on muscle activation as well as speed of the movement [24]. For example, the feed-forward response was identified when movements of the elbow and shoulder were performed but not when only the wrist and thumb were moved [24]. EMG research has identified that when the arm was moved, onset of TrA precedes the deltoid by 30 ms [39] and when the leg is moved, activation of the TrA precedes the deltoid by more than 100 ms [58]. Hodges [24] concluded that this earlier activation is due to the greater forces on the spine being present when the leg is moved due to its greater mass. Previous studies have suggested that limb movement is delayed in tasks where the postural demand is increased [148, 149] due to the extra time needed to prepare the body for the larger resultant forces.

The pattern of muscle activation during limb movements has been investigated using fine-wire EMG analysis, for example, when rapid shoulder flexion is performed, Hodges et al. [67] found the TrA showed a greater magnitude of activity at the onset of movement followed by continuous activation at a lower level during the movement. Cresswell [91] found that the abdominal muscles were only active during acceleration

(when they generated the movement) and deceleration (when they opposed the movement). Therefore their muscle activation is directional dependent and is involved in the global mobilisation processes during such movements. Research on the optimum speed and order of loading on the muscles is limited, therefore it remains unclear what speed and direction of movement should be used to train the muscles optimally [19, 99]. The only clear conclusion that can be made is that any training should be functional and sport-specific for the individuals needs [11, 15]. Whether these targeted movements are to be low- or high-load will have a significant effect on the type of training programme implemented.

The apparent contradiction between the traditional dynamic approach of the strength and conditioning coach compared to the more modest movements prescribed by physiotherapists typically has led to confusion as to which core training method is most effective. Future research should focus on establishing which exercises are sufficient for improving each part of core stability (i.e. neural, passive and active systems) and core strength (e.g. neural adaptations) to be able to target these performance goals more effectively and maximise the potential for the skills and training benefits to be transferred into performance [71, 112, 150]. An overview of the principles of core training and the potential training adaptations and benefits that could result are outlined in Figure 1.7.

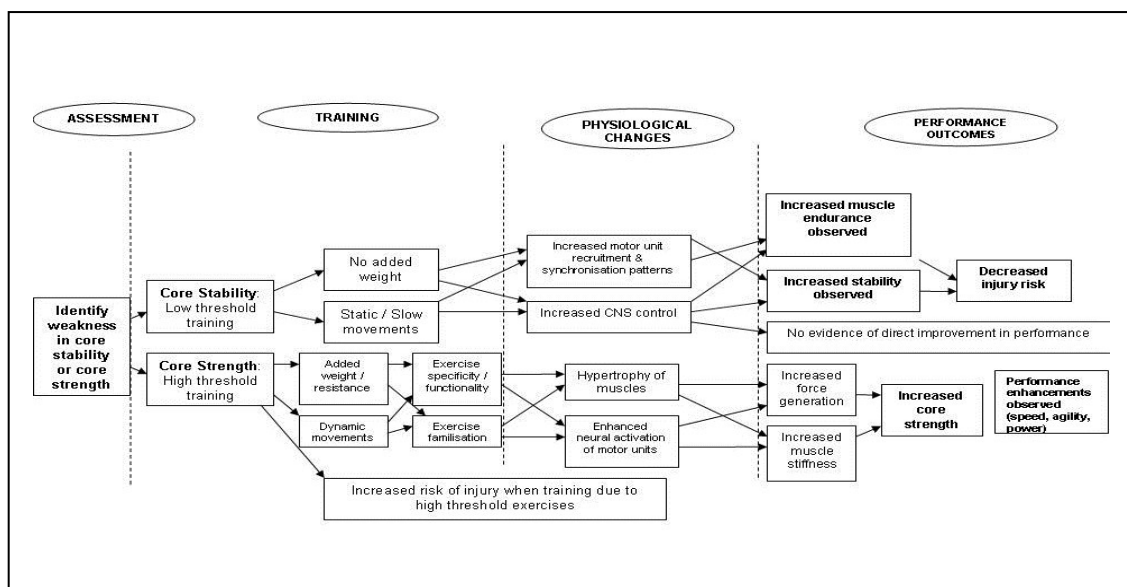


Figure 1.7. Core training: Principles of low- and high-load training and the subsequent effects on core stability, core strength and resultant performance (modified from Hibbs et al. [8]).

As has been suggested, the majority of published research into core stability and core strength fails to measure what the effect of a training programme is on actual performance, whether it be performing everyday tasks or a sporting activity at a world class level [11, 26, 50, 151-155]. Some of those studies that have reported the effectiveness on improving subsequent performance have failed to show any performance enhancement following core training programmes [50, 97]. This could be due to numerous factors such as; the exercises not being functional and therefore any improvements not being transferable, the exercises not targeting the correct muscles and/or activating the muscles to the required activation levels and failing to incorporate all types of core training (strength, stability and endurance) which may be needed to result in performance enhancements. This is supported by Myer et al. [105] who implemented a training programme consisting of all forms of training that included; low- and high-load weights, strength and stability exercises, plyometric and balance exercises and identified an improved sporting performance following their intervention. Therefore many core training programmes that do not include all of these factors are subject to failure before they even begin. A full understanding and detailed planning of an intervention programme needs to take place prior to any programme being initiated.

Battinelli [61] outlined performance as the increased synergistic patterning of proficiency and competency acquired through the conditioning and training of developed structural and functional capacities, abilities, and skills relative to nutrient and metabolic utilisation that can be demonstrated during the execution of designated physical activities. Figure 1.8 outlines the different processes that contribute to performance and highlights the potential contribution of an individuals' core stability. Watson [62] supports this contribution of core stability on performance by suggesting that performance is influenced by genetic and environmental factors, some of which can be modified by specific training (for example, joint mobility, a muscles capacity to do work and overall muscle strength). This suggests that there is a strong link between performance and core stability of an individual.

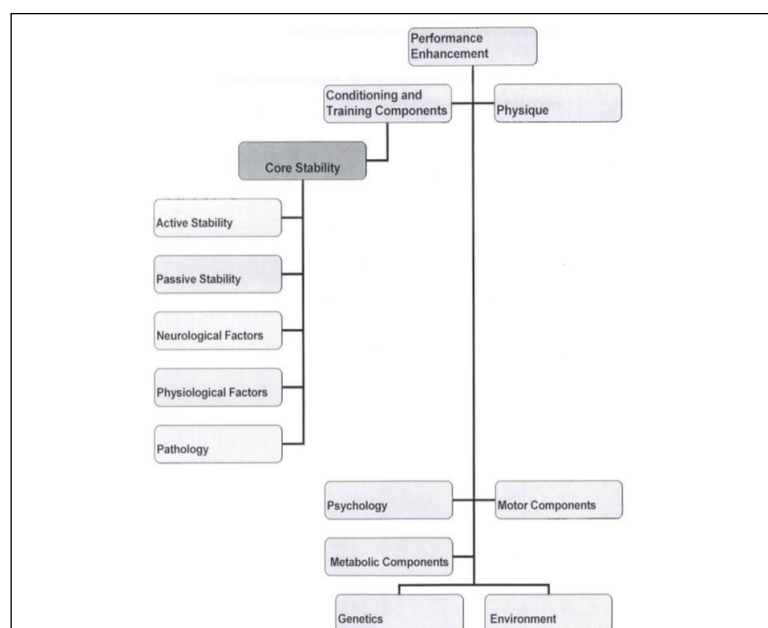


Figure 1.8. The components and processes that contribute to performance (modified from Mclean [9]).

As a result of the strong theoretical link between core stability and performance, it is important to establish the effectiveness of different core training programmes to identify which methods are optimal to result in performance enhancements and which methods are unsuitable for training an individual's core stability and core strength. To establish the effectiveness of a training programme, a detailed intervention study that investigates the progress of the individuals before, during and after the training needs to take place.

### 1.7 Evidence of Core Training Benefit

Research focusing on core stability in the rehabilitation sector has focused mainly on spine pathology and LBP research [32, 47, 156-158]. In the sporting sector, it has been noted by a number of researchers that there is a lack of research looking at the effect of core stability training on improvements in actual athletic performance [11, 26, 50, 151-155]. Some studies have implied that there is an effect on performance by improving core stability but mostly these conclusions are assumptions based on basic testing [64, 159]. A summary of a selection of these studies from both the rehabilitation and sporting sectors can be seen in Table 1.2.



Table 1.2. Summary of example research studies on core training and the resultant benefits on core stability, core strength, muscular endurance and performance.					
Study	Result	Performance Measures Used	Data Collection Method	Subjects Used	Training Programme
Leinonen et al. [160]	Stability improved	Time out of balance.	Stability platform	Healthy College Students (9 men, 7 women)	Forward and Side Bridge Birdog
Vezina and Hubley-Kozey [100]	Stability improved	Repeated tests 6 weeks later. Basic core stability exercises	Surface EMG (3 abdominal and 2 trunk muscles)	24 healthy men	TST Level 1, pelvic tilt, abdominal hollowing
Urquhart and Hodges [31]	Stability improved	EMG muscle activity	Intramuscular EMG (TrA, EO,IO) Surface EMG (RA)	11 healthy non-athletic subjects	Rapid, unilateral shoulder flexion in sitting and standing
Cosio-Lima et al. [90]	Stability improved but no strength increase	EMG muscle activity. Strength on Cybex machine (back, abdominals, knee).	Surface EMG (RA and ES) Intramuscular EMG (TrA)	Untrained 30 college females	5 week swiss ball training programme; curl-ups and back extensions
Nadler et al. [161]	Strength increase and fewer injuries	Strength Dynamometer exercises	Force plate, Dynamometer	>200 college sports players	Structured core strengthening programme
Saal and Saal [89]	Fewer injuries reported	Injury occurrence	Video Dynamometer	52 subjects with lower back pain	Flexibility exercises Joint mobilisation Stabilisation exercises
Jeng et al. [162]	Occurrence of back pain decreased with increased strength	Strength: back, legs and abdomen Stabilisation	Strength tests	Untrained subjects with history of back pain	Structured core strengthening programme
Pollock et al. [163]	Improved stability, strength	Strength: lumbar back	Strength tests Stabilisation tests	Healthy non-athletic subjects	12-20 week programme Resistance training Pelvic stabilisation
TrA – Transverse Abdominis, EO – External Oblique, IO – Internal Oblique, RA – Rectus Abdominis, ES – Erector Spinae, EMG – Electromyography.					

### 1.7.1 Evidence of Core Training Benefit in Rehabilitation Research

Most research in the rehabilitation sector focuses on how core stability influences LBP [32, 47, 156-158], with many conditioning programmes being based around training the abdominal muscles to improve their strength and subsequently the stability of the spine [164]. This is based on the knowledge that strong abdominal muscles provide support for the lumbar spine during day to day activities [164].

Rehabilitation programmes have used swiss balls to train the core musculature and improve core stability with some benefits being documented [165, 166]. Behm [88] suggests that using a swiss ball provides an unstable surface which challenges the core muscles to a greater extent and improves core stability and balance. As a result it can be used as a training tool to increase core stability, balance and proprioceptive ability. Cosio-Lima et al. [90] tested two groups of subjects, one training on the floor and one using a swiss ball and found that the swiss ball group had a significantly greater change in muscle EMG activity during flexion and extension exercises and greater balance scores than the floor exercise group. However muscle strength was not improved (supported by [24]) following the swiss ball training. This may be due to insufficient levels of activation of the core muscles during this type of exercise (activations of over 60% MVC are believed to be required for strength adaptations to occur) [100]. As a result many researchers advocate using a swiss ball as a low-threshold rehabilitation tool to improve balance, posture and proprioception [167-169]. This has led to modern day rehabilitation programmes using a mixed conditioning approach which includes a range of methods to improve core stability and core strength. Saal and Saal [89] investigated the effectiveness of an exercise training programme on LBP sufferers which consisted of; a flexibility programme, joint mobilisation of the hip and the thoracolumbar spinal segments, a stabilisation and abdominal programme (low load exercises [42]) and an aerobic gym programme. Saal and Saal [89] reported successful recoveries for 50 of the 52 subjects (96%). However it is not possible to conclude how much of this improvement was due to the core stability work directly (other factors such as medication, injections and healing over time would all have had an additional effect). Saal and Saal's [89] study identified that a general core strengthening programme was successful in helping subjects to recover from and improve back problems without performing high threshold sport specific core training.

Nadler et al. [161] and Leinonen et al. [160] identified that poor endurance and delayed firing of the hip extensor (GM) and abductor (GMe) muscles is observed in individuals with lower extremity instability or LBP [34, 35, 157]. This is supported by Devita et al. [35] who noted alterations in firing of the proximal hip musculature in those with anterior cruciate insufficiency and Nadler et al. [170] who observed significant asymmetry in hip extensor strength in female athletes with reported LBP.

Jeng et al. [162] found that the occurrence of LBP may be decreased by strengthening the back, legs and abdomen to improve muscular stabilisation. A possible way of improving this strength is with specific training techniques. Pollock et al. [163] showed that resistance training with pelvic stabilisation improved development of the lumbar extension strength which may lead to an improvement in core stability and therefore reduce the injury risk of LBP.

Vezina and Hubley-Kozey [100] used sEMG on three abdominal and two trunk extensor muscle sites and performed three low-load core exercises; pelvic tilt, abdominal hollowing and level 1 of the trunk stability test to compare muscle activation. They identified that the three exercises recruited the five muscles differently, with the EO muscle showing the highest activation levels during the pelvic tilt (25% MVC). However they did conclude that these exercises did not elicit enough activation to result in any improvement in strength of these muscles, but would be sufficient to bring about a stability benefit. The authors state that an activation of >60% MVC is required to result in a strength benefit (this is supported by [171]). However, stability and muscle endurance benefits can be achieved by MVC of <25% [100, 172]. Therefore these exercises would not be sufficient to improve an individual's core strength but could be used to target an individual's core stability and improve their stabilisation.

Arokoski et al. [57] observed that in ten healthy males, standing exercises involving upper extremity movement resulted in higher core muscle activity when compared to exercises performed in other positions (e.g. lying). This is due to the higher centre of gravity resulting in a more challenging body position to maintain as opposed to when lying. Cholewicki and Van Vliet [173] observed that the contribution of different trunk muscles to core stability and core strength was dependant on the direction and magnitude of load during the exercises. Kavcic et al. [174] also found that in ten healthy male individuals, muscles that were in an antagonistic position during the dominant moment of the movement were most effective at increasing lumbar spine stability. This supports the theory that muscles have different roles during the same exercise depending on their orientation and fibre type [12, 18]. From the research conducted to date, it can be concluded that both free weight stable exercises (targets

core strength) and unstable exercises (targets core stability and core endurance) should be performed to improve overall core ability [26, 119, 122].

This thesis has implied that whether a training programme results in an improved performance or not depends on the functionality of the core exercises performed. This may explain why some research has resulted in contradictory research on the efficacy of some rehabilitation programmes to train the core muscles [24, 175]. The effectiveness of an exercise is determined by factors such as; functionality and specificity, intensity, familiarisation and frequency of the movement [11]. Different core exercises that challenge the core musculature at different intensities of muscle activation are required to result in stability or strength enhancements [11] but these must be specific to the performance goals. In conclusion, research in the rehabilitation sector has been conducted which has begun to assess how core muscles respond to low-load core stability exercises and their effect on LBP and suggests that by performing certain core training exercises, performance relating to injury risk and recovery could be improved [50, 97, 105, 161]. However many questions remain unanswered as to what the optimal rehabilitation programme may be for different types of injuries and quantifying the affect that core training has on improving a core ability weakness to reduce the injury risk of that individual.

How core muscles respond to high threshold exercises and movements (seen regularly in sporting environments) cannot be elucidated from the rehabilitation studies and methodologies outlined above. For example, Cosio-Lima et al. [90] performed their research on the general public and found that the core training programme (swiss ball and conventional floor core stability exercises) had advantageous effects on improving core stability and balance in women. However, this study was not performed on elite athletes, and it remains to be seen whether the same results from the exercises would have had the same effect on more trained individuals who already have a certain level of core ability. This is due to the exercises used in Cosio-Lima et al.'s study [90] not involving any added resistance (just the individual's body weight) whereas most sporting movements are performed with some resistance against or added to the body. Therefore the exercises performed may not be functional (sport specific) or sufficiently demanding enough to stress the athlete's core musculature to the required levels to

result in the physiological adaptations needed to potentially improve their core ability and sporting performance further. Willardson [150] also believes that the static balance test used in Cosio-Lima et al.'s [90] study to measure core stability may not be representative of the dynamic balance required for many sports skills. Brown [17] does suggest that some publications to date do identify the activation patterns and timings of the core muscles during some sports tasks [90, 97, 100], but highlights that there is a lack of research focusing on elite athletes and using high threshold exercises to assess an individual's core stability and core strength.

As has been discussed, when subjects with LBP performed rapid limb movements, the onset of TrA activity was significantly delayed [24]. The activation of the superficial muscles (RA, EO, IO) are also delayed but only with movements performed in a single direction. This is supported by Comerford and Mottran [42] who conclude that there is a motor control deficit (poor recruitment) of the TrA muscle in all subjects who have lower back pain (TrA muscle activity was delayed by approximately 50 – 90 ms, resulting in activation after limb movement has begun). By not pre-activating the TrA muscle, this allows forces to be imparted on the spine without the required protection or stability of the spine to cope with this extra stress. Similarly Hodges and Richardson [69] observed a change in the recruitment of the TrA muscle in injured individual's. They reported that the TrA muscle did not act independently of the other superficial core muscles in subjects with LBP (unlike in healthy subjects) therefore resulting in a change in muscle recruitment which fails to protect the spine as efficiently. In conclusion, injury to the lower back results in significant changes in how the core muscles act and their ability to stabilise the spine. This highlights the importance of maintaining or developing good core stability and strength to prevent injuries to the lower back and other regions of the body.

### **1.7.2 Evidence of Core Training Benefit in Athletic Performance Research**

Research performed to date has highlighted benefits of training core stability and core strength for LBP sufferers and for carrying out every day activities [143, 160]. However less research has been performed on the benefits of core training in elite athletes and how this training should be carried out to optimise sporting performance with many reporting contradictory findings and conclusions [11, 17, 20, 24, 90, 94,

172, 173, 176]. Despite this, many elite athletes continue to undertake core stability and core strength training as part of their overall training programme.

To establish whether training core stability and core strength are important in enhancing sporting activities, research needs to establish what impact training these areas may have on resultant performance. What is termed as performance (as with the definitions of core stability and core strength) differs between the rehabilitation and sporting sectors. In the rehabilitation sector, an improved performance for a LBP sufferer would be the ability to perform everyday tasks sufficiently [12, 177], whereas in the sporting sector, an improved performance may be characterised by improving technique in order to run faster, throw further or jump higher [105], although it could also include the reporting of fewer injuries [178, 179]. Reducing an individual's injury risk may therefore lead to a greater ability and productivity during their sporting performance [105]. Furthermore, by observing improvements in proprioception and stability, it is believed that these subsequently contribute to injury prevention and result in an enhanced exercise economy and ability which may lead to an improvement in the athletes sporting performance [180]. Although some studies have implied that there is an advantageous effect on performance by improving core stability and strength, these conclusions are largely assumptions based on basic strength testing and not on actual sporting performance measurements [20, 64, 159]. For example, Heidt et al. [181] investigated the effect of implementing a core training programme on reducing injury risk. The authors found that they were able to gain an injury prevention effect through a speed and agility protocol. They found a reduction of lower extremity injuries of 19% in those that completed the training programme but failed to establish whether sporting performance was subsequently heightened.

It is theorised that by having a good core stability and core strength, this has a beneficial impact on actual sporting performance [155]. This is due to the optimum recruitment of the core musculature to prevent one muscle from taking over the control of the movement and preventing the co-ordination of recruitment in the core muscles [151]. Subsequently this would increase the injury risk to the core muscles and result in the inhibition of the normal muscle activation pattern for that movement and therefore potentially decrease the sporting performance ability [182]. Despite the

strong theoretical link between core stability and strength ability and sporting performance, Thompson et al. [183] conclude that there has been very little research which studies the effectiveness of functional training programmes on the improvement of sports performance or functional fitness. Willardson [59] states that there is no defined set of tests to evaluate core stability in healthy athletes. Some of these studies that have investigated the area are summarised in Table 1.3.

Some studies have found that targeted training programmes do improve core ability (stability, endurance and/or strength) but not sporting performance [1, 23, 25] (studies 1 - 4 in Table 1.3). For example, Stanton et al. [97] observed a significant difference in core stability following a swiss ball core training programme but observed no improvements in  $VO_2$  max or running economy performance. They suggested that the swiss ball training was not specific enough to transfer the improvements in core stability to sporting performance. Other studies have found improvements in core ability and sporting performance following core training programmes (studies 5 - 9 in Table 1.3). For example, Thompson et al. [183] observed that following an eight week progressive functional core training programme (three sessions of 90 minutes per week) which included exercises such as; squats, lunges and trunk rotations and included core stabilisation, static and dynamic and muscular strength exercises, club head speed during the golf drive was increased along with improvements in functional fitness. Additional positive effects on golf performance have been reported elsewhere [182, 184]. These positive findings following a core training programme are supported by Cressey et al. [151] who observed improvements in male soccer players performance measures. Cressey et al. [151] observed that following a ten week training programme involving free weight core strength exercises (such as; deadlifts, squats and lunges with added resistance), where one group performed the exercises on the floor and another on an inflatable rubber disc (to represent an unstable surface) both groups resulted in improvements in drop jump and countermovement jump height along with sprint times. However the group that trained on the stable surface resulted in greater improvements in performance. It was suggested that this was due to the greater force that can be produced during more stable movements which increases the demands on the core musculature and increases the training load which would result in a greater training adaptation [151].

Table 1.3. Examples of published sport specific core stability and core strength training programmes and their effectiveness on enhancing sporting performance.

Study	Subjects	Training programme	Exercises	Performance measures	Findings
1. Stanton et al.[97]	18 male athletes	6weeks – 2 times per week	Swiss ball	Stature, Body mass Core stability EMG (abdominals and back) VO2 max, Running economy	Core stability improved No effect on EMG activity No effect on VO <sub>2</sub> max or running economy
2. Tse et al.[50]	45 rowers	8 weeks – 2 times per week	Trunk endurance	Flexion / extension tests Vertical jump Shuttle run, 40 m sprint overhead medicine ball throw 2000 m max ergo row	Improvements in trunk extension test No differences for any functional performance tests
3. Cosio-Lima et al.[90]	15 non athletic women	5 weeks	Curl-ups and back extensions	EMG abdominals and erector spinae Cybex strength measures Balance tests	Higher EMG activity Improved balance scores No change for strength measurements
4. Myer et al.[105]	41 female athletes	6 weeks	Core strength Balance Resistance training Speed training	1RM squat & bench press Single leg hop Vertical jump Sprint time	Increased squat (92%) and bench press (20%) lifts Single leg hop distance increased (9cm) Speed improved by 0.07sec
5. Nadler et al.[55]	NCAA college athletes	30-45mins during season: 4-5times per week Off season: 2-3times per week	Sit ups Pelvic tilts Squats, Lunges Leg press Free weights	Injury occurrence Extensor strength Hip strength	No significant reduction of injuries Extensor strength no different Hip strength was effected and improved
6. Cressey et al.[151]	19 male soccer players	10 weeks- 27 sessions:	Deadlifts Lunges, Squats Single leg balances	Bounce drop jump Countermovement jump 40 and 10yard sprints Agility tests	Improved drop jump (3.2%) and countermovement jump height (2.4%) for stable group Improved sprint times (40yd: stable 3.9%;unstable 1.8%)
7. Myer et al. [185]	19 female athletes	7 weeks-3 times per week	Plyometric group: maximal jumping No balance training Balance group: stability & balance	Impact force and centre of pressure during single hop and hold Isokinetic strength Power (vertical jump)	Both groups decreased centre of pressure in medial direction Both groups increased power in vertical jump
8. Yaggie and Campbell [186]	36 active subjects	4 weeks- 20mins; 3 times a week	Balance training	Postural displacement Shuttle run Vertical jump	Displacement & sway reduced Shuttle run time decreased No change in vertical power
9. Thompson et al. [183]	18 male golfers	8 weeks – 3 times a week, 30mins	Squats, lunges Trunk rotations Stability and strength exercises	Golf club head speed Stability tests Balance tests	Balance tests improved Functional fitness scores improved Club head speed increased



Nadler et al. [161] investigated how hip muscle imbalance and LBP in athletes influences core strengthening (by reducing the likelihood of segmental buckling) [11]. The authors measured hip strength throughout the year using physical examinations. The subjects performed a core-strengthening programme which consisted of; 30 - 45 minute session, 4 - 5 times per week in pre-season and 2 - 3 times during the season. The training programme targeted abdominal, paraspinal and hip extensor strengthening. The exercises performed included; isolated abdominal strengthening using sit-ups and pelvic tilt exercises (targeting RA, EO and IO muscles), squats and lunges which emphasis multiple joint activation of the ankle, knee and hip (strengthen proximal hip, quadriceps and paraspinal muscles), leg press (strengthen quadriceps, hamstrings and gluteus maximus muscles) and strength training with free weights using dead lifts and hang clean exercises (targeting the hamstrings, quadriceps, hip and shoulder musculature). Nadler et al. [161] concluded that the lack of significant findings in the study may be due to the small number of subjects that reported LBP during the season (which may in itself reflect positively on the core training programme implemented) and due to the core exercises only included frontal and sagittal plane movements which may have affected the results due to not being sport specific enough to transfer over to sporting performance. From the study [161] it was observed that the incidence of LBP decreasing by 47% in male athletes but increasing slightly for females. This may be due to the use of some extremely demanding exercises, such as the roman chair exercise and females being more susceptible to LBP [187]. Nadler et al. [161] observed an increase in hip extensor strength (for 90% of subjects) and they identified clear gender specific differences following the training programme, supporting other studies which found that females may be more prone to LBP and hip strength imbalances [15].

Leetun et al. [15] found that 41 (28 females, 13 males) of 139 athletes (basketball and track) sustained 48 back or lower extremity injuries during an athletic season (35% of the females, 22% of the males). They identified that the athletes sustaining an injury had poor core stability (i.e. weaker hip abduction and external rotation strength which decreased their ability to maintain stability) and concluded that there were greater demands on the female lumbo-pelvic musculature which resulted in a greater injury

risk to the lower back of females. This is also supported by McGill et al. [102] who observed that females were 8% more likely to suffer from LBP than males due to the different skeletal build of the female pelvis and hip area and that there tends to be greater core instability between postural sides in females compared to males, which may lead to a higher injury risk [15]. Subsequently core training could play an important role in injury prevention, especially in females [178, 179, 187].

It is important for core training programmes to be sport-specific and functional to the individual so that the improvements are carried over into the performances [11, 50]. Some researchers have identified poor training programmes in some sports, for example, Fig [22] identified that many strength programmes for swimmers use only arm exercises and do not involve the core. A strong core in swimmers enables energy to be transferred from the core to the pull (arm) and kick (leg) components of the swimming stroke, therefore making the swimmer more efficient by maximising propulsion and minimising drag [77]. Core strength is also needed to maintain proper posture, balance and alignment in the water. If this is not maintained, an inefficient swimming stroke develops and resistive forces increase in the water [13]. It can be concluded from this that developing a strong core in for example swimmers, is essential and that many of the principles outlined above can be transferred to most sporting movements. It is therefore important that elite athletes have suitable core stability and core strength and an effective core training programme as part of their day to day training schedule. Specific core training and demands on the body during swimming will be discussed in more detail later in this Chapter.

Myer et al. [105] suggest that core training programmes are effective in improving sporting performance. They suggest that benefits include increased power, agility and speed [99, 188] and are achieved by increasing active joint stabilisation, reducing muscle imbalances, improving functional biomechanics, increasing strength of structural tissues (bones, ligaments and tendons) [189, 190] and by reducing subsequent injury risk. Myer et al. [105] found improvements in performance following a core training programme with significant performance improvements in; vertical jump height, single leg hop distance, speed, bench press and squat strength and improved biomechanical motion (range of motion). However, Tse et al. [50]

implemented and evaluated a core endurance intervention programme on college-age rowers which was less effective. The core training took place two days a week for eight weeks (16 days total) on 45 rowers (each session was approximately 30 – 40 minutes long) and measured core endurance (flexion, extension and side flexion tests). Functional performance tests included; vertical jump height, shuttle run and 40 m sprint speed, overhead medicine ball throw distance and a 2000 m ergo maximum rowing test. The results revealed significant improvements in the side flexion tests of the core group, however no significant differences were observed in the functional tests between the two groups. Tse et al. [50] suggested that this may have been due to the margins for improvement in the subjects being relatively small in this high-conditioned group of athletes. It may also be due to the exercises performed not being functional enough to improve performance to result in a significant difference. The frequency of intervention (two sessions a week) may also have not been sufficient to result in a performance enhancement.

The use of unstable equipment to train core stability has increased in popularity among healthy athletes. This is due to some studies reporting advantageous performance effects following core training programmes completed on unstable surfaces which improved the individual's power and strength [165, 191]. It is believed the unstable surface makes the exercises more specific to the sporting movement (i.e. the swimming stroke has no stable surface where force can be generated against when in the water) and ultimately any improvements in core ability are then transferable to actual sporting performance [192]. However, research has shown that when exercising using unstable exercises, the force output and rate of force development is reduced [193]. This could be due to the muscles having a greater stabilisation role in maintaining balance rather than producing and transferring forces through the body [133]. For example, McBride et al. [193] observed that peak force was reduced by 45.6% and rate of force development by 40.5% during unstable exercises. They observed a reduction in muscle activation during the unstable exercises of 37.3% in the VL and 34.4% in the VM muscles. This reduction in force output and muscular activation would reduce the effectiveness of the exercise for athletes who are training for strength and power improvements and therefore questions the appropriateness of these exercises for the athletic population (due to higher levels of muscle activation being needed to result in

adaptations to the muscles to bring about strength gains). Activation of over 60% of maximal strength has been reported to be required to result in strength benefits from a training programme [194, 195]. Davidson and Hubley-Kozey [196] suggest that training loads need to be greater than 60% of the individuals one repetition maximum. This is supported by Myer et al. [105] who observed improvements in performance (vertical jump height, single leg hop distance, speed and improved biomechanical range of motion) following a high-load training programme that included squats and bench press exercises that focused on improving core strength.

Conversely, some research has identified that there is greater muscle activity (e.g. TrA and oblique muscles) during unstable exercises when compared to the same exercises performed on stable surfaces [197], for example, when a sit-up is performed on a swiss ball, muscle activation of 50% MVC is observed compared to 21% MVC when the sit-up is performed on the floor [197]. However, Willardson [59] points out that these findings along with other similar findings [133, 198] have still only observed muscle activation levels of below 60% MVC which is not sufficiently high enough to lead to enhancements in muscle strength as was highlighted earlier [195]. Willardson [59] and Hamlyn et al. [132] suggest that higher muscle activation levels can be achieved by performing exercises with heavy ground-based free weights. Therefore to develop core strength, exercises performed on a stable base with free weights may be more effective. Unstable exercises using equipment such as a swiss ball may still be useful for core training by improving core musculature endurance and stability rather than strength or power [87]. Therefore these unstable exercises could be included for example during a maintenance phase of a core training programme or when processes such as core endurance are being targeted [165]. This highlights the importance of establishing periodisation within training programmes and targeting individual's specific needs to maximise any training benefit on the resultant sporting performance [52, 59].

The use of free weights has been increasingly popular with elite level healthy athletes. Free weight exercises involve moderate levels of instability (due to the weight of the load / resistance) with high levels of force production [73, 106, 241, 286], resulting in potential improvements to core stability and core strength. However, these types of lifts (e.g. deadlifts, squats and overhead press) are only performed in the sagittal plane

and these exercises need to be progressed to include rotation and unilateral movements to mimic the true sporting movement which usually occurs in all three planes of movement [59].

### **1.7.3 Evidence of Core Training Benefit in Swimming Research**

Good core stability and core strength has been suggested to be essential for successful swimming performance [73, 77]. It is thought that having good core ability (stability, strength and endurance) enables the swimmer to transfer the forces created by the muscles through the body more efficiently, enabling the body to be propelled through the water quicker [13]. The best way to train a swimmer's core musculature is yet to be established. The unstable nature of the water and not having a point of contact with, for example the ground to produce forces, is hard to mimic during training. Swim benches and resistance cords have been used in swimming training programmes for many years [28, 121, 150, 159] despite these exercises not having any firm conclusions as to their true effectiveness on targeting the core musculature and subsequently improving an individual's core ability.

In swimming specific studies (Table 1.4) some have reported encouraging effects on swimming performance following dry-land weight training programmes [116, 119, 199], while others reported no improvements on swimming performance following such training [117, 155]. These conflicting findings could be due to the need of very functional and specific exercises to target the same muscles that are used when swimming in the water. It has been suggested that dry-land training programmes do not result in transferable skills that can then be used when swimming, and therefore does not enhance swimming performance even though improvements in strength and power are observed [117]. However some previously published studies have observed improvements in swimming performance following dry-land training which include resistance exercises that specifically target the major muscles used during the freestyle swimming stroke (i.e. core musculature, upper arms and legs) [118, 199]. These exercises include; barbell exercises involving squats and lunges and free weight dynamic movements (i.e. shoulder press, bench press).

Study	Subjects	Training programme	Exercises	Performance measures	Findings
Trappe and Pearson [199]	10 males	6 weeks core training: 2 times a week (testing after 12 weeks of swim training)	Assisted weight group Free weight group Increased weight over weeks	Swim bench strength measures Sprint and endurance swimming performance	Weight assisted group increased power and sprint swimming speed Both groups improved on endurance swimming speed Dry land weight training enhanced swimming performance
Girold et al. [118]	21 (10 males, 11 females)	12 weeks: 2 times per week; 45 minutes	3 groups; control, dry-land, wet-land Increased weight over weeks	Dry-land: barbells, squats, lunges Wet-land: elastic cords in water Strength Isokinetic dynamometer Speed, stroke rate, depth and length 50m swim performance	Dry-land: strength improved 45% No difference between dry (2.8%; 1.05sec) and wet land (2.3%; 0.96sec) groups but both improved more than control group (0.25second)
Strass [119]	males and females	6 weeks	Assisted press and draw exercises Bar-bell exercises	Strength measures 25m and 50m swim performance	20-40% increase in strength measures; e.g. elbow extensors 4.4% (25m) and 2.1% (50m) improved swimming performance
Sharp et al. [116]	40 (18 males, 22 females)	4 weeks	Upper body Isokinetic strength training	Swim bench training 25 yard swim performance	Arm power increased 18.6% 3.6% improved swimming performance (25 yards)
Tanaka et al. [117]	24 males	8 weeks; 3 times per week	2 groups; swim only and resistance training and swim group	Swim bench power Swim performance	Both groups increased power but were similar to each other (increased 25-35%) No difference between swimming performance

Swimming movements are performed in water with the swimmer having no base of support to help aid force development within the body which makes the core and the centre of mass the reference point for all movement [59]. This increases the importance of being able to control the body in unstable environments. Due to this it has been suggested that the use of swiss balls may mimic this environment more than performing exercises on stable bases such as the floor [2, 150, 158], however this has not been supported in swimming specific studies [155]. Scibek et al. [155] implemented a six week core training programme and compared the effect of a swiss ball training programme on various performance measures (e.g. vertical jump, forwards and backwards medicine ball throw and timed swimming performance). They observed improvements in two of the performance measures; forward medicine ball throw and postural control. However, no improvements were observed for swimming performance, suggesting that the improvements in core stability from the swiss ball training were not specific enough to be transferred to the core stability requirements during swimming.

It is important that all muscles are targeted and trained specifically to a suitable level to result in training adaptations and improvements. However it is impossible to establish this unless muscle activity data is collected during these exercises. Therefore it is proposed that the use of sEMG could provide this information and enable exercise comparisons to be made regarding their effectiveness and intensity. As it has been highlighted in the previous chapters, this method has not been used extensively and many questions remain regarding which core training exercises are most effective in activating the core musculature to the required training adaptation levels and what effect the characteristics of the training programmes have on the subsequent activation of these muscles during core exercises.

To date there has been no swimming specific study (using sEMG analysis) establishing the effectiveness of a core training programme on the core musculature training adaptations and swimming performance. Previous swimming studies have only used performance measures to establish the effectiveness of a core training programme (see Table 1.4). These performance measures reflect gross performance changes but fail to establish what component of the body has changed, to what extent and whether this improvement is due to changes in the recruitment and strength of the core musculature that provides core stability and strength to the body.

In conclusion, it remains unclear as to which exercises best rehabilitate an individual back to normal health or identify those that are optimal for improving core strength or stability for improving sporting performance. This is despite widespread acceptance that core stability and core strength impacts on sports performance and the large number of individuals who regularly perform core training programmes. Further research needs to be performed to establish whether the claim that core training can enhance performance can be substantiated. The lack of effect on performance observed in many studies may be due to the core training programmes not being functional enough to transfer into sporting performance. This is due to the poor understanding of what the demands are when performing the core exercises and the role that specific muscles have during these exercises. Future research needs to establish what these roles are for these muscles to be able to implement the optimum training programme

for individuals. Furthermore, it may be due to the low-load exercises which are solely included in many of the published training programmes not being sufficient to result in a large enough improvement in core ability to affect the subsequent performance.

### **1.8 Conclusions**

The definitions of core stability and core strength are yet to be clearly established in the rehabilitation and sporting sectors and as a result, this has led to many contradictory and confusing findings [19]. These definitions need to be established before clear conclusion as to which type of exercises and training programmes most effectively result in performance enhancements. Akuthota and Nadler [19] suggest that there are very few focused studies of core strengthening or similar programmes that show improved performance or sporting activity, and that despite this, the literature still promotes many programmes and exercises for performance enhancement. They conclude that (other than studies in the treatment of LBP) core stability research is severely lacking. Tse et al. [50] also suggested that there is a lack of studies comparing strengthening of the core musculature and its effect on physical performance parameters such as power, speed, agility and muscular endurance. Cosio-Lima et al. [90] did find an improvement in balance performance following core stability training, but this was using untrained and not highly trained athletes and it remains to be seen whether this performance benefit is seen in highly conditioned athletes. This is due to the differing demands on the core musculature during everyday activities (low-load, slow movements) and sporting activities (high-load, resisted, dynamic movements) research performed in the rehabilitation sector can not be applied to the sporting environment and subsequently data regarding core training programmes and their effectiveness on sporting performance are lacking. Despite this many elite athletes undertake core stability and core strength training as part of their training programme despite contradicting findings and conclusions as to their efficacy [18, 24, 75, 76, 132, 150]. This is mainly due to the lack of a gold standard method for measuring core stability and strength when performing sporting movements. Few studies have observed any performance enhancement in sporting activities despite observing improvements in core stability and core strength following a core training programme [199]. It might be that improvements made in stability and strength only impact indirectly on sporting performance by allowing athletes to train injury free more



often. A clearer understanding of the roles that specific muscles have during core stability and core strength exercises would enable more functional training programmes to be implemented which may result in a more effective transfer of these skills to sporting activities. Therefore there are still many questions that need to be investigated in this area before the concept of core stability and core strength is fully understood.

## **Chapter 2**

# **Planning an Intervention in an Athletic Setting based on the Medical Research Council Framework for Complex Interventions**

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## 2.1 Introduction

Currently there is conflicting evidence regarding training of the core musculature and its benefit on improving performance [9, 17, 19]. Some studies have identified positive training implications [117, 199], while others have found no effect [50, 97]. A possible explanation for these conflicting findings is the lack of a gold standard for scientifically measuring and training the core musculature. Many studies fail to use control groups in their intervention studies [55, 151] or fail to establish whether the results are as a direct result of the intervention itself or other external variables [89]. Both of these are important components of a scientifically sound intervention [200]. Failure to comply with these scientific regulations leaves the research open to failures in data collection, analysis and evaluation [201, 202]. The Medical Research Council (MRC; a government-funded organisation for conducting and supporting medical and related scientific research) developed a ‘Framework for development and evaluation of randomised control trials (RCTs) for complex interventions’. Using this framework to structure a research study provides a scientifically sound method to formulate a complex intervention as it uses predictive theories to inform the choice of interventions that will improve the likelihood of a successful intervention [201]. The framework has been used in the clinical sector to establish innovative complex intervention strategies which up until then had resulted in conflicting findings [202-205]. For example, Blackwood [203] reported how it proved useful in defining and evaluating the components of a nurse-directed intervention for weaning patients off mechanical ventilation in intensive care units. Robinson et al. [204] also used the framework to develop an intervention for carers of stroke patients, which up until then had many conflicting suggestions regarding the best methods for carers to use which were not theoretically well supported.

Other frameworks have been implemented in the literature to help design intervention studies [206]. For example, the Management Information Systems (MIS) research framework [207]. This framework provides a structure for designing and directing MIS research and identifying worthwhile areas of research in the area. Evans [206] outlines a ‘Hierarchy of Evidence’ framework which can be used to enable different research methods to be ranked according to the effectiveness, appropriateness and feasibility of the methods. This framework has largely

been used in clinical practice and helps determine the best evidence where multiple research methods have been used (i.e. different populations and settings). Both the MIS and Hierarchy of Evidence frameworks provide a good rationale and structure for a research project, however the MRC framework provides the better progression of phases building on initial research findings leading up to an intervention (which was the aim in this thesis). In the sporting sector, the MRC framework has not been used to formulate complex intervention strategies. It can be suggested that by implementing this approach in such a context, positive measures could be taken to develop a scientifically sound and gold standard experimental methodology. This study will be the first to implement such a framework in the sporting sector to design a complex intervention programme for highly trained athletes.

This thesis is to adopt a MRC framework approach in the collection of data and formulation of its conclusions [2, 10, 200]. The MRC developed the framework to help researchers choose the appropriate methods, understand the constraints on experimental design and evaluate the available evidence in light of the methodological and practical constraints of randomised controlled studies [10]. This framework is based on the implementation of exploratory trials that establishes general trends and theories of the topic area, which are then investigated further with more in depth conclusions and understanding outlined (see Table 2.1). Where there is a current lack of published research in an area (such as core stability and core strength) it is important to establish initial theories surrounding the topic and subsequently test these in controlled trials and draw on the findings to provide a more in-depth understanding. Many studies to date have failed to implement an exploratory study prior to conducting their main intervention trial [155, 185]. This may be why many core training intervention studies to date have failed to observe actual performance improvements [50, 97]. This is due to the researchers failing to accurately establish which core exercises are the most effective in activating the core musculature to the required level for their performance tests and failing to establish the repeatability of their performance measures which is needed to be able to identify important performance changes [208]. In the current thesis, a general literature review on core stability has been carried out (pre-clinical phase), followed by a study investigating the repeatability of using sEMG for collecting core musculature data and investigations comparing

different methods of sEMG data analysis (Phase I). This is followed by an investigation into different types of core stability and core strength exercises and a short-term and long-term exploratory study being completed (Phase II). An outline of the MRC framework and its phases is shown below (Table 2.1). The main aim of completing an intervention is to establish any changes as a result of its implementation. To establish any potential change, the researcher must measure and quantify the active ingredient involved, for example in this project, the active ingredient would be the sEMG activity of the core muscles. It is important that this muscle activity is quantified in a repeatable manner to establish whether benefits from such training occurs (i.e. muscle activations of over 60% MVIC for strength benefits or activations of 10-25% MVIC for stability adaptations) [100]. Using Phase I and II studies as outlined in the MRC framework can help establish these.

Table 2.1. The Medical Research Council (MRC) [2] framework for designing complex interventions (RCT – randomised controlled trial).	
Pre-Clinical - Theory	Explore relevant theory to ensure best choice of intervention and hypothesis
Phase I - Modelling	Identify the components of the intervention and the underlying mechanisms by which they will influence outcomes
Phase II - Exploratory Trial	Describe the constant and variable components of a replicate intervention
Phase III - Definitive RCT	Compare a fully-defined intervention to an appropriate alternative using a theoretically defensible, reproducible and adequately controlled protocol
Phase IV - Long-term Implementation	Determine whether others can reliably replicate your intervention and results in uncontrolled settings over the long term

Phases III and IV of the MRC framework cannot be implemented in the current thesis due to the nature of the topic area being studied. The theories relating to the design of the

interventions are largely unproven and the data collection methods are in their early days regarding the reliability of the data, subsequently a fully-defined intervention cannot take place. Phase IV of the framework is not possible due to the subject population being studied. Elite and sub-elite level athletes have a relatively short career span which prevents long-term studies (i.e. >10 years) from being conducted. Furthermore, during an athlete's career many factors would affect the measured outcomes of a long-term study, for example, chronic injuries and changes to the training programme depending on the athlete's competition / event focus and changes related to increasing age (i.e. high threshold training would decrease as the athlete gets older and the body becomes more predisposed to injuries). This would prevent clear, definite conclusions to be made regarding the interventions effectiveness.

### **Aim of Chapter**

To establish the structural and methodological framework needed to enable the implementation of a core training programme in elite and sub-elite athletes.

## **2.2 Methodological Framework**

Prior to establishing a core training programme, it is essential to perform an assessment on the individual's current core stability and strength [48]. Exercises such as; the lunge, step-down, single leg press and balance tests have been used in the past [48, 60]. However, many of these have not been well researched in their effectiveness on actually improving sporting performance but have appeared to be reliable in identifying an improvement in core ability (stability, strength and endurance) [209]. For example, the multidirectional reach test, Sahrmann core stability test, star-excursion balance test and single leg squats have been found to be reliable and valid core ability tests [210, 211]. Stabilisation exercises, such as the curl-up, side-bridge and the birddog have also been well reported [56, 197].

Most core strength and stability assessments to date have focused on testing joint range, muscle strength (power and endurance), muscle extensibility and trying to establish functional tests for core stability and strength [48]. Comerford [48] outlined a reliable, low threshold assessment of motor recruitment to assess the stability function or dysfunction in individuals. He stated that a 'pass' required no movement induced pathology and pain free function.

Comerford [48] also outlined a measure for assessing muscle strength. He suggested that this is measured as the ability to pass (good power, endurance, high-load performance) or fail (weakness or loss of performance) a test of resisting or supporting a high-load. Ball et al. [92] suggested that tests can be used to identify deficiencies in low threshold muscle recruitment and motor control, which can help establish a correlation between poor motor control and musculoskeletal injury. Previous research has suggested that deficits in low-load threshold recruitment and motor control can be identified prior to an injury occurring [48] as it is these dysfunctions that lead to the onset of pain and injuries [47]. It is important that the dysfunction is identified prior to pain arising, therefore establishing valid and reliable monitoring tests is essential, especially for high performing athletes when performance needs to be maximised.

However, the tests outlined above do not provide an objective quantified measure for core stability or core strength ability. It only enables a subjective ‘pass or fail’ decision to be made. It is important to be able to establish the different activation levels of the individual core muscles to be able to highlight any specific weaknesses of an individual’s core ability and to be able to distinguish between the more effective core training exercises which activate the core musculature to the optimal level. Using a measure such as electromyography (EMG) enables such information to be established as long as valid and reliable data can be recorded [120].

### **2.2.1 Validity of sEMG**

Validity of a measurement is important to establish to enable the researcher to be confident that the measurements recorded accurately represent the variable being tested. sEMG has been used in scientific studies for many years to quantify the characteristics of the musculoskeletal systems during almost all types of body movement [77, 121]. The validity of this measurement and how accurately it reflects the actual muscular activity being produced within the muscle has also received much attention [120]. It is generally accepted that sEMG is a valid method of measurement, however there are important methodological issues that need to be considered to optimise this validity of the signal recorded [4, 121].

The number of trials obtained from an individual influences the stability of the measure and resultantly how valid the measure appears to be [205, 234, 235]. Only performing one or two trials may not represent the true performance response. By collecting sEMG data on multiple trials, a stable and typical performance response can be obtained. Previous research has established that for different activities, different numbers of trials are required to achieve sufficient stability of the sEMG data (running 8 trials [212], walking 10 trials [213], jumping 12 trials [214] and landing 4 - 8 trials [215]). This variation in number of trials needed may be due to the different demands on the body during the different movements, for example, the higher loading and more demanding movements (e.g. jumping) will have more variation between trials, requiring more to be performed to establish the common value. Movements that have a lower demand and are more 'predictable' may only need 3 - 6 trials to establish a stable value. Therefore the number of trials to be performed needs to be considered when designing a study to make sure that the typical performance response is obtained.

Generally (for scientific studies) it is not recommended to use only one subject as this prevents generalisation of findings to the wider population [216]. This is due to the possibility that the chosen subject may not show the typical response of that specific population of individuals that they belong to. However, single subject designs have been used in previous literature [217, 218] and have been found to result in generalisable results as long as adequate repetition and careful subject selection has taken place [219]. Single subject designs have been used in the past to help establish early hypotheses for new areas of research [219, 220], for example, by being able to establish if between subjects variations also occur within subjects. Currently, there has been no published research into the within-subject repeatability of the core musculature when performing core stability and core strength exercises. Therefore, by carrying out this research (as this thesis proposes to do, Chapter 3) using both methods stated above (multiple subjects and single subject) an early hypothesis regarding the repeatability of the core musculature muscle activation during core strength and core stability exercises can be established. This information then has important consequences on establishing the ability of being able to identify significant changes in performances following a core training intervention programme.



### 2.2.2 Repeatability of sEMG

Atkinson and Nevill [216] suggest that repeatability is the amount of measurement error that has been deemed acceptable for the effective and practical use of a measurement tool. Hopkins [221] defined reliability as the reproducibility of values of a test in repeated trials on the same individuals. Meanwhile, Viitasalo and Komi [222] defined reliability as the reproducibility of measurements within a test session and consistency as the reproducibility of measurements between test days. Atkinson and Nevill [216] suggest that reliability can be defined in terms of the source of measurement error; internal consistency reliability (the variability between repeated trials within-day) and stability reliability (the between-day variability in measurements). It has been suggested that there are three components of repeatability that are important; change in mean performance, within-subject variation and retest correlation [223]. Hopkins et al. [223] suggest that the within-subject variation is the most important as this is used to help define the sample size required for any subsequent experimental study.

Reporting absolute and relative reliability of a test is also important as the two measures provide different information regarding the reliability of the test [216, 224]. Absolute reliability is the degree to which repeated measurements vary for individuals (reported usually as a proportion of the measured units; e.g. CV, SEM, TE) [216]. While relative reliability is the degree to which individuals maintain their position in a sample over repeated measures (reported usually as a correlation coefficient; e.g. ICC) [224]. Reliability has also been defined in terms of the source of the measurement error. Baumgartner [225] suggested that the variability observed between repeated trials within-day should be referred to as internal consistency reliability, while between-day variability should be termed stability reliability. As these two types of reliability refer to different characteristics of the data, it is recommended that a measure is calculated which represents both forms of reliability (e.g. CV and ICC) [216]. For example, relative reliability could be affected by the range of values measured, while absolute measurements are not affected by this variable [216]. Atkinson [216] highlights some of the advantages and disadvantages of both types of measurements, for

example, using absolute methods makes it easier to extrapolate results to new individuals and compare between measurement tools. Meanwhile, reporting relative reliability enables conclusions to be made regarding how consistently the measurement tool distinguishes between individuals in a particular population [216].

Quantifying the measurement error and variation in the EMG signal enables the researcher to establish what extent of the difference between two sets of the same measurements is due to measurement error and what may be due to for example, an intervention programme. If the measurement error of a signal is quantified, it is then possible to account for this in any subsequent measurement changes when the data is re-collected. It can be assumed that any difference outside of the error measurement established by the repeatability study is subsequently due to the intervention programme.

Whatever method of data collection is used, whether it is sEMG, fine-wire EMG or ultrasound data, the repeatability of the collected data needs to be quantified. For example, if sEMG data is being collected before and after a specific training programme, the sEMG signal and equipment set-up need to be as identical to the first data collection as possible (e.g. the reliability of putting electrodes on the same landmark). This enables any changes in muscle activation (as a result of training adaptations) to be identified. Good repeatability is essential when small (but potentially significant differences) represent a performance improvement, as has been seen in core training studies to date [18, 62, 80, 199].

If the measurement error is large (and the repeatability therefore low) this makes it difficult to accurately identify and measure any significant changes in the measurements. If the variation observed between trials when the exercises are performed on the same day is large then this variation is assumed to only be increased if these exercises are performed by multiple subjects or performed over a number of days. It represents no repeatability in the data values measured and makes it very difficult to identify whether there has been a true significant effect on performance due to the intervention.

By performing a repeatability analysis this provides the data needed to be able to accurately establish the required sample size for an experimental data collection. Sample size estimations are based on the power of the signal being measured and how confident the researcher is on the accuracy of the measurement being taken [226]. If the repeatability of a signal is high and consistent, a smaller sample size would be required as the researcher can be more confident that the measurements they are taking are representative of the wider population. If the measurement error is large and repeatability of the signal is low, a larger number of trials or subjects would be needed for the researcher to be confident that the data they are collecting is representative of the wider population and therefore is an accurate representation of the desired measure. Therefore establishing the repeatability of a signal and data collection protocol is essential in a research study. Failure to quantify the measurement error in the data makes it difficult to conclude what effect an intervention has had (as there is no way of separating what is due to error and what is a true change in the signal due to the intervention).

sEMG is susceptible to large variations in data recorded due to the nature of the signal being quasi-random in nature and because of the substantial effect that the data collection procedure has on the resultant signal obtained from the muscle [120]. As a result it is essential that any research using sEMG establishes the repeatability of the data collection procedure used to enable the subsequent data to be of any value [121]. Measurement variations should represent true differences in muscle activity between different exercise conditions and different subjects [227].

To establish the repeatability of a signal it is necessary to quantify the within-subject variation. This includes measuring random (results from biological and mechanical variation of muscle activation and inconsistencies in measurement protocol, i.e. change of technique used) [228] and systematic errors (change in mean of a measure between consecutive trials as a result of factors such as; learning, fatigue and motivation) [216]. These errors need to be quantified and subsequently eliminated from estimates of within and between-subject variations if they are outside of the acceptable limits [221]. Some muscles show more variability in muscle activation than others both between and within-subjects [100]. This variation could be due to

a number of factors such as; muscle orientation, electrode placement accuracy, muscle composition and the role of the muscle during the movement (i.e. stabiliser or mobiliser) [120, 121].

Within-subject repeatability has been reported in electromyography studies to establish how effective data collection protocols are in producing the same response from the human body over multiple trials [227, 229]. This enables the measurement error that is deemed acceptable for the effective practical use of a measurement tool to be quantified [216]. Therefore it is important to establish within-subject repeatability and determine trial to trial and between-day trial variations [216]. Within-subject repeatability has in the past been reported in terms of coefficient of variation (CV) and reported as a % of variation and represents the typical within-subject trial to trial variation [221]. To establish within-subject CV values, two methods can be used. Firstly, one individual is tested multiple times using exactly the same experimental set-up and data collection procedures, or secondly, multiple subjects perform the same exercises but fewer times. Both methods provide within-subject variation data that can be used to establish the repeatability of a set of data. Intraclass Correlation Coefficient (ICC) has also been used as a measure of reporting the repeatability of within-subject variation during EMG data collection [227, 230] (see Table 2.3). An ICC describes how strongly units in the same group resemble each other and can be summarised as the ratio of between-groups variance to total variance [231].

Pincivero et al. [232] suggest that measures of maximal force or torque within a day are highly reproducible [207, 214, 215] and reported an ICC of 0.93 for knee extension torque. However EMG activity measures have been reported to display a higher variation [233, 234] with ICC values of between 0.7 - 0.8 [232]. This greater variation is due to the nature of the EMG signal being dependent on technique used and physiological fluctuations in the number and rate of motor units recruited during movements (quasi-random nature) [120]. Juker et al. [103] referred to this as myoelectric variability and suggested that even highly skilled athletes have difficulty repeating certain tasks due to this neural variation. Therefore EMG data will always have some variation between data measures but it is essential that this variation is

minimised to only the uncontrollable neural factors and that all other errors are removed. The reproducibility of EMG data is dependent on many factors and explains the large variations sometimes observed when using EMG between-subjects [231] and between-days [235], for example; electrode placement [121], electrode size [120], width (ms) of the signal averaging window [235], skin temperature, body fat and muscle fatigue [122]. However if these factors are closely controlled and kept constant throughout testing then reliable sEMG data can be collected [235, 236]. For example, Marshall and Murphy [68] investigated the validity and reliability of sEMG for core muscle analysis. The authors concluded that the signal representing the TrA muscle accurately demonstrates the functional activity of the muscle. However, Comerford [48] suggests that fine-wire EMG recordings are the only reliable assessment that enables the automatic recruitment of local stabiliser function to be reported. Vezina and Hubley-Kozey [100] did observe high between-subject CV for sEMG activation amplitudes (in some cases up to 50% variation). Although they do point out that similar differences have been identified in EMG traces of the gait movement, which is a well-learned cyclic activity. They concluded that the variation may be due to the subjects lack of experience performing the exercises required and due to the variation in physical activity of the subject sample. The authors also concluded that some of the variation between subjects is due to the normal instability of motor recruitment between muscle activations and the natural variation of muscle recruitment.

### **2.2.2.1 Between-Subject Variability**

Within the EMG literature published to date, there is a large amount of research which suggests that factors such as, body composition [122] and muscle fibre type [237] (which are reflected in gender differences) [120] do influence the resultant EMG signal [121]. This would in turn prevent male and female subjects being grouped together in EMG studies [121]. Despite this many studies use mixed genders for their sample population [206-208, 216, 219]. For example, Behm [238] reported no gender differences in the repeatability of muscle activity which supports research that has found no gender differences when performing MVC exercises [232, 237]. Therefore it is possible when comparing within-subjects, to group the

different genders together and furthermore, between-subject measures can be recorded as long as a normalisation method is applied to the data [239].

When collecting EMG data between-subjects (which are to be grouped together) it is essential that a normalisation procedure is followed [239, 240]. This enables multiple subjects of differing muscular strengths to be grouped together [241]. The normalisation procedure involves individuals performing a series of resistance exercises which usually elicit a maximal muscle contraction [242]. This value can then be used as a reference for the individual's 100% muscle activation level and subsequent muscular contractions are normalised to this level of activity [240]. Winter and Yack [243] suggested that the normalisation process reduces the possible pre-test variability between subjects when collecting EMG data. The normalisation process and the different methods available will be discussed in more detail later in this Chapter (section 2.2.2.5).

#### **2.2.2.2 Within-Subject Variability**

The potential for within-subject variation during sEMG data collection is greater than when other parts of the musculoskeletal system are analysed as small differences in technique can affect the subsequent core muscle activation levels [244]. Therefore the variation within and between-subjects could potentially be very high if different techniques are used for the same exercise [245]. This variation needs to be quantified and kept to a minimum by including methods such as exercise familiarisation. For example, Sarti et al. [244] observed differences in EMG amplitudes when the pelvic tilt was performed with correct and incorrect technique. Therefore it can be assumed that reliability and consistency of the EMG activation pattern can be improved with learning and repetition of an exercise over time [246].

#### **2.2.2.3 Between-Day Variability**

The variability of data collection between-days is essential when collecting sEMG data from the same or multiple subjects over a number of days to minimise the measurement error. Yang and Winter[234] determined the variability of sEMG within and between-days when nine subjects performed a range of MVC exercises (30%, 50% and 100%) over three days.

They observed that within-day CV values were similar for all three MVC levels (100%, 50% and 30%) ranging from 12% to 16%. As a result, when collecting sEMG data on multiple subjects on different days, it is essential that the experimental protocol is kept the same (e.g. electrode placement, speed of movement, skin temperature) as much as possible to minimise the potential measurement errors.

Yang and Winter [234] observed that between-day variability (12 - 16%) was higher than within-day variability (8 - 10%). This is supported by Vitasalo and Komi [230] who found MVIC rectus femoris within-day ICC values of 0.77 - 0.92 in 12 subjects, while between-day ICC values were 0.34 - 0.88. This is also supported by further studies [129, 230]. This difference is largely due to the removal of the EMG electrodes between-days and the lack of accuracy on replicating the same position and orientation on the muscle when reattaching the electrode in further testing sessions. This has important implications for EMG data collected on multiple days as it is important to establish a repeatable data collection protocol that can be performed on multiple days, on multiple subjects with very little variation. By establishing this, the external factors influencing variability will be minimised and the measurement error reduced which subsequently makes identifying any changes in resultant sporting performance easier to identify.

#### **2.2.2.4 Within-Day Variability**

Veiersted [247] observed within-day CV values of 23% when sEMG was used on the trapezius muscle and MVIC exercises were used for the normalisation process. This value is lower than that observed by Winter [248] who found CV ranging from 41 - 91% in 11 normal subjects but is in accordance with values observed by Knutson et al. [231]. Knutson et al. [231] suggest that this variation seen between-subjects may not necessarily be bad as it enables group differences to be identified and implies a complete sample of the population. However when looking at a particular group of individuals that are highly trained and trained to perform the same movement (e.g. a swimming stroke), a small group variation (low CV) would be preferred [216].

### 2.2.3 EMG Data Analysis Methods

The variability reported by different studies may be in part due to the data processing method used. The size of the signal averaging window used to smooth the EMG signal has been found to affect the variability observed in the resultant EMG signal used for analysis. Bamman et al. [235] reported that larger overlapping windows of 500 ms and 1000 ms increased the repeatability of EMG data. This is supported by Heinonen et al. [249] who observed CV of 12, 10, 7 and 6% for windows of 100, 500, 1000 and 2000 ms respectively. However, a limitation of the larger averaging window is that it results in an over-smoothed data set and makes it harder to establish true maximal values and subsequent differences in EMG data. Bamman et al. [235] also observed that the method of data analysis affected the subsequent repeatability conclusions of the data. When the ICC method was used to analyse repeatability of the RF muscle during a isometric knee extension exercise, Bamman et al. [235] found that a moving window of 100 ms resulted in ICC values of 0.89 for trial to trial reliability and 0.85 for between-day reliability compared to 0.72 and 0.88 when a 500 ms moving window was used. This highlights the effect that the method of measurement has on the subsequent findings (this has also been found in other areas of research where different statistical methods have resulted in dissimilar findings) [215].

When using EMG data for analysis of levels of muscular activation, it is necessary to normalise the data and reduce the variability observed between the subject's data [239]. The most common method of normalising EMG data is to use a form of maximal contraction of the muscle under investigation and use that value as a reference for the individual [240]. A variety of exercises have been used to produce a MVC of muscles for normalisation of EMG data [184, 204, 225]; isometric and dynamic exercises, 50% and 100% efforts of contraction. What value is subsequently used from these exercises varies with both the peak [227, 239] and mean [231, 235] values being used previously. Burden [240] provides a comprehensive review of EMG normalisation studies published to date and summarises the repeatability and sometime conflicting findings of these different methods reported to date.



The repeatability of MVIC exercises has been previously reported and has been expressed in many ways [190, 206, 208, 216, 223]. A simple form is to use the typical standard error of measurement. This is the standard deviation of an individual's repeated measurements and is usually expressed as a CV (percentage of the mean) [107, 209, 216, 226, 227]. Other methods such as ICC [216] and variance ratios (VR) [221] have also been used to quantify the repeatability of sEMG data (see Table 2.3).

Study	Normalisation method	Repeatability Method		
		ICC	CV (%)	
			Within-subject	Between-subject
Bamman et al. [235]	Isokinetic	0.93	8.4	9.5
Pincivero et al. [232]	Isokinetic	0.85-0.96	none	none
Bolgla and Uhl [227]	Isokinetic	0.93	11-22	55-77
	Dynamic – mean	>0.85	11-22	19-61
	Dynamic - peak	>0.85	11-22	19-61
Knutson et al.[231]	Isokinetic	0.80	38.1	91.3
	Dynamic – mean	0.54	26.5	37.2
	Dynamic - peak	0.66	23.8	41.9
Yang and Winter [242]	Dynamic - mean	none	none	52-119
Winter [248]	None stated	none	25-38	41-91
Viitasalo and Komi [230]	None stated	Within day ICC 0.77-0.92	Between day ICC 0.34-0.88	
Viitasalo et al. [236]	None stated	Within day ICC 0.95-0.98	none	
Liemohn et al. [250]	None stated	Within day ICC 0.71-0.95	Between day ICC 0.51-0.94	

Previous research findings suggest that the MVIC normalisation process can provide a satisfactory method of normalising sEMG data that reduces between-subject variability. For example, Bamman et al. [235] established that by using a MVIC exercise targeting knee extensor muscles, it was possible to produce reliable sEMG data. This is supported by

Knutson et al. [231] who analysed a hip abductor muscle during dynamic and isometric MVC exercises and calculated within-subject CV values of 11 - 18%. Bolgla and Uhl [227] also reported within-subject CV ranging from 11 - 22% for both MVIC and dynamic MVC exercise methods.

To date, research has investigated the reliability of sEMG data for both the upper [239] and lower extremities [251] but little research has assessed the reliability of sEMG data when performing MVIC exercises on the core musculature. It is essential that this data is obtained and quantified as any large variability in the data recorded would influence subsequent calculations and conclusions regarding the level of the core muscles involvement in the activities performed [216].

MVIC normalisation methods must establish the movement and body position that produces the largest possible EMG amplitude for that muscle [239]. Ekstrom et al. [239] established that no one muscle test produced a MVIC for all individual's. Therefore to normalise, at least two or three MVIC tests need to be performed. Current research suggests that the use of MVIC can provide reliable measure of muscular demands during lower extremity exercises [231, 252]. Prior studies [170, 253] have suggested that by using restraints and making sure that the subjects are familiar with the MVIC exercise reliable MVIC values can be obtained (ICC value  $>0.92$  [235]) and so it can be suggested that MVIC exercises are a proven technique for eliciting maximal contractions.

Therefore, when performing an EMG study there are a number of important factors to consider. Firstly, the repeatability of the pre- and post-testing methods following an intervention programme (e.g. the repeatability of putting electrodes on the same landmark). This is essential if data is going to be compared for any significant differences, especially when small differences may represent an improvement. Secondly, the MVIC methods must be used carefully when analysing surface EMG results and when comparing between muscles to a single exercise or a sub-maximal effort [11, 68, 135]. Veniza and Hubley-Kozey [100] suggest this is especially important when looking at the abdominal muscles as they are not

activated in a linear manner and that different exercises elicit different maximum EMG values from different muscles in different people. Although some researchers [246] found problems bringing about a maximal response in muscles, Vezina and Hubley-Kozey [100] maintain that using this measure provides a basis for interpreting the EMG and comparing them among muscle sites. If the MVIC was not maximal then the reported activation during the exercises would be an overestimate. This has to be kept in mind during any interpretation of the EMG findings. Thirdly, how the sEMG data is analysed also influences the findings, for example, if peak muscle activation is used as a reference and a % of MVIC identified for an exercise, this does not represent the duration of muscle activity. For example, one exercise may result in a high % MVIC but for only a short duration (e.g. hanging leg raise), while another exercise may result in a low % MVIC but sustain a moderate activation for a long period of time (e.g. isometric side bridge support) [94]. It is not straightforward therefore to say that the higher % MVIC exercise is a better exercise as this would depend on what the objective of the exercise was, for example, core strength improvements or enhancing core endurance.

As has been highlighted above, many studies have been performed on the repeatability of different normalisation methods using maximal, sub-maximal, isometric and dynamic contractions to elicit muscular contractions using sEMG [240]. Less research has been carried out on the repeatability of the subsequent performance measures such as core stability exercises. To the author's knowledge, there are currently only two published studies that evaluate the repeatability of sEMG data collection on the core musculature when performing core stability and core strength exercises [238, 250]. Behm [238] calculated ICCs for the isometric side bridge support exercise of 0.96 and 0.98 for the dynamic bird dog exercise, which can be classed as excellent. Liemohn et al. [250] established ICCs for the front support bridge exercise of 0.90 and values ranging from 0.71 to 0.95 for other low threshold core stability exercises. More research needs to be performed to establish the repeatability of data collection procedures when performing core stability and core strength exercises both within and between-days. This would establish whether reliable muscle activation data can be recorded from the core musculature when performing core stability and strength exercises to

enable conclusions regarding which core exercises may lead to an improvement in overall core stability, strength and sporting performance to be established.

When performing core exercises it is important that they are performed and executed correctly by the individuals. Not only will this improve the likelihood of any neural adaptations and improvements in core stability and strength but it will reduce the likelihood of the individual suffering an injury due to excessive loading on the spine [12]. The subjects' should have sufficient time to familiarise themselves with the movements and exercises to reduce this injury risk and remove any potential learning effect during the performance of the exercises.

By establishing the repeatability of the data collection method being implemented, conclusions can be made regarding the sample size required for the subsequent intervention studies. This is to enable a sufficiently powerful sample which could lead to statistical significance in any adaptations measured as a result of the intervention.

#### **2.2.4 Sample Size Calculations**

Most sample size calculations are based on establishing the required number of subjects needed to establish inferences about a population mean effect. Repeatability studies can provide a useful tool in establishing what sample size is required for an investigation to take place that will result in a statistically powerful conclusion. Any justification of sample size is affected by the reliability of the dependent variable due to the effect of error on uncertainty [221]. Therefore if a test has high repeatability (observed error < smallest important effect) only a few subjects would be needed [221]. If there are reliability correlations between 0.7 - 0.9 or errors of ~2 - 3 times the smallest important effect are observed, then Hopkins [221] recommends that a sample of 150 - 200 subjects is needed. This poses problems for scientific studies that use complex methods of data collection and analysis, such as EMG. The data processing and analysis for these types of studies is complicated and very time consuming and sample sizes of over ten are very rarely seen because of this. Sample size 'on the fly' has also been suggested by Hopkins [221] as a method of allowing for individual differences seen between subjects as a response to the same intervention. This method does not put a definite

number on sample size, rather subjects are continually assessed until a sufficient trend is established between the subjects.

Sample size is proportional to;

$$(1-r) = e^2/SD^2$$

(r = test-retest reliability correlation coefficient)

(e is the error of measurement; within-subject standard deviation)

(SD is the observed between-subject standard deviation) [254]

Sample sizes can also be calculated based on the standard deviation of a measurement from a previous study [255]. Using this approach, the smallest worthwhile change and the standard deviation of the variable are calculated and affect the sample size required for a statistically powerful test to be conducted. For example, if the smallest worthwhile change is 18 for the variable with a standard deviation of 30, the required sample size per group would be 46 subjects [255]. Sample size is largely affected by the design of the study (a repeated measures design would require more subjects to a cross over design) [256]. For example, statistically it is stated that if a researcher wants to detect a 2% change in performance and the coefficient of variation is 2% in a repeated measures design then 32 subjects would be needed in both the control and experimental design or 16 subjects in a crossover design ( $p = 0.05$ , 80% power) [254]. Allocations for subject drop-outs during intervention and longitudinal studies should also be accounted for.

Hopkins [256] suggests that researchers can justify a sample size on the grounds that it is similar to those in similar studies that produce clear outcomes. Hopkins [256] also suggests that the defaults for establishing a studies smallest important effect are a change in the mean of 0.20 or a change in correlation of 0.10. It is therefore understandable that larger effects require a smaller sample size to establish a conclusive outcome. Subsequently, any justification of sample size should be based on a justification of the smallest important effect to be measured [257] (it has been noted that the smallest effects for performance measures

directly related to solo athletes are  $\sim 0.5$  of the competition to competition variability in performance) [208, 257].

Hopkins [254] suggests that when using an athletic population it is better to use within-subject variation to estimate sample size. This is due to the importance of establishing the enhancement that increases the performance of the top athlete and not the average athlete [254]. Hopkins [254] suggests that for track athletes, this minimum effect is 0.5 of the typical variation in an athlete's performance between events (if typical variation is 1%, then looking for enhancements of 0.5%). However because small enhancements in performance are being sought, to detect 0.5% with a typical variation of 2%, it is suggested that 1024 subjects would be needed. Clearly this is impossible to achieve with the general population let alone the elite athlete population, therefore it is essential that the reliability of the performance tests used are as repeatability as possible to make the detection of important changes in performance detectable. This leaves the question as to what is an important and worthwhile change in performance following an intervention training programme. Further questions such as; is this affected by the skill level of athlete? or the type and length of time of the sporting movement performed? also remain. Recent studies have attempted to quantify this worthwhile performance enhancement and are outlined below.

### **2.2.5 Establishing Worthwhile Performance Enhancements**

Hopkins et al. [223] suggest that research into measuring worthwhile performance enhancements is at a very early stage of development and the exact affect that validity, reliability, sample size, athlete behaviour and experimental test design have on this measurement are not yet established. To identify what difference is a worthwhile change in performance to result in an effect on the outcome of a sporting event the researcher needs to establish what the natural random variance of that sporting event is. For example, Hopkins et al. [223] analysed the 100 m sprint event and found that the normal variation between sprinters running the same race again and again would be  $\sim 0.6\%$ . They subsequently identified that by obtaining an enhancement of just half this natural random variation would result in a real enhanced chance of winning the race more often. Interestingly they also noted that this CV

increased as event duration increased, for example during a 5000 m running race the CV was 1.7% between races. Therefore the CV and the worthwhile performance enhancement level varies with type and duration of the performance event [223].

Hopkins et al. [223] also showed that the skill level of the athlete affects the performance enhancement needed to be achieved to result in a performance enhancement. They showed that during a 100 m sprint race, the athlete who usually comes 10<sup>th</sup> in the field, and who only wins 1% of the time (based on natural variation), would need an increase in performance of 1.3% of the CV to increase this winning percentage to 11%. In turn, the athlete who usually wins the race (38% of the time), would only need an increase of 0.3% to increase his chances of winning each time to 48%. Therefore improvements of only 0.3% are required for the best athletes. With sub-elite athletes, the potential to make improvements in performance is greater, however the observed enhancement needed for this sub-elite group would need to be larger to have an effect on winning ability. It is also more likely that the intervention or tests will have greater between-subject variations with some benefiting and others not so in a sub-elite population. However due to the larger enhancement effect being looked for, the required sample size for this population in an experimental study is reduced and therefore provides a more accessible population to study.

Using the above estimate of needing to establish a performance enhancement of 0.3% and using laboratory tests to try and bring about this effect which have reliability levels of around 1 - 3% (e.g. cycle to exhaustion, run for lactate threshold) [223], Hopkins et al. [223] concluded that to achieve the required precision in the data, hundreds or even thousands of subjects would be required (350 for a crossover study and 1400 for a control group design). Hopkins et al. [223] go on to state that the usual number of subjects in performance enhancement design studies is ten subjects. This means that the precision of the conclusions is not as accurate and instead of being able to state an effect of between 0.0% and 0.6% (95% confidence interval), this would be reduced to an effect anywhere between 2.3% and -1.7%, therefore resulting in a conclusion spanning a performance enhancement or a performance reduction. In this instance Hopkins et al. [223] recommends reporting the findings on the

basis that they may produce a performance enhancement that might benefit competitive athletes, but would need to be tested on more athletes to be sure [223].

Hopkins et al. [223] state that the need for statistical significance is not necessary when looking at performance enhancements as small as those that are significant within elite athletes. Because of the small sample sizes and small changes in effect, establishing statistical significance ( $P < 0.05$ ) is highly unlikely. Hopkins et al. [223] suggest that the best method is to state the 95% confidence intervals and the observed change in performance and then explain this change and observed confidence intervals as to the potential impact on overall performance. They suggest that statistical significance is not needed and is more likely to result in incorrect conclusions to be drawn and effective enhancements in performance being thrown out as ineffective. For example, Madsen et al. [258] reported a non-significant performance enhancement of 3 minutes during a 160 minute cycle time trial. This represented a 1.8% enhancement, which Hopkins et al. [223] argue that this is actually a worthwhile improvement.

Previously published swimming studies that have investigated the effect of core training programmes on swimming performance have reported improvements of between 2.1 - 4.4% of swimming performance. Girolid et al. [118] found improvements of 2.8% (1.05 seconds) during a 50 m swimming time trial and 2.3% (0.96 seconds) during 25 m swimming time trial following a training programme involving dry-land stability exercises and wet-resistance training exercises respectively. This is supported by Strass [119] and Sharp et al. [116] who found improvements of 4.4% (25 m) and 2.1% (50 m) following a six week training programme and a 3.6% (25 yards) improvement in swimming performance after an eight week swim bench training programme respectively. Trappe and Pearson [199] reported an improved sprint swimming performance of 0.3 seconds over 22 yards following a six week fixed and free weight training programme. Therefore based on previously published literature, improvements in performance of over 0.3 seconds in swimming performance could be concluded as a significant improvement in performance. This length of time would depend on the distance of the analysed swimming time trial with smaller improvements in the shorter



distances representing a significant improvement. For example, a 2% improvement in 25 m time of 20 seconds would be 0.4 seconds, with a 2% improvement in 100 m time of 90 seconds being 1.8 seconds.

## **2.3 Structural Framework**

This thesis proposes to implement a series of experimental studies to establish the reliability and inter-relationship of EMG methods of measurement, explore the effectiveness of core stability and core strength training exercises and establish the effectiveness of a specifically designed core training intervention programme for highly trained swimmers. These will be carried out following the MRC proposed framework for complex interventions [10].

### **2.3.1 Phase I: Development of the Intervention**

Following the initial assessment of an individual's core ability, a suitable core stability and/or core strength training programme can be devised and implemented [99]. It is essential that this training programme is specific and functional for the individual so that any improvements in core stability and/or strength are transferable to the sporting or everyday movements that are required to be performed [71]. It is recommended that the training programme is constructed by individuals who have a good understanding of the physiology and mechanics of the body and also in developing exercise training programmes to ensure that the most effective programme is implemented [101]. Focus groups or steering groups have been used within the MRC framework to help design intervention programmes [202, 205]. Murchie et al. [205] suggested that using this type of group discussion enables a blend of perspectives from different disciplines and enables individuals to share their knowledge and expertise of the area to formulate the optimal solution.

The timing of the training intervention programme in the swimming season needs to be carefully planned and could have a major impact on the effectiveness of the training programme to result in improved performances. It is important to implement the training in the correct periodisation phase of the athletes' training [99]. For example, if the training

programme takes place during a busy competitive period of races, physical and mental fatigue could reduce the quality of the core training sessions and as a result, reduce the potential benefits that this training may provide. Performing the training programme early on in a swimming season may be the best time to implement an intervention study, as the training focus may be on smaller races and restoring the athlete's fitness. Based on previous research findings, training intervention programmes of six weeks or more in duration have resulted in positive adaptations on core stability, core strength and subsequent sporting performance [119, 199]. Some studies have used two sessions per week and found that no improvements were observed which may have been a result of a lack of training on the targeted muscles [97, 155]. Previous intervention programmes of six weeks duration that have used three sessions per week (30 - 40 minutes) have observed favourable results in improving core strength and stability [117] and observed a reduction in injury risk [161]. This suggests that this frequency of training could be beneficial to acquiring performance enhancements.

Any training intervention programme needs to follow a progressive series of exercises and include a gradual increase of intensity and/or frequency to result in the overload principle [3, 49, 52] which will lead to the physiological adaptations within the muscles enabling strength and stability improvements [99]. As the training progresses the individuals should become more accustomed to the exercises and the muscles adapt to the training demands. Therefore to keep overloading the muscles to adapt further, greater demands need to be placed on the muscles. This can either be done by increasing the weight or external resistance during the exercise or by increasing the number of repetitions that are performed either by adding another set or increasing the amount of repetitions during the current number of sets. The progression and overloading of the core muscles during the training programme is theorised to result in a variety of physiological adaptations to the muscles [101]. But it is essential that the training movements activate the muscles to the required levels to enable these training adaptations to take place and subsequently have an impact on performance.

It is important that training exercises are performed in a similar manner to that of the sporting performance to maximise the potential for training adaptations to be represented in an

improved sporting performance. For example, with swimmers, it is important that core training exercises are performed at a rate that is similar to that used when swimming during high intensity sessions and races. During 50 m freestyle swimming races, stroke rates of 44 - 49 strokes per minute are observed in elite level swimmers [259] (for sub-elite swimmers it can be assumed that this would be slightly decreased). Therefore exercises should be performed at a similar rate, for example, the overhead squat exercise could be performed so that the downward movement is completed in two seconds and the upward movement the same with a continuous movement between repetitions to simulate the continuous swimming cycle of the arms and legs.

In published studies to date, a range of core muscles have been analysed using sEMG methods [12, 138, 232]. Most of these are restricted to the ‘traditional’ core muscles; TrA, RA, EO, IO and ES muscles [12, 18, 70, 181, 193]. It is commonly accepted in the current literature that the core includes more than these trunk muscles and extends to the upper legs [252] (e.g. RF) and shoulder (e.g. LD) [75]. It is especially important to include these extra muscles outside of the trunk when analysing sporting movements that are performed in all three planes of movement and involve multi-joint movements and force transfer through the body. Studies have identified the main muscles involved during freestyle swimming [165, 172, 180] and these include leg, trunk and arm muscles to varying extents during the swimming stroke [82]. As a result, a training programme must target and train these muscles in a functional sport specific manner. For example, exercises should include; static and dynamic exercises, low and high threshold exercises and symmetrical and asymmetrical movements. Current research in this area is severely lacking, with very few core training exercises having been analysed and subsequent muscular activity during these quantified. Exploratory trials can be used to establish these values and subsequently highlight any trends in the data.

### **2.3.2 Phase II: Exploratory Trials**

The MRC recommends that an exploratory intervention is performed prior to the main intervention being implemented [10]. This can be used to test the assumptions and strategies established in the theory and modelling phases and help provide vital information regarding

the variants of the intervention and their possible effects on the outcomes (for example, subject recruitment and measurement of the outcome).

The simplest form of a subject research design study is an 'AB design' [220]. This is where the subjects perform a set of measures prior to an intervention period and then repeat the same set of measures following the intervention period. This assumes that any difference between the measures is due to the intervention programme. However, it is possible that factors such as; a learning effect, natural trends over time and other training conditioning effects may also influence the re-test values. It is important between the test and re-test sessions that no new training or activities are taken up during this time which may affect the re-test data and that a detailed training diary is kept during the intervention period.

It is important to collect data not only on the intervention training group but also on a group of individuals that do not perform the training programme. This is to be able to measure what the effect of the training programme is above the normal improvements that might be seen over time from the other types of training that the subject sample is performing (e.g. pool-based swimming sessions). Clear conclusions can then be made regarding the effectiveness of the core training programme on the core training group. Some studies have reported positive effects of a training programme on one group of subjects following an intervention programme [11, 116]. However quantifying the effect of the intervention on performance cannot be established as they fail to report whether a non-intervention performance improvement occurred in a control group during the study.

To be able to identify any alterations to performance, it is important that the subjects are of a similar ability and all have experience of performing the core exercises. This makes the group more homogenous and improves the repeatability of the data [254]. In previous studies a wide range of subject populations have been used from full college year groups [187] to selected swimmers of a certain level of ability [199]. Trappe and Pearson [199] observed positive results from a sample of ten male swimmers (five of whom received the training and five formed the control group). Girolid et al. [118] also found positive results from training a

group of 21 swimmers in three different training conditions. During intervention studies, large groups of subjects make it hard to monitor and closely control what training is actually being performed, whereas a smaller group of athletes that perform the correct amount and level of training may result in a more controlled and accurate intervention study [260].

To be able to evaluate the effectiveness of the core training programme it is essential that performance measurements are taken prior to the core training programme taking place. Many types of performance measures have been used in the past, for example, vertical jump height, balance tests, strength measurements on isokinetic machines and actual sporting performance (e.g. 2000 m row, treadmill running test) [24, 104, 119, 120, 132, 151]. As with the exercises performed, it is important that the performance measures used reflect the movements that were trained and activate the muscles in the same way. There is little point in training the muscles using slow and long repetitions to improve muscular endurance and then use a performance measure such as vertical jump height (which requires explosive power and strength) as the muscles were not trained to improve this ability [208]. It is also important to perform a number of performance measures as it may be that the training has improved one area but not another, for example, shoulder strength but not balance ability. A comprehensive approach to test selection makes conclusions regarding the effectiveness of the training programme more accurate and comprehensive [208, 223]. Following the core training programme, the proposed performance tests and sEMG analysis can be used to establish the effectiveness of the training programme by quantify and establishing any improvements or changes in; muscle activation of the core musculature, core stability, core endurance, core strength and sporting performance [116, 199].

Collecting sEMG data during an intervention study enables comparisons of the muscle activation and level of activation during the exercises to be made, not only between the exercises, but pre- and post-training as well. This will highlight any changes in muscle activation as a result of the core training. For example, it could be suggested that following a core training programme, muscular activity may be reduced in some of the muscles as the role of the muscles (during the exercises) change. Equally, there could be greater ARV EMG

muscle activity for some specific muscles due to an improvement in muscle recruitment of the core stabiliser muscles which represents the body recruiting the correct muscles that stabilise the body rather than depending on (and overloading) the larger, global mobiliser muscles.

### **2.3.3 Phase III and IV: RCT and Longitudinal Study**

Following the exploratory studies, which establish the trends and theories, the MRC framework suggests that the main randomised controlled trial (RCT) can take place. Whether this is performed in the health or sporting sector, the RCT requires adequate power, randomisation and outcome measures to be identified [2]. Where this may be possible in the health sector, where larger populations of subjects are available and true randomised designs can be implemented, this poses more of a problem when collecting data in the sporting sector. When looking to use sub-elite or elite level athletes, this population sample is relatively small in number, making it very hard, if not impossible, to collect data on a sample which is sufficient in size to meet the recommended statistical power of the data. With this in mind it is not possible to carry out a truly randomised controlled design in the sporting sector. Many elite athletes are also pre-selected into training groups of similar ability and/or age, making a truly randomised design not possible. With this in mind, any intervention study performed in this area is classified as a Phase II exploratory study in the MRC framework.

Phase IV of the MRC framework states that a long-term surveillance needs to take place to establish the long-term and real-life effectiveness of the intervention [2]. This could involve an observational study of the sample population over time and is invaluable in establishing the positive or negative benefits of an intervention. Within the sporting sector this poses some complications. To establish the true long-term effects of an intervention, observations would need to be carried out over a number of years. In the elite sporting environment, the time that an athlete is at full fitness and performing consistently fluctuates hugely, with many factors impacting on their performances, making any true evaluations of the long-term effectiveness of solely the intervention impossible. Short-term evaluations can be established, based on short-term performance achievements following the implementation of the intervention. Long-term effects of the intervention are much harder to clearly establish. The health sector is

more open to this type of long-term investigations with the performance measured being more stable and open to fewer effecting variables.

Phases III and IV of the MRC framework will not be performed in the current project due to the nature of the sample selected for analysis, however implementing the Pre-clinical, Phase I and Phase II of the framework will enable clear theories and trends to be quantified.

## **Chapter 3**

# **Establishing a Repeatable Measurement of Core Musculature Activity during MVIC and Core Exercises**

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### 3.1 Introduction

One of the main issues with EMG analysis is obtaining repeatable data [120]. It is important to establish the repeatability of an EMG data collection protocol so that the researcher can be confident the data will reflect true changes in performance and not be subject to large artefacts [121]. Establishing a repeatable protocol that results in small errors in the data enables smaller changes to be identified following, for example, training intervention programmes, which subsequently help identify the most effective training method [216]. Currently there is a considerable lack of published data regarding the repeatability of EMG muscle activity during core exercises using highly trained athletes.

It is important to quantify the within-subject repeatability (the typical within-subject trial to trial variation) of sEMG data while performing MVIC and core exercises. This is achieved by establishing the repeatability of the data collection protocol, MVIC and core exercises and the core muscles analysed. This can be done by collecting data in two ways; firstly, from a single subject who performs the exercises multiple times over numerous days, and secondly, with multiple subjects performing the same exercises but fewer times on the same day. Repeatability measures such as; CV and ICC values can then be used to establish the repeatability of each exercise and core muscle analysed [120].

Collecting normalised EMG data during a variety of challenges to the core musculature will assist professionals in understanding the roles of these muscles to optimise rehabilitation and training programmes that target core ability [103]. To enable this, repeatable data collection needs to take place so that measurement variations in the collected data represent true differences in muscle activity among each exercise condition [227]. This can only be achieved by carrying out repeatability studies into the EMG data collection and the normalisation process when performing such exercises [11, 135, 232].

A consideration when collecting EMG data is the variability of the data both within and between-subjects [181, 183-185]. Factors such as cross talk [248, 261] and the quasi-random nature of the EMG signal due to differing neural recruitment patterns, makes the signal

susceptible to large variations between measurements [120]. While it has been observed that following careful data collection procedures, repeatable sEMG data can be obtained [189, 190, 251-254], the variability in the measures can be high (10 – 30%) [262]). Furthermore, although no published data on the CV for the core musculature exists, CV values of 30 – 50% from ultrasound studies on the core musculature have been reported [263]. It is therefore expected that variability is a likely problem for assessing core musculature which could obscure interpretation of differing demands and muscle roles during core exercises.

Most studies to date have reported repeatability by using statistical methods such as CV (variation seen between multiple data sets) [231] and ICC (measure of similarity among trials relative to differences among subjects) [264]. Previous MVIC repeatability studies have reported a wide range of values for these measures, for example, Bamman et al. [235] reported that previous investigations studies have observed CV ranging from 5 - 22.8% for MVIC exercises using sEMG, while other studies [231, 248] have found CV values ranging from 11 - 77%. This variation between studies may be partly due to the EMG data being affected by the type of muscle contraction performed. Heckathorne and Childress [265] and Axler and McGill [94] also demonstrate how the magnitudes of EMG amplitudes are affecting by changes in muscle length and rate of muscle contraction. This is due to the increase of inertia forces on the limbs when performing a fast movement subsequently requiring higher muscle activity to resist these forces [146]. Similar can be said of exercises that have large ranges of motion and those that have added muscular load by using resistance bands or weights. Bolgla and Uhl [227] found that EMG muscle activity was greater during concentric (shortening) contractions compared to isometric (static) contractions, therefore the potential for greater variation in muscle activation may occur during dynamic movements due to the rate of force changes influencing EMG amplitudes. This may have a significant effect on which type of normalisation method is used when looking to collect repeatable data during static and dynamic movements [240].

Knutson et al. [231] analysed the hip abductor during dynamic MVC and MVIC exercises and calculated within-subject CV. They observed that CV was lower for the dynamic MVC

conditions, however the ICC analysis suggested reproducibility was best using EMG data from MVIC exercises. Bolgla and Uhl [227] also compared MVIC and dynamic MVC exercises (using mean and peak EMG values). Their reported ICC and CV values suggest that the MVIC method provided the greater repeatability for determining differences in activation amplitudes. Therefore previous research suggests that the use of MVIC exercises can provide a repeatable measure of muscular demands during lower extremity exercises [231, 252]. By using restraints and making sure that the subjects are familiar with the MVIC exercises [170, 253] repeatable values can be obtained (ICC value  $>0.92$  [235]). Therefore it can be suggested that MVIC exercises are a proven technique for establishing normalisation of sEMG data.

As has been highlighted, many studies have been performed on the repeatability of different normalisation methods using maximal, sub-maximal, isometric and dynamic contractions to elicit muscular contractions using sEMG [240]. To date, research has investigated the repeatability of sEMG data for both the upper [239] and lower extremities [251] but little research has assessed the repeatability of sEMG data when performing MVIC exercises on the core musculature. It is essential that this data is obtained as the core musculature is potentially susceptible to a higher variation in the EMG signal than, for example, the leg musculature. This is due to the more complex arrangement of muscles in the core area and the orientation of these muscles in the body making accurate placement of electrodes hard for repeatable data collection. To the authors' knowledge, there are currently only two published studies that report the repeatability (ICC) of sEMG data on the core musculature when performing core exercises [238, 250]. There is no published literature to the author's knowledge of CV data on the core musculature to establish between-day and within-subject repeatability during MVIC and core exercises.

The repeatability of collecting sEMG data between-days is essential when collecting muscular activation on the core musculature from single or multiple subjects over a number of days to minimise measurement error. As a result, when collecting sEMG data on single or multiple subjects on different days, it is important that the experimental protocol is kept exactly the same to minimise the potential measurement errors (e.g. electrode placement, speed of

movement, skin temperature) [120, 121]. By establishing this repeatability, the effect of training programmes on subsequent core ability can be analysed by recording the muscular activation pre- and post-intervention to establish if any adaptations have occurred. It is essential that measurement errors are minimal to be able to distinguish any significant changes in muscle activation.

EMG data processing is complex and muscle activity can be summarised using different output variables [120]. Two of the common output variables are peak EMG and Average Rectified Variable EMG (ARV EMG). The calculation of both variables involves normalising the EMG data where the subject performs a preliminary restrained exercise that elicits an assumed MVIC of a given muscle [239]. The peak EMG variable can then be expressed as a percentage of this MVIC [11, 75, 81, 136]. The peak EMG variable gives a measure of the maximal activity of the given muscle during the exercise and has been used to quantify muscle activity during core exercises [94]. In contrast, the ARV EMG is a measure of the area under the normalised EMG time-series curve divided by the time period [245-247] (Figure 3.1). This variable includes an indication of all sub-maximal muscle activity which occurs during the stabilisation of the body [1] particularly when performing exercises on an unstable surface or with a small base of support (as occurs during many core exercises). Previous research on the core muscle activation patterns [245, 266] has found that by using different EMG data reduction procedures, variations in the reported level of muscular activity during the same core stability exercises are reported. For example, Hildenbrand and Noble [245] reported mean integrated EMG activity by calculating the area under the rectified EMG curve and dividing this by the elapsed time for five sit-up exercise repetitions. Meanwhile, Warden et al. [266] calculated peak EMG values from the core muscles during the sit-up technique. Subsequently the two studies reported differing levels of EMG activity for the same muscles and concluded that this could have been due to the different data reduction procedures. This highlights the potential importance of measuring more than one EMG processing method.

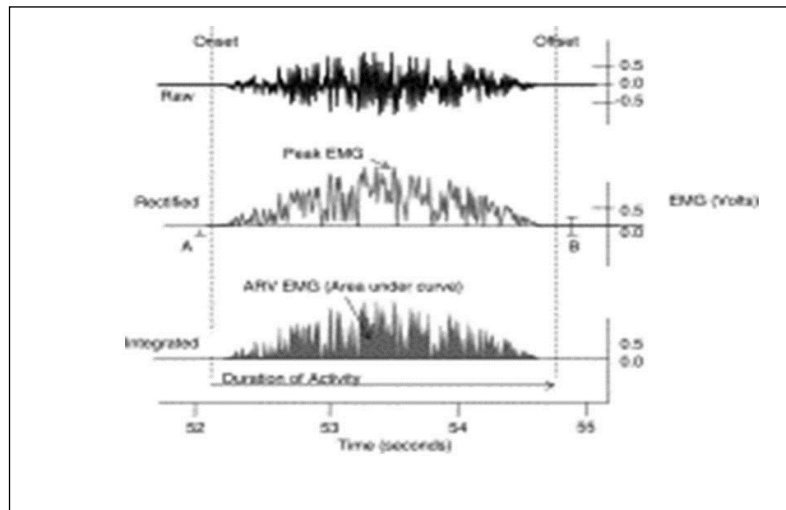


Figure 3.1. The processing method used to determine peak and ARV EMG variables. EMG data were processed between the onset (A) and offset (B) time points.

Therefore there is a lack of research quantifying both within-day and between-day repeatability of core exercises using sEMG data reduction measures. Past literature has established that MVIC exercises can result in repeatable sEMG data [235] however much of this data has not been performed on the core musculature. It has been suggested that due to the highly complex nature of the core musculature recruitment during dynamic movements, greater variation and measurement errors could be observed [8]. Therefore it is important that the potential variations and the level of repeatability of the signal are quantified.

### **Aim of Chapter**

To develop a repeatable measure of muscle activity using surface electromyography during a range of core exercises

## **3.2 Methods**

### **3.2.1 Subjects**

Eleven athletes (ten men, age,  $18 \pm 1.02$  years; height,  $177 \pm 1.5$  cm; body mass,  $76 \pm 2.1$  kg; one woman, age, 18 years; height, 175.5 cm; body mass, 71 kg) volunteered to participate in the study. All subjects were highly trained athletes with minimal body fat and were of similar age and stature, therefore minimising the potential variables that could reduce the sEMG repeatability. Ten subjects performed the protocol on a single day and one subject repeated the protocol on three separate days (to establish between-day variation; day 1 sets 1 - 3, day 2 sets 4 - 7 and day 3 sets 8 - 10). Within each data set, the subject completed three repetitions of each exercise.

Experimental test protocols were approved by the Teesside University ethical committee (Appendix F). All subjects volunteered to participate in the study after signing an informed consent document (Appendix E) and a medical questionnaire (Appendix C). All subjects were highly trained and experienced in performing core stability and strength exercises thus minimising the potential for any learning effects. The subjects were in full health and did not report any feelings of pain when performing the tests.





### **3.2.2 Exercise Details**


Due to the athletes being familiar with performing core exercises, the learning effects of performing these exercises are expected to be low. Any learning effect was further minimised by introducing the exercises to the subjects one week prior to data collection. Subjects were provided with a written explanation of each exercise, shown a demonstration and practised each MVIC and core exercises at the required repetition rate.

#### **3.2.2.1 MVIC Exercises**

Previous studies [239, 267] have recommended using more than one MVIC exercise to ensure a maximum activation for a muscle. Accordingly, five MVIC exercises were performed three times (with one minute rest between each) for five seconds (details of exercises in Table 3.1).

In order to minimise the effect of the muscle length–tension relationship on the resultant EMG output [31, 268] the MVIC exercises were performed in a similar body position to those of the core stability exercises (Table 3.2). For the resisted exercises, the amount of weight needed to prevent body angle movement was established for each subject (this ranged from 20 to 35 kg of free weights). Subjects were given verbal encouragement during each MVIC exercise to help ensure a maximum and consistent effort during the EMG data collection period.

Exercise	Muscle targeted	Description	Repetition rate	Duration (seconds)	Diagram
Resisted sit-up	rectus abdominis	Lie on floor with knees bent to 90° with back in neutral position, place weight on chest and hold with folded arms across chest. Subject attempts to perform sit-up. Weight should be heavy enough to prevent any substantial movement of the upper body	Continuous	5	
Resisted back extension	gluteus maximus longissimus multifidus	Using a horizontal extension bench, lie with hips over edge of bench and feet fixed under bar. Flex hips so head is near ground. With a weight in arms attempt to extend the back. The weight should be heavy enough to prevent substantial upper body movement	Continuous	5	
Resisted trunk rotation	external oblique internal oblique	Seated position on the floor with legs straight out in front and arms across chest. Subject rotates upper body while external resistance is placed on shoulder to prevent substantial upper body twisting	Continuous	5	
Resisted hang	latissimus dorsi	Hang from a wall bar with arms straight. Secure feet (use external resistance pulling down on ankles) so no movement upwards can be achieved. Attempt to pull body upwards using shoulders and arms	Continuous	5	




Exercise	Muscle targeted	Description	Repetition rate	Duration (seconds)	Diagram
Resisted hip flexion	rectus femoris	Subject sits on bench with thighs fixed and knees bent at 80°. Subject attempts maximal knee extension and hip flexion	Continuous	5	

### 3.2.2.2 Core Exercises

Five core stability and core strength exercises were performed (Table 3.2). The exercises were selected based on previous research that highlights them as important in developing core stability and core strength [15, 31, 32, 75, 85, 89, 94, 133]. These included low threshold (less demanding, posture related exercises which focus on muscle recruitment) and high threshold exercises (greater stress on the core musculature thus promoting core strength development) [1]. Some of the exercises are classified twice (for example the medicine ball sit-hold-twist exercise is classified as both a dynamic high threshold exercise and an asymmetrical exercise).

The core exercises were performed continually for a minute and then repeated with one minute rest between the sets. The order that the exercises were performed in was a crossover randomised design for each subject. The duration and number of repetitions over which these exercises were performed varied due to the demands of the exercises (Table 3.2) but these were subsequently time-normalised to muscle activity per second to enable direct comparisons between the exercises. Repetition rates were determined by a certified UK strength and conditioning coach and monitored using a stopwatch. Subjects were instructed to perform controlled, smooth movements in order to minimise the variability of the EMG signal [267].



Table 3.2. Description of core exercises performed during trials (* based on exercise descriptions from Brandon [3]).				
Exercise	Description	Repetition rate	Duration (s)	Diagram
Side bridge* (static)	Lie on side, ensuring top hip is 'stacked' above the bottom hip. Push up until there is a straight bodyline through feet, hips and head	Hold for 60 s	60	
Birddog* (asymmetrical)	Position hands below shoulders and knees below hips. Position back in neutral, extend one leg backwards and raise the opposite arm until level with back. Ensure back does not extend and shoulders and pelvis do not tilt sideways. Bring leg and arm back to start position and swap sides	2 s change sides–3 s hold in position	60	
Bent leg curl-up (dynamic low threshold)	Lie on floor with knees bent to 90° and feet resting on floor. Position back in the neutral position and arms folded across chest, raise head, shoulders and upper back off the floor, hold and return to start position	2 s hip flexion (up)–2 s hip extension (down)	60	
Overhead squat (dynamic high threshold)	Using a weighted bar, place hands shoulder width apart. Raise the bar above head and straighten arms. Feet shoulder width apart, squat down as low as possible while maintaining balance, keeping bar, head and back vertical. Straighten legs and repeat	2 s hip flexion (down) – no hold – 2 s hip extension (up)	60	
Medicine ball, sit-hold-twist (asymmetrical)	Sit up with knees bent and lean back at 45°. Feet off floor, keeping back in neutral, using a 4 kg medicine ball, twist waist and shoulders to one side with ball held out in front of you. Return to forward and repeat to other side	2 s move from left to right and return (4 s total)	60	

### 3.2.3 Data Collection

EMG signals were recorded from the right side of eight muscle sites (see Table 3.3) with the electrodes positioned across the muscle fibres; rectus abdominis (upper), external oblique, internal oblique, multifidus (lumbar L4-5), latissimus dorsi, gluteus maximus, longissimus and rectus femoris. The reference electrode was placed on the right iliac crest landmark (conductive gel was used). These muscles were selected based on previous research that highlights these muscles as important to core stability and core strength [29, 32, 61, 62, 68, 80, 125, 139, 257, 258]. Each landmark was identified (by a qualified physiotherapist), shaved and cleaned using alcoholic wipes to remove any dead skin cells so minimising the impedance of the muscle signal. All electrodes were securely taped to the skin to reduce movement artefacts.

Muscle	Position of Electrode (right side)
Rectus Abdominis – upper (RA)	Positioned vertically on centre of muscle belly, 5 cm above umbilicus, 3 cm lateral from midline
External Oblique (EO)	3cm above iliac crest, at 45 degrees above the anterior superior iliac spine (ASIS) level with the umbilicus
Internal Oblique (IO)	Positioned horizontally 2 cm inferomedial to the ASIS
Multifidus (MF)	Positioned vertically 3 cm lateral to spine, L4-5 spinous process
Longissimus (LG)	Positioned vertically 3 cm lateral to spine, L2 region
Gluteus Maximus (GM)	On centre of muscle belly
Latissimus Dorsi (LD)	Positioned obliquely, 25 degrees from horizontal in inferomedial direction, 4 cm below inferior angle of scapula
Rectus Femoris (RF)	Positioned vertically on midline of thigh, midway between between ASIS and proximal patella

During the multiple subject (MS) design the electrodes were not removed from the skin at any point. During the single subject (SS) design, the electrodes were positioned on the landmarks at the beginning of the day and remained in position until the end of the days data collection where (on the first and second day) the electrode landmark locations were marked with a permanent marker to ensure the same placement the following day [120].

EMG data was collected (sampling rate 1000 Hz) using Delsys Wireless Myomonitor III device with surface electrodes (Delsys DE-2.3 Single Differential Surface Electrode; inter-electrode distance 1 cm; bar type electrode, contact dimensions  $10 \times 1$  mm, 99.9% Ag; Gain 1000; Bandwidth 20 – 450 Hz; common mode rejection ratio of  $-92$  dB, pre-amplifier gain 1000 V/V  $\pm$  1%, input impedance of  $>10^{15}$   $\Omega$ //0.2 pf) and saved using Delsys EMGWorks Acquisition software. Data collection took place in the same room with the same room temperature (20 - 22°C) to modulate subject skin temperature. On the day of testing sEMG data was first recorded with the muscles fully relaxed (subject lay prone on the floor) to define the baseline for each muscle channel.

### 3.2.4 Data Processing

Raw sEMG signals for both MVIC and the core exercises were bandpass filtered at 20 – 450 Hz and analysed using Acknowledge software program (Biopac Systems Inc., Goleta, CA). A Root Mean Square (RMS) method with a moving average window of 50 ms was adopted. This method was used as oppose to a low-pass filter as it rectifies the EMG data and enables a representative mean value of the data to be established. Using a low-pass filter would have required rectifying the data first and then filtering the data which may have potentially removed the true peak activation in the EMG data. As peak EMG was being calculated, it was felt that the RMS method provided the more suitable and recommended method. To identify the start and end of the repetitions for the dynamic exercises (for the MVIC and static core exercises, the middle three and five seconds were used respectively) onset and offset values were calculated using the equation below [245, 246, 262, 263] (and see Figure 3.1). The onset of the repetitions was accepted when the muscle activity exceeded the mean resting value by more than three standard deviations for over 30 ms and the cessation of the repetition established when the activity fell below the mean resting value by more than three standard deviations for over 30 ms [269].

$$\text{Onset / Offset value} = \text{Mean} + (3 \times \text{Standard Deviation})$$

Peak and ARV EMG values were obtained for both the MVIC (to enable normalisation of the EMG signals) and core exercises. Peak values were established by calculating the peak EMG activity during a three second period for each of the three MVIC repetitions for each muscle. ARV EMG values were established by calculating the average muscle activity per second for each muscle during each MVIC exercise. These values were used to normalise the EMG data during the core exercises. Normalisation of sEMG data is not essential to calculate peak or ARV data if subjects are being treated separately, however when subjects (as required here) are grouped together, normalisation is required to standardise the data and allow for variations in subject muscle strength.

To establish peak and ARV EMG values during the core exercises, three repetitions of each exercise were analysed. The EMG data was normalised by expressing the peak EMG value for each muscle as a percentage of the peak EMG value for a subject's highest corresponding MVIC exercise. The highest normalised EMG data value from the three core exercise repetitions was then used in all subsequent analysis as the peak EMG value. To calculate the ARV EMG, the sum of the EMG area under the curve was divided by the total number of data points between the onset and offset times, to give an ARV in volts for the repetition [269, 270]. This was normalised as a percentage of the maximum ARV EMG activity during the MVIC exercises. A mean value was obtained from three repetitions of each core exercise for each muscle. The average of the linear envelope (rather than the total area under the curve) was calculated due to the duration of the exercise repetitions varying. By calculating muscle activation per second this provided a more accurate comparison of the muscular activity during each movement. For example, an exercise of 3 seconds per repetition (birddog) compared to an exercise of 1.5 seconds (sit twist) would not provide an accurate comparison as these exercises may result in a similar %MVIC when total time is used but this would not reflect the shorter time that this muscle activity had to be produced over during the sit twist exercise and subsequently would not distinguish between high and low threshold exercises.

### 3.2.5 Statistical Analysis

#### 3.2.5.1 Repeatability during MVIC Exercises

For the single subject design the within-day CV was established. CV measures were used as this calculation of repeatability standardises the standard deviation (SD) to the mean and so removes the variability of the data due to the magnitude of the mean [271]. The CV was established using the equation stated below for each day (day 1 sets 1 – 3, day 2 sets 4 – 7, day 3 sets 8 – 10). The greatest minimum to maximum CV difference occurring on any of these days was expressed as an indication of within-day variation and the difference between these values, used as an indication of between-day variation [234].

$$CV = (SD / \text{mean}) \times 100 \quad [234]$$

For the multiple subjects design the repeatability of the summary measures were calculated using the log-transformed CV method [235] for each MVIC exercise for each of the core muscles. This was then subjected to back-transformation as stated below [272] (where e is the exponential and SD is the standard deviation):

$$CV = 100 (e^{SD} - 1)\% \quad [272]$$

Log-transformation was used to minimise the potential effect of the variation of the pre-test values. By transforming the data, any skewed values are transformed to a normal distribution [273]. Hopkins suggests that this can be used to obtain uniformity over the range of subjects which can then be subject to back-transformation to express the value as a CV (% of the predicted value) [221, 272].

#### 3.2.5.2 Repeatability during Core Exercises

For the single subject design the within-day and between-day CV was established for each core muscle for peak and ARV EMG. The CV was established using the equation stated above that was used to calculate the MVIC within- and between-day CV for the single subject design. Same as the MVIC exercise process, the greatest minimum to maximum CV difference occurring on any of these days was expressed as an indication of within-day variation and the

difference between these values, used as an indication of between-day variation [234]. For the multiple subjects design (as stated above during the MVIC exercises) the CV were calculated using the log-transformed method [235] (see equation used above) for each core muscle and expressed as a percentage of MVIC for peak and ARV EMG. Two-way mixed consistency ICC values (using SPSS version 12.0) were computed on the sEMG data using peak and ARV EMG values. ICC values were calculated using ICC (3, 1) and the equation below [274]:

$$\text{ICC (3, 1)} = \frac{\text{BMS} - \text{EMS}}{\text{BMS} + (k - 1) \text{EMS}} \quad [274]$$

(where BMS, between-subjects mean square; EMS, error mean square; k, number of repetitions).

95% confidence intervals were also established for the ICC values. To establish the measurement error between the trials, consecutive pairs of trials were examined (trials 1 and 2, trials 2 and 3). All three trials were then compared to establish total measurement error (CV). If this three trial CV value was below 26% that value was reported, if the value was above 26%, the two trial CV value that showed the lowest variation was reported. This was adopted because, based on previous work on the arm [239] and leg muscles [231, 235], an acceptable limit of variation for sEMG (to enable further data to be collected) would be a CV value of below 26% and an ICC value of >0.7. These limits were chosen allowing for the uncontrollable quasi-random nature of the EMG signal but still remove any EMG signals that show great variation within subjects due to for example, difficult electrode placement. Any values that show a large variation between trials would make the identification of a significant change in performance impossible.

### 3.3 Results

#### 3.3.1 Repeatability during MVIC Exercises

Within-day and between-day variability during the MVIC exercises derived from a single subject are shown in Table 3.4. CV values are shown for the muscles in the exercises that

elicited a maximum in three or more of the data sets performed. Within-day CV ranged from 0% to 70% for peak muscle activity and from 2% to 71% for ARV muscle activity. Between-day CV ranged from 6% to 57% for peak EMG muscle activity (excluding LG during the sit up; CV = 93%) and from 8% to 51% for ARV EMG (excluding LD during the sit up; CV = 89%). For both peak and ARV EMG, the lowest variability occurred for RF and MF muscles and the highest occurred for LD and LG muscles.

Table 3.4. Within-day CV derived from a single subject during the MVIC exercises. Between-day CV range shown in brackets. Green boxes represent values that are below the recommended reliable level (< 26% CV).

MVIC	EMG	RA	EO	IO	MF	LD	GM	LG	RF
Resisted Sit up	ARV	28 (20-43)		12 (3-50)		89 (10-71)	15 (3-31)	51 (3-61)	
	Peak	14 (7-19)		15 (9-21)			47 (5-66)	93 (22-70)	
Resisted Back Extension	ARV		38 (12-50)		18 (2-23)	12 (6-11)	8 (5-9)	48 (2-23)	
	Peak				11 (5-11)	35 (4-47)	6 (3-9)	49 (3-23)	
Resisted Trunk Rotation (right)	ARV		46 (3-22)			46 (3-22)			
	Peak		19 (3-9)			57 (7-33)			
Resisted Trunk Rotation (left)	ARV			41 (8-22)					
	Peak			48 (13-48)					
Resisted Hang	ARV				37 (2-27)	23 (3-7)			
	Peak		20 (11-21)	31 (0-24)		29 (6-13)			
Resisted Hip Flexion	ARV								26 (5-29)
	Peak								24 (8-25)

Within-day variability derived from multiple subjects is shown in Table 3.5. Peak EMG CV ranged from 3% to 33% while ARV EMG CV ranged from 8% to 27%.

Table 3.5. Within-subject coefficients of variation (CV) derived from multiple subjects during the MVIC exercises. The 95% confidence intervals are shown in brackets. Values are shown for muscles in exercises that elicited a maximum in more than three subjects. Green boxes represent values that are below the recommended reliable level (< 26% CV).

MVIC exercise	EMG	RA	EO	IO	MF	LD	GM	LG	RF
Resisted Sit up	ARV	21 (19–52)	20 <sup>a</sup> (17–36)	19 <sup>a</sup> (18–38)					13 <sup>b</sup> (6–15)
	Peak	28 <sup>a</sup> (16–33)	23 (13–36)	24 (23–50)					8 <sup>b</sup> (6–25)
Resisted Back Extension	ARV				8 <sup>a</sup> (8–17)	19 (16–38)	27 <sup>a</sup> (14–29)	19 (10–25)	
	Peak				11 (6–15)	33 <sup>a</sup> or <sup>b</sup> (14–38)	15 (13–26)	12 (8–28)	
Resisted Trunk Rotation (right)	ARV		17 (14–29)						
	Peak		19 (13–27)						
Resisted Trunk Rotation (left)	ARV			8 (4–11)					
	Peak			3 (2–9)					
Resisted Hang	ARV			27 <sup>b</sup> (13–29)		7 (14–30)			
	Peak			17 (15–30)		19 (5–21)			
Resisted Hip Flexion	ARV								24 (18–30)
	Peak								23 <sup>b</sup> (19–28)

<sup>a</sup> Used trials 1 and 2, <sup>b</sup> Used trials 2 and 3 following pairwise correlation comparison tests.



### 3.3.2 Repeatability during Core Exercises

Within-day and between-day variability during the core exercises derived from a single subject is shown in Table 3.6. Within-day CV ranged from 1% to 65% for peak EMG and from 0% to 56% for ARV EMG. Between-day CV ranged from 7% to 66% for peak EMG (excluding RA during the weighted squat; CV = 77%) and from 7% to 54% for ARV EMG (excluding LG during the side bridge; CV = 61%). LG and EO muscles showed the largest variation within-day and between-day for peak and ARV EMG measures. The RF, GM and MF muscle activity were the most repeatable both between-day and within-day.

Exercise		RA	EO	IO	MF	LD	GM	LG	RF
Side bridge	ARV	27 (2-9)	25 (5-53)	13 (2-16)	34 (16-34)	18 (1-18)	20 (3-15)	61 (0-24)	4 (4-5)
	Peak	47 (4-16)	22 (7-47)	36 (6-47)	22 (5-25)	21 (12-23)	28 (6-18)	66 (1-17)	10 (8-14)
Birddog	ARV	35 (5-38)	26 (5-56)	20 (1-36)	9 (3-8)	23 (7-32)	11 (6-13)	44 (2-14)	16 (6-11)
	Peak	7 (1-6)	24 (8-51)	17 (4-17)	7 (2-12)	20 (8-12)	13 (2-22)	36 (2-5)	20 (13-31)
Bent leg curl-up	ARV	12 (8-12)	47 (10-53)	15 (3-18)	41 (3-46)	11 (5-11)	13 (2-19)	50 (1-18)	7 (3-8)
	Peak	20 (8-23)	25 (6-50)	21 (1-17)	17 (1-22)	17 (7-14)	11 (4-19)	17 (12-23)	12 (2-9)
Overhead squat	ARV	11 (4-13)	45 (2-30)	21 (3-47)	15 (4-16)	28 (3-17)	11 (2-16)	51 (6-18)	21 (15-27)
	Peak	77 (37-46)	33 (5-59)	22 (7-15)	10 (1-12)	33 (6-18)	14 (4-18)	41 (4-10)	22 (18-27)
Medicine ball sit-twist	ARV	15 (8-21)	29 (2-54)	12 (0-15)	24 (1-17)	11 (3-9)	11 (4-13)	54 (1-20)	11 (5-16)
	Peak	29 (11-12)	46 (8-65)	20 (1-15)	61 (2-65)	23 (3-28)	26 (3-29)	29 (2-44)	10 (2-12)

Within-day variability derived from multiple subjects is shown in Table 3.7. Peak EMG CV ranged from 5% to 28%, while ARV EMG CV ranged from 2% to 28%.

Table 3.7. Within-subject CV derived from multiple subjects during the core exercises. The 95% confidence intervals are shown in brackets. Green boxes represent values that are below the recommended reliable level (< 26% CV).									
Exercise		RA	EO	IO	MF	LD	GM	LG	RF
Side bridge	ARV	23 (16–42)	17 (12–31)	13 (9–25)	14 (10–26)	5 (3–8)	2 (1–3)	23 (16–42)	9 (6–16)
	Peak	13 (9–23)	8 (6–15)	5 (3–8)	10 (7–18)	9 (6–17)	13 (9–25)	8 (6–15)	9 (6–17)
Birdog	ARV	22 (16–34)	16 (11–25)	6 (4–9)	16 (11–25)	5 (3–7)	17 (12–26)	14 (10–22)	11 (8–17)
	Peak	17 (13–27)	15 (11–23)	10 (7–16)	9 (7–15)	23 (17–36)	13 (10–21)	16 (12–25)	12 (9–18)
Bent leg curl-up	ARV	22 (16–35)	10 (7–16)	5 (3–7)	11 (8–17)	2 (1–3)	5 (3–7)	7 (5–12)	13 (10–21)
	Peak	10 (7–16)	8 (6–13)	13 (10–21)	23 (17–36)	7 (5–12)	9 (6–14)	12 (9–19)	14 (11–23)
Overhead squat	ARV	28 <sup>b</sup> (19–51)	16 (12–26)	11 (8–17)	22 (16–34)	17 (13–28)	9 (6–14)	8 (6–13)	7 (5–10)
	Peak	18 (13–29)	28 (19–50)	22 (16–34)	6 (4–9)	22 <sup>a</sup> (15–40)	14 (11–23)	9 (7–15)	11 (8–17)
Medicine ball sit-twist	ARV	21 (16–33)	11 (8–17)	11 (5–12)	21 (15–32)	7 <sup>b</sup> (5–12)	7 (5–12)	19 (14–29)	8 (6–13)
	Peak	14 (10–22)	15 (11–23)	15 (11–23)	16 (11–25)	13 <sup>a</sup> (9–23)	24 (18–39)	16 <sup>a</sup> (11–25)	13 (9–20)

<sup>a</sup> Used trials 1 and 2, <sup>b</sup> Used trials 2 and 3 following pairwise correlation comparison tests

Within-subject ICC values during the core exercises are shown in Table 3.8. Values over 0.7 were deemed to be sufficiently repeatable.

Table 3.8. Within-subject ICC during the core exercises. The 95% confidence intervals are shown in brackets. Green boxes represent values that are above the recommended reliable level (>0.7 ICC).

Exercise		RA	EO	IO	MF	LD	GM	LG	RF
Side bridge	ARV	-0.02 (-0.03-0.23)	0.68 (0.61-0.78)	0.21 (0.15-0.36)	0.44 (0.32-0.54)	0.94 (0.90-0.98)	0.99 (0.94-0.99)	0.38 (0.32-0.49)	0.76 (0.68-0.79)
	Peak	0.18 (0.1-0.32)	0.63 (0.51-0.76)	0.84 (0.75-0.89)	0.76 (0.56-0.87)	0.85 (0.80-0.89)	0.48 (0.43-0.54)	0.52 (0.45-0.61)	0.68 (0.60-0.74)
Bird dog	ARV	0.74 (0.68-0.77)	0.84 (0.73-0.89)	0.90 (0.73-0.97)	0.76 (0.63-0.84)	0.93 (0.87-0.97)	0.65 (0.58-0.69)	0.40 (0.35-0.49)	0.72 (0.65-0.79)
	Peak	-0.16 (-0.12-0.21)	0.64 (0.50-0.71)	0.82 (0.72-0.91)	0.29 (0.20-0.39)	0.48 (0.40-0.52)	-0.06 (-0.1-0.12)	-0.24 (-0.31-0.3)	0.12 (0.07-0.2)
Bent leg curl-up	ARV	0.50 (0.43-0.59)	0.84 (0.71-0.89)	0.97 (0.86-0.99)	0.36 (0.30-0.53)	1.00 (0.96-1.0)	0.95 (0.87-0.97)	0.97 (0.90-0.98)	0.68 (0.59-0.70)
	Peak	-0.04 (-0.08-0.19)	0.11 (0.09-0.19)	0.74 (0.63-0.82)	0.58 (0.50-0.64)	0.97 (0.91-0.99)	0.91 (0.84-0.97)	0.18 (0.12-0.29)	0.42 (0.35-0.47)
Overhead squat	ARV	0.22 <sup>b</sup> (0.18-0.36)	-0.22 (-0.28-0.21)	0.81 (0.69-0.89)	0.65 (0.54-0.71)	0.59 (0.49-0.63)	0.70 (0.62-0.79)	0.72 (0.67-0.76)	0.60 (0.54-0.68)
	Peak	0.24 (0.16-0.38)	0.02 <sup>b</sup> (0.01-0.13)	0.64 (0.52-0.69)	0.79 (0.70-0.82)	0.24 <sup>a</sup> (0.18-0.28)	0.56 (0.50-0.60)	0.28 (0.21-0.39)	0.23 (0.17-0.3)
Medicine Ball sit-twist	ARV	0.32 (0.25-0.39)	0.07 (0.03-0.20)	0.86 (0.78-0.96)	0.62 (0.57-0.70)	0.51 (0.45-0.59)	0.94 (0.88-0.96)	0.67 (0.6-0.76)	0.10 (0.05-0.2)
	Peak	-0.31 (-0.38-0.12)	-0.33 (-0.35-0.10)	0.36 (0.28-0.43)	0.68 (0.60-0.78)	0.97 <sup>b</sup> (0.89-0.97)	-0.17 (-0.2-0.29)	0.56 <sup>a</sup> (0.48-0.6)	0.20 (0.15-0.24)

<sup>a</sup> Used trials 1 and 2. <sup>b</sup> Used trials 2 and 3 following pairwise correlation comparison tests.

### 3.4 Discussion

The current Chapter aimed to quantify the repeatability of sEMG muscle activity during core exercises by quantifying the within-subject variation observed in the core musculature during MVIC and core exercises using multiple and single subject designs. Within-subject and within- and between-day CV (MS and SS design) and ICC values (MS design) were established for peak and ARV sEMG muscular activity for eight core muscles.

Three studies have reported the ICC repeatability of sEMG data collection on the core musculature when performing core exercises [231, 250, 269]. Behm [238] found ICCs for the isometric side bridge support exercise of 0.96 and 0.98 for the dynamic bird dog exercise.

Liemohn et al. [250] observed ICCs for the front bridge support exercise of 0.90 and values ranging from 0.71 to 0.95 for other low-threshold core stability exercises. Similarly, Edwards et al. [269] observed a high repeatability ( $ICC > 0.9$ ) for the VM and VL muscles during a sit-to-stand movement. The current study has reported similar ICC values for some muscles during similar low threshold core stability exercises (for example, LD during the side bridge and bent leg curl-up exercises and the IO during the birddog exercise;  $ICC > 0.7$ ). However, some muscles analysed during the core stability exercises resulted in lower ICC values than those previously reported ( $ICC < 0.7$ ). This may be due to the more complex exercise movements being performed and the greater number of core muscles being analysed, with not all of these muscles being continually involved in the exercises which would result in a greater variability in the data. Despite this, many of the exercises and muscles did result in acceptable levels of ICC ( $> 0.70$ ) and CV ( $< 26\%$ ).

The muscles EO, IO, MF, RF and GM reported acceptable CV values of  $< 26\%$  during one or more of the MVIC exercises which suggests that the exercises performed in this study are suitable for sEMG normalisation procedures (based on previously published literature; Table 2.2 Chapter 2). This supports previous studies that have observed repeatable values for the core muscles during MVIC exercises [227, 235]. The LD (29%) and RA (28%) muscles produced CV values just outside the 26% acceptance level (based on the MS design). Comparing the SS design results to the MS design CV values, similar findings are found for these two muscles; the LD muscle resulted in CV of 33% (ARV EMG) and the RA muscle a CV of 28%. This suggests that these muscles (LD and RA) have a lower repeatability when performing maximal contractions. However with close control and accurate electrode placement, these muscles could still be used to collect sEMG data during such exercises. The LG muscle resulted in the largest within-day variation (peak 49%; ARV 48%) (SS design). Comparison with the MS design also established this large variation observed between subjects for this muscle (peak 19%, ARV 33%). These findings suggest that sEMG may not be suitable to analyse this muscle (LG) during these exercises. This may be due to the complex orientation of the muscle and the location within the core musculature which makes accurate EMG electrode placement difficult. The role of the LG as a stabiliser muscle may

also affect the repeatability of the signal as the activation of the stabilisers depends greatly on the technique used for a movement. This is due to the muscle not being activated to a high level (is a stabiliser rather than mobiliser) where small increases in activity can subsequently be reported as large variations. As a result, small adjustments and corrections in body position during one trial but not another would result in a big variation in muscle activity between trials.

Previous research has suggested that normalising EMG data to 100% MVIC increases the within-subject variability [234] compared to using 50% MVIC values due to the effect on, for example, subject motivation and fatigue. However, other research has shown that repeatable EMG data can be obtained from using 100% MVIC exercises when factors such as recovery period and exercise familiarisation are controlled [249]. This is supported by the current study that observed CV values for the RF muscle of 24% (SS design) and 23% (MS design) when performing a MVIC hip flexion exercise, whereas Yang and Winter [242] observed a CV of 119% for the same muscle when the gait cycle was normalised to 50% MVC. Yang and Winter [242] concluded that their large CV was due to the lack of stability of the joint during the dynamic MVC which resulted in large within-subject repeatability between the three trials. This highlights the importance of selecting the optimal MVIC exercise for a muscle to elicit a maximal contraction and using a consistent body position each time.

A number of studies have used similar electrode placements to those used in this study to locate specific muscles when investigating the core musculature. For example, the MF muscle (involved in the local stabilising system) [238] in the L5-S1 region [46, 266, 267] has been investigated using sEMG analysis. However, Stokes et al. [275] reported that accurate assessment of the MF requires an intra-muscular electrode due to its deep positioning within the core musculature. However this study found that the MF muscle can produce a repeatable signal during maximal contractions and was the most repeatable muscle signal from the eight core muscles analysed during the MVIC exercises (SS design: peak CV 11%; ARV CV 18%; MS design: peak CV 8%; ARV CV 11%).

During the MVIC exercises, the Peak EMG CV values for the MS design ranged from 3 - 33% while ARV EMG CV ranged from 8 - 27%. For the SS design, CV ranged from 6 - 57% for peak EMG muscle activity (excluding the outlier LG sit-up; CV = 93%) and from 8 - 51% for ARV EMG muscle activity (excluding outlier LD sit-up; CV = 89%). This range of values is in agreement with previous research that have also observed a large range of CV [231, 242]. When these CV values are compared to the MS design CV values they represent a much poorer repeatability between trials. However it has to be emphasised that this is to be expected as the SS design is based on ten trials (MS design was over three trials) and also includes between-day variability as these trials were collected over three days.

There were a number of large CV values observed during the MVIC exercises between trials. For example during the MVIC sit-up exercise, the LD and LG muscles reported values of 89% and 93% respectively across the ten trials (SS design). This could be due to these muscles not being prime movers during this movement, resulting in the muscle activation being low and subsequently any small increase in muscle activity (due to balance correction or change in technique) being exaggerated and reflected by a higher CV value. As a result of this, in the current study, that MVIC exercise was not used to calculate the maximum from those muscles for the normalisation process, a more specific exercise was used (in this study, the maximal shoulder hang for the LD and maximal back extension exercise for the LG). Therefore these high CV values should not be of a concern for future testing, but it does highlight the effects that small changes in muscle activation can have on the resultant EMG data when overall muscle activity is low.

The MVIC exercises during the MS design showed a variation between the three measured trials for the eight core muscles. Trials 2 and 3 showed the least variation and suggest that there may either have been a learning effect occurring between the first and second trials, or a 'muscular preparation' change between these trials (i.e. the first trial represented a warm up for the muscles, with the second and third trials being similar due to the muscle being pre-prepared). This might be expected during the MVIC exercises, where the muscles are put under maximal strain and may become more efficient and exert a more consistent force

following a previous maximal effort (in this case, trial one). The more unfamiliar nature of the MVIC exercises may also have resulted in a learning effect during the trials which would explain some of the variance seen across the trials. However, each subject did perform and fully understand the requirements of each exercise prior to data collection by attending the exercise familiarisation session.

It is important to not only measure and evaluate the repeatability of the MVIC exercises but also the exercises and muscle activations that these values will be used to normalise, in this study the core exercises. The repeatability observed within- and between-day during the sEMG data collection of the core exercises are exaggerated by some outliers which skew the CV data range observed. These outliers have subsequently been highlighted in the data analysis below.

For the MS design, the eight muscles analysed during the five core exercises (except the RA during the weighted squat exercise; 28%, ICC 0.22), for both peak and ARV EMG values, were below the 26% CV level set by the current study as an acceptable level for establishing repeatable data to analysis core exercises (peak CV, 5 - 28%; ARV CV, 2 - 28%). The larger variation observed for the RA muscle during the weighted squat exercise is due to the high demands that are placed on this muscle during this exercise depending on the technique used. If sufficient core stability and strength is present, the back muscles take the main work load, however if these muscles lack strength, the squat is performed relying more on the abdominal muscles (as a result of a more flexed hip position during the lift) [276]. This suggests that some of the subjects in the current study used different techniques to perform this specific exercise during the three trials, resulting in the larger variation in muscle activation. From analysing the CV values in Table 3.7, the RA (CV 10 - 28%; ICC -0.31 - 0.74), LD (CV 2 - 22%; ICC 0.24 - 0.99) and the MF (CV 6 - 23%; ICC 0.29 - 0.76) muscles reported the greatest variation within-subjects. However these three muscles still reported values below or just above the acceptable CV limit set for this study (26%) and are in agreement with previously published literature [206, 216].

Table 3.7 shows that during the core exercises and the SS design, within-subject CV ranged from 7 - 66% for peak muscle activity (excluding the outlier RA overhead squat; CV = 77%) and 7 - 54% for ARV muscle activity (excluding the outlier LG side bridge; CV = 61%). The LG and EO muscles showed the largest variation within-day. The RF, GM and MF muscles showed the most repeatable muscle activity between-day. When these values (SS design) are compared to the MS design CV values (peak CV 5 - 28%; ARV CV 2 - 28%) they represent a higher variation and subsequently poorer repeatability. However, the SS design CV values (as highlighted earlier) includes between-day variation as well as within-day trial variation. When the minimum CV values observed on any one day using the SS design is used, the CV values are more agreeable (peak CV 1 - 37%; ARV CV 0 - 16%). This highlights the variation observed when the same exercises are performed on separate days. Therefore it is important to establish between-day variability as well as within-day variability. This highlights the great care that needs to take place when locating these specific muscles during sEMG electrode placement to make sure that the differences observed between muscles and subjects are true differences as a result of the exercises and not due to experimental set-up differences.

The data suggests that the level of the repeatability is influenced by the type of exercise being undertaken. It was observed that low threshold exercises were more repeatable exercises than high threshold exercises. This interpretation is supported by previous studies that have found that sitting tasks are less repeatable than prone tasks [262], cycling tasks are less repeatable than climbing stairs [277] and studies that have observed high CV average values of over 80% during highly dynamic taekwondo kicks [278].

The high threshold core strength exercises (i.e. overhead squat and sit-twist exercises) reported a higher variation across the three trials (CV 6 - 28%) compared to the static (CV 5 - 23%) and low threshold exercises (CV 2 - 23%). This would be expected as the greater demand that is placed on the body during the high threshold exercises would lead to a greater variation in muscular activity between trials, especially if there is a weakness in core stability and/or core strength. This is due to the muscles being recruited differently each time and the activity of these muscles varying during the exercise due to postural changes and balance adjustments



which would be sporadic in nature. By observing this greater variation in the current study during high threshold exercises and not during low threshold exercises, it can be suggested that low threshold exercises recruit the same muscles in a similar manner more regularly. For example, the larger variation observed between low and high threshold exercises (Table 3.7) is observed between the one static (side bridge exercise) and the remaining four dynamic exercises. The side bridge exercise results in the lowest CV variation seen for the core musculature muscle activity (peak 9%; ARV 13%). This is then followed by the low threshold symmetrical exercise (bent leg curl up; peak 12%; ARV 9%), the low threshold asymmetrical exercise (birddog; peak 14%; ARV 13%) and the high threshold symmetrical exercise (overhead squat; peak 16%; ARV 15%). One would expect this trend as symmetrical exercises pose less demand on the muscles as there is less rotational challenge on the body (as one side is doing the same as the other) and subsequently less balance and postural alternations are required. During asymmetrical exercises, one side of the body is moving in one direction while the other is moving in a different direction. This results in extra torque and balance adjustments to be made which increases muscular activity and the amount of potential balance corrections to take place. These occur in varying amounts between subjects (depending on their core ability) resulting in a larger variation between trials and subjects.

Based on the CV values observed in the current study generally being less than 26% and therefore representing a sufficiently replicated EMG signal between the trials, it can be suggested that there was a minimal learning effect during the three trials of the core exercises. For the five measures that did show the largest CV (LD overhead squat peak EMG, medicine ball sit-twist peak and ARV EMG measures, LG medicine ball sit-twist peak EMG and RA overhead squat ARV EMG measures) the difference between trials 2 and 3 were the greatest, with trials 1 and 2 showing the most similar values (MS design). This implies that there may have been a fatigue effect during the third trial. This is supported by the larger variation only being observed during the high threshold exercises (overhead squat and medicine ball sit-twist exercises). It is therefore recommended that a longer recovery period (more than one minute) is needed between trials for this type of exercise.

The difference in CV variation between peak and ARV EMG values does appear to be consistently exercise and muscle dependent. There is a trend that suggests that low threshold exercises report a higher integrated muscle activity CV (ARV EMG) while high threshold exercises report a higher peak muscle activity CV. This would be expected due to low threshold exercises being less dynamic in nature and therefore place the muscles under less strain, resulting in a lower variation observed for the peak value measured during the exercise. During low threshold exercises the greater variation and demand is placed on balance and body position control which utilises the smaller stability muscles and has a large amount of sub-maximal muscle activity. Due to the heightened balance requirements of the exercise (especially if individuals have poor core stability) the sub-maximal muscular activation (to be able to hold the position) and variation seen between trials (due to sporadic postural changes) would be large. Whereas, during high threshold exercises (such as the overhead squat and sit-twist exercises) these require the muscles to be activated to a greater extent to be able to successfully perform the movement, subsequently increasing peak muscle activity. Due to these larger activations, and the more complex nature of these exercises (e.g. more muscles being recruited), technique changes are also likely to occur more often, resulting in large variations between trials. Furthermore, if the individual has insufficient core strength to maintain the posture during the exercise, the muscles will show peaks of activity when positional corrections are required to maintain body position due to muscular fatigue and/or weakness. These peaks will vary between trials and subjects and could be significant in size, hence increasing the variation seen in peak EMG activity within-subjects.

Along with the type of exercise performed, the variability of muscle activation also depends on the role of the muscle during the exercise. It is proposed that this is due to the more demanding, unstable, rotational exercises being more susceptible to spikes of activity in the stabiliser muscles to maintain balance and posture (this would show a higher variation both between- and within-subjects). This is due to the greater demand on the core musculature and the random corrections to balance that may take place. This study found that if the muscle had a primary role during the exercise (e.g. either limb movement or back stability), variability was generally reduced (e.g. SS design; MF, birddog exercise CV peak 7%, ARV 9%), whereas

if the muscle was not heavily involved in the exercise, the variability between trials was higher (SS design; MF, side bridge exercise CV peak 22%, ARV 34%). This is due to the muscle not being greatly active for most of the exercise and is therefore susceptible to slight increases in activity as a result of balance adjustments or slight changes in technique and would subsequently increase the muscle activity for that trial, which would then be enough to increase the variability between that trial and the trials that did not incur this extra muscle activity.

When looking at the within and between-day CV values for the eight muscles during the core exercises (SS design) (Table 3.6), it can be concluded that within-day CV (0 - 65%) was lower than between-day CV (7 - 77%) which supports previous findings [235, 251]. During the MVIC exercises this was also observed (Table 3.4) with the within-day variation ranging from 0 - 71% and the between-day variation from 6 - 89%. These findings highlight that the core exercises appear to be slightly more repeatable than the MVIC exercises both within- and between-days. This may be due to the technique used during the MVIC exercises which is more susceptible to alterations between trials and days with them being affected by motivation and fatigue. The large CV values observed in the current study (both within- and between-day) for certain exercises may reflect a weakness in the individuals recruitment of the core muscles during that exercise. For example if the subject has insufficient core stability and core strength to maintain the same technique during multiple trials then a large variation in muscle activity would be expected as balance and postural alterations would be made erratically during some of the trials. Therefore this large variation may not be a negative finding in the study but an important one which highlights a weakness in the individual's core stability and core strength.

The RF and GM muscles reported the most repeatable muscle activity during the core exercises both between-day (maximum range, RF, 4 - 22%; GM, 11 - 28%) and within-day (maximum range, RF, 13 - 31%; GM, 2 - 22%) (SS design) and as a result suggests that these muscles are repeatable enough for sEMG data collection during the exercises presented here. The EO, IO, MF, LD and RA muscles all reported sufficiently acceptable CV values (< 26%)

for most of the exercises with the greatest variations seen during the high threshold exercises. It is suggested that fatigue may have contributed to this increase in variation observed between trials during the more demanding exercises. This is despite the one minute rest periods that were included in the experimental protocol. However repeating the protocol ten times over three days (SS design) may have been more demanding than the experimenter anticipated on some of the muscles analysed.

The variation seen between trials in subjects in the current study could be due to a range of factors, including biological, psychological and experimental factors. Biological factors include; skin temperature, body fat and the random activation of neural muscular fibres during muscular contractions. Each time a muscle is contracted, different muscle fibres are activated and recruited [122], this could result in different muscle activation levels between trials. This factor is hard to control for and represents the uncontrollable quasi-random variation observed between trials and individuals when EMG data is collected [120]. Psychological factors include subject motivation [221] which would mainly affect the MVIC exercises and the maximal contraction that is produced. If a subject is less motivated to performing the exercise, they will subsequently not put in the same effort and would result in lower muscle activation. These psychological factors can be controlled and minimised to help obtain more repeatable data by providing motivational feedback to the subject. Experimental factors include; EMG electrode muscle placement (Veiersted [247] found that by moving the electrode placement by 12 mm along a muscle, larger deviations in EMG amplitude are observed), exercise technique employed, equipment noise during data collection, data processing methods (e.g. identification of muscle activity onset) [279] and movement velocity (where variability is higher at slower speeds) [280, 281]. The signal averaging overlapping window time period that is used has been found to effect the resultant variation of EMG signals between trials [235]. The current study used a window of 50 ms which is in agreement with previous studies [232, 279] who have demonstrated that it is possible to obtain repeatable data when using this method. Bamman et al. [235] on the other hand recommended that a window of at least 500 ms should be used for an EMG study. However by using a 500 ms window, this increases the smoothing effect on the data and potentially removes the 'true' peak EMG value. A 50 ms moving

window reduces the smoothing effect on the maximum EMG amplitude of the muscles but still smoothes the data to remove any unwanted artefacts. It is an important balance between achieving a true MVIC value of a muscle and over-smoothing the data (potentially losing the maximum value).

### 3.5 Conclusions

The eight core muscles analysed reported CV values of  $< 26\%$  during at least one of the 100% MVIC exercises which suggests that the maximal exercises used in this study are repeatable and can be used for sEMG normalisation. During the MVIC exercises, it was observed that the largest variation occurred between trials 1 and 2 which imply that some learning effect or warm-up process may have taken place following trial 1. This highlights the importance of each subject being familiar with the exercises prior to data collection. In reverse, for the core exercises, it was trials 2 and 3 that varied the most. As this larger variation was only observed during the high threshold exercises it can be concluded that a longer recovery time was needed between the trials for this type of exercise. The current study is also in agreement with previous research [234, 235] where it has been found that between-day variability is higher than within-day MVIC variability. This highlights the complex nature of collecting sufficiently repeatable data using sEMG on the core musculature over multiple days.

Peak and ARV EMG CV values have been reported here using two methods (single subject and multiple subject) to calculate the typical within-subject variation. Both methods showed acceptable limits of repeatability ( $CV < 26\%$ ) and suggests that either of the methods can be used to establish repeatability. The measured sEMG values did appear to show that the type of exercise affected the EMG value. Low threshold exercises resulted in a large variation in the ARV EMG data, while high threshold exercises resulted in a large variation in peak EMG data. This could be expected due to the greater demand on the muscles during high threshold exercises which result in larger muscular activities to overcome the higher torques and forces on the body to maintain balance. Meanwhile, low threshold exercises result in more sub-maximal muscular activity to maintain balance. Based on the current findings it can be suggested that the core muscles in the current study do produce sEMG data that is sufficiently

repeatable and that the data collection protocol and subsequent analysis methods used (peak and ARV EMG analysis) are repeatable enough for further data collection and research to take place.

## **Chapter 4**

# **Establishing the Level of Core Musculature Activity during Core Exercises to Determine the Content of a Core Training Programme**

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**(Phase I: Modelling)**

#### 4.1 Introduction

It is important when establishing a core training programme that the exercises chosen are not only functional for the athlete and the sporting movement but also activate the core musculature to the required level to result in core stability and/or core strength enhancements that can be transferred to performance enhancements [100]. Subsequently, it is essential to train using sport specific exercises [99]; dynamic and static, low and high threshold, symmetrical and asymmetrical types of movements (which take place in all three planes of movement) [60, 94]. Exercises need to be sufficiently demanding enough to elicit a stability or strength response from the muscle [31, 72, 151] to result in physiological adaptations to the muscles. Therefore it is important to be able to quantify the demands on, and the extent to which, the different muscles are working during these exercises [75, 125]. It is essential that research provides an accurate assessment of core training exercises and establishes which muscles are involved, to what extent, for how long and whether this is sufficient to result in training benefits to those muscles [267]. At present, this has not been established and there is a lack of published data which quantifies these muscle activation levels and demands for the different types of core exercises commonly performed by individuals. This is especially so regarding high threshold and highly dynamic core exercises which are functional exercises for the sporting population. As a result, coaches and athletes are unable to confidently select the most specific training exercises which activate the core musculature to the same extent as during their sporting movement. If these activation levels are quantified in future research (as proposed here), it would be possible to select the optimum exercises for athletes to perform based on a scientific-based rationale that matches the required activation levels that the muscles need to be trained at.

The goal of core training exercises is to challenge and subsequently enhance the core ability (stability, strength, endurance) (depending on the type and intensity of the exercises) of the core musculature to increase the individual's ability to transfer and withstand forces placed on the body during sporting movements [19]. Current theory suggests that muscle activations of 10 - 25% MVIC have the ability to improve the neuromuscular pathways and subsequent recruitment of the core muscles for stabilisation of the body [176, 196]. Strength



improvements to the core muscular (as a result of muscle fibre hypertrophy) are believed to result following strength training which activates the muscles above 60% MVIC [195].

Different types of core exercises that are commonly performed in core training programmes include; static, dynamic, symmetrical, asymmetrical, with and without external resistance and using stable and unstable bases. These different types of exercises result in varying demands on the core musculature [222, 232, 233] with some activating the muscles to a higher extent than others [16, 92, 220]. This has important implications for training programmes, as ideally, an individual should perform exercises that elicit the same level of muscle activation in training as in competition and exercises that produce the same muscle activation each time. An exercise that sometimes produces a high activation and other times a low activation would not be as effective as one that produces high muscle activity each time that it is performed.

To date the effectiveness of core stability and core strength training programmes has largely been based on functional anatomical evaluations, empiric measurements or subjective perception [267]. This may explain why many such programmes are ineffective in improving core stability, core strength and/or sporting performance [155]. Core stability training programmes are widely available in the public domain and each one consists of different exercises (many using devices such as wobble boards, swiss balls and resistance bands) to create resistance or demands on the body musculature [50, 199]. However many of these training programmes are not based on scientific findings as to which exercises are optimal for recruiting the chosen muscles to the required activation levels needed to result in physiological adaptations [100].

### **Aim of Chapter**

The main focus of this thesis is to develop a methodologically sound core training programme for highly trained swimmers. To establish this, an effective core training programme needs to be designed which elicits sufficient levels of muscular activity to result in physiological adaptations to the core musculature. Therefore the aim of this study is to quantify the core musculature activity and evaluate the muscular response during a range of core exercises.

## **4.2 Methods**

### **4.2.1 Subjects**

Five highly trained female athletes (age;  $17.8 \pm 1.2$  years old; height;  $167.1 \pm 7.4$  cm; body mass;  $60.5 \pm 5.2$  kg) and six highly trained male athletes (age,  $19.2 \pm 2.8$  years; height,  $186.4 \pm 6.2$  cm; body mass,  $82.5 \pm 7.6$  kg) were selected for the study. All participants volunteered for the study and completed informed consent documents which, along with the medical questionnaire and test protocol, were approved by the Teesside University Ethics Committee. All participants were experienced in performing core stability and strength exercises (both static and dynamic in nature) and were in full health prior to the testing and did not report any feelings of pain when performing the tests. All participants were in full health prior to the testing and did not report any feelings of pain when performing the tests.

### **4.2.2 Exercise Details**

One week prior to data collection, each subject was provided with a written explanation for each exercise, shown a demonstration of each exercise and subsequently practiced each MVIC exercise (Table 3.1) and core exercise (Table 3.2) at the required repetition rate prior to testing.

#### **4.2.2.1 MVIC Exercises**

The five MVIC exercises used in Chapter 3 (Figure 3.1) were repeated in this study. The number of trials and recovery between repetitions were as reported in Chapter 3.

#### **4.2.2.2 Core Exercises**

For the trials the subjects were grouped into two. The first group which included the five females performed five core exercises (Table 3.2) for 60 seconds (with two minute rest between each). The second group which included the males performed sixteen core exercises (ten dynamic, six unilateral; Table 4.1). Each of these exercises was performed twice with two minutes rest between each. The order of exercise was randomised for each subject. These exercises were selected based on previous research that have highlighted them as important in determining and developing core stability and core strength [6, 15, 31, 32, 75, 89, 94, 212] and

to cover each type of core training exercise (static and dynamic, low and high threshold, symmetrical and asymmetrical). The repetition rate at which the exercises were performed at varied due to the demands of the exercises and was monitored using a stopwatch. The repetition rates were decided upon following discussions with qualified strength and conditioning coaches and were kept the same for each subject to minimise inertial effects of limbs on the muscles and EMG movement artefact. All exercises were performed on the same day.

Table 4.1. Description of the sixteen core stability and strength exercises performed. Descriptions marked \* are based on Brandon [3]





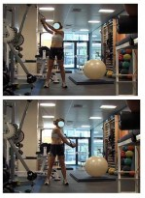
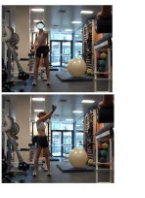
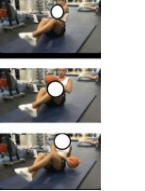
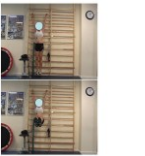
Exercise	Description	Repetition rate	Duration (seconds)	Diagram
CORE TRAINING EXERCISES – STATIC EXERCISES				
Forward bridge* (static)	Hold a straight body position supported on elbows and toes. Contract the abdominal muscles and hold back in neutral position	Hold for 60s	60	
Side bridge* (static)	Lie on one side, ensuring top hip is positioned above the bottom hip. Push up until there is a straight bodyline through feet, hips and head	Hold for 60s	60	
CORE TRAINING EXERCISES – LOW THRESHOLD EXERCISES				
Birddog* (asymmetrical)	Position hands below shoulders and knees below hips. Position back in neutral, extend one leg backwards and raise the opposite arm until level with back. Ensure back does not extend and shoulders and pelvis do not tilt sideways. Bring leg and arm back to start position and swap sides	2s change sides–3s hold in position	60	
Bent leg curl-up (symmetrical)	Lie on floor with knees bent to 90° and feet resting on floor. Position back in the neutral position and arms folded across chest, raise head, shoulders and upper back off the floor, hold and return to start position	2s hip flexion (up)–2s hip extension (down)	60	

Table 4.1. Description of the sixteen core stability and strength exercises performed. Descriptions marked \* are based on Brandon [3]

Exercise	Description	Repetition rate	Duration (seconds)	Diagram
Leg extensions (asymmetrical)	Lie on back with knees and hips flexed to 90°. Extend one leg out so heel rests just above floor keeping other leg flexed. Return extended leg to starting flexed position and repeat with other leg	2 s hold position – 1 s change side – repeat for opposite side	60	
Back extensions (symmetrical)	Using an horizontal extension bench, lie with hips on edge of bench and feet fixed under bar. Flex hips so head is near ground. With arms folded across chest, extend back until in neutral, hold and then return to start position	2s hip extension (up) – 2s hold – 2s hip flexion (down)	60	
One leg squats (asymmetrical)	Standing with back in neutral and hands on hips. Flex left knee to 90° so foot is off floor and balancing on right leg. Keeping head looking forward and hips straight, flex the right hip and knee. Squat as low as possible, hold and return to starting position, remain balanced on right leg and repeat	2s hip flexion (down) – 2s hold – 2s hip extension (up)	60	
Unweighted squat (symmetrical)	Using a wooden stick, place hands shoulder width apart on stick. Raise the bar above head and straighten arms. Feet shoulder width apart, squat down as low as possible while maintaining balance, keeping bar, head and back vertical. Straighten legs and repeat	2s hip flexion (down) – no hold – 2s hip extension (up)	60	
CORE TRAINING EXERCISE – HIGH THRESHOLD				
Weighted squat (symmetrical)	See Unweighted Squat description but using a 20 kg weight lifting bar with no added weight discs on ends of bar.	2 s hip flexion (down) – no hold – 2 s hip extension (up)	60	
Straight leg raises (asymmetrical)	Lie on back with knees extended on floor. Place back in neutral position and lift both legs straight up keeping legs extended. Hold with hips flexed to 90°, then return slowly to start position	2 s hip flexion (down) – 2s hold – 2s hip extension (up)	60	

Table 4.1. Description of the sixteen core stability and strength exercises performed. Descriptions marked \* are based on Brandon [3]

Exercise	Description	Repetition rate	Duration (seconds)	Diagram
Bar bell roll-outs (symmetrical)	Using lifting bar with a rolling weight on either end of bar. With knees on floor and hands on bar, slowly extend hips and shoulders using the bar to guide you down. Reach as far as you can hold then return to start position by 'rolling' the bar back. Ensure back is in neutral for duration	3s hip extension – no hold – 3s hip flexion (roll back)	60	
Diagonal pull-down* (asymmetrical)	Stand with feet shoulder width apart facing forwards by side of pulley column. Position handle attachment at above head height so arms are straight. Fix hips square to the front and back in neutral. Twist through the waist, keeping shoulders and upper body in line, pulling down the handle to hip height, hold and return handle slowly to above head height	2s pull down – 1s hold position – 2s return to start	60	
Diagonal pull-up* (asymmetrical)	See above, but start with handle at hip height and pull up to above head height	2s pull up – 1sec hold position – 2s return to start	60	
Medicine ball sit-twist (asymmetrical)	Sit up with knees bent and lean back at 45°. Feet off floor, keeping back in neutral, using a 4 kg medicine ball, twist waist and shoulders to one side with ball held out in front of you. Return to forward and repeat to other side	2s move from left to right and return (4s total)	60	
Medicine ball lunge twist (asymmetrical)	Using a 3 kg medicine ball, hold out in front at shoulder height. Place one foot forward and lunge so knee is flexed 90°. Twist through waist (staying upright) to the side of the forward foot, keep shoulders and head fixed. Return to front, stand up on front foot. Repeat for other leg and twist to other side	3s per lunge (one side). 6s for one rep	60	
Straight hanging leg raises* (asymmetrical)	Hang from a bar with arms straight. Keeping legs straight, flex hips and raise both legs to horizontal. Ensure back is kept in neutral and legs remain inline in front of body. Return slowly to straight body position	1s hip flexion (up) – no hold – 1s hip extension (down)	60	

### 4.2.3 Data Collection

The data collection protocol outlined in section 3.2.3 of Chapter 3 for the performing of the MVIC and the core exercises was repeated in this study. This included collected sEMG signals were from the right side of eight core muscle sites (Table 3.3).

### 4.2.4 Data Processing

EMG signals were bandpass filtered at 20-450 Hz using Delsys EMGworks 3 software and subsequently analysed using Acknowledge software program (Biopac Systems Inc., Goleta, CA). The EMG signal was processed as stated in Chapter 3 of this thesis. Onset and offset points for each repetition were also calculated as stated in Chapter 3 (Figure 3.1). MVIC, peak and ARV EMG values and data analysis followed the same normalisation process as outlined in Chapter 3 and Hibbs et al. [282] to establish peak and ARV %MVIC EMG values for each muscle for each type of core exercise. The sixteen exercises were ranked based on the muscle activity (peak and ARV EMG %MVIC) for each muscle analysed and averaged across all muscles.

### 4.2.5 Statistical Analysis

Means and standard deviations were calculated for the five and sixteen core exercises to establish %MVIC peak and ARV EMG values for each core muscle. The sixteen core exercises were ranked in order of %MVIC muscular activation level for peak and ARV EMG with 1 being the highest activation level (100%) recorded and 16 being the lowest activation level recorded (0%) from the sixteen core exercises.

## 4.3 Results

Table 4.2 shows that the different types of core exercises (static, dynamic, asymmetrical, symmetrical, low and high threshold) do activate the core musculature to a sufficient level to potentially result in core stability (10-25% MVIC activation) and/or core strength (>60% MVIC activation) enhancements. The overhead squat exercise resulted in the greatest muscle activity being produced in four of the eight core muscles (MF, LD, LG and RF muscles). Certain muscles (RA, GM and RF) resulted in a large variation in muscle activity between the

calculated peak and ARV EMG muscle activity during some of the core exercises (e.g. the side bridge and the bent leg curl-up exercise).

Table 4.2. Mean peak %MVIC and ARV %MVIC during five types of core exercises for each core muscle (n = 5). Standard Deviations are shown in brackets. Green boxes represent values that are within the core stability training range (<10-25% MVIC). Blue boxes represent values that are within the core strength training range (>60% MVIC).

Exercise	EMG	RA	EO	IO	MF	LD	GM	LG	RF	Average
Side bridge	Peak	59 (10.3)	66 (3.1)	34 (4.7)	43 (14.6)	10 (4.6)	21 (4.5)	53 (5.2)	11 (1.4)	37
	ARV	48 (9)	60 (8.6)	39 (4.6)	38 (4.6)	8 (5.6)	52 (7.1)	40 (7.9)	59 (8.7)	43
Birddog	Peak	7 (1.3)	47 (7.6)	20 (5.1)	64 (9.2)	12 (6.4)	69 (6.9)	55 (8)	55 (5.6)	41
	ARV	10 (3.2)	29 (2.9)	32 (3.9)	48 (7.5)	8 (4.6)	61 (10)	37 (5.9)	60 (7)	36
Bent leg curl-up	Peak	90 (12)	82 (13.9)	61 (3.6)	12 (2.4)	4 (1.4)	17 (3.1)	27 (3.2)	20 (8.1)	39
	ARV	44 (2.4)	41 (4.3)	50 (3.8)	20 (1.9)	6 (2.1)	41 (8.8)	9 (2.1)	35 (5.4)	31
Overhead squat	Peak	24 (6.2)	27 (3.9)	37 (3.6)	77 (12.7)	19 (4.8)	26 (4)	79 (6.8)	68 (9)	45
	ARV	12 (4.3)	20 (8.4)	34 (4.3)	57 (6.1)	9 (3.20)	44 (7.5)	54 (4.3)	65 (11.1)	37
Medicine ball sit-twist	Peak	79 (13.3)	96 (12.7)	52 (3.3)	21 (5.4)	10 (3.2)	28 (4.9)	8 (1.7)	40 (11.1)	42
	ARV	50 (8.7)	84 (15.1)	53 (3.2)	16 (3.0)	7 (4.9)	42 (9.4)	9 (2.1)	98 (15.2)	45
Average		42	55	41	40	9	40	37	51	42

RA-rectus abdominis, EO- external oblique, IO – internal oblique, MF- multifidus, LD- latissimus dorsi, GM- gluteus maximus, LG- longissimus, RF- rectus femoris

Table 4.3. Peak and ARV EMG %MVIC values for the eight core muscles during sixteen core exercises (n = 6). Standard deviations shown in brackets. Green boxes represent values within core stability training range (<10-25% MVIC). Blue boxes represent values within core strength training range (>60% MVIC).

Exercise	EMG	RA	EO	IO	MF	LD	GM	LG	RF	Average
Forward bridge	Peak	53(13)	57(10)	71(19)	21(3)	20(7)	40(8)	24(12)	25(6)	39
	ARV	43(8)	76(23)	53(8)	28(5)	30(5)	34(5)	15(8)	29(9)	39
Side bridge	Peak	26(4)	76(16)	81(17)	53(6)	39(8)	45(7)	40(11)	6(3)	46
	ARV	21(5)	80(9)	70(19)	41(6)	36(7)	42(9)	33(6)	15(4)	42
Bird dog	Peak	8(2)	29(6)	96(22)	58(5)	19(6)	77(10)	54(12)	47(8)	49
	ARV	6(3)	32(7)	23(7)	44(8)	24(6)	50(11)	36(7)	31(5)	31
Bent leg curl-up	Peak	91(16)	77(18)	77(6)	62(11)	11(3)	39(8)	31(10)	11(3)	50
	ARV	53(10)	57(10)	66(8)	25(7)	16(4)	34(6)	16(8)	16(5)	35
Leg extensions	Peak	37(6)	53(8)	53(7)	34(7)	10(4)	50(7)	17(5)	51(8)	38
	ARV	35(8)	63(7)	65(8)	24(4)	15(3)	34(6)	20(5)	52(9)	39
Back extensions	Peak	8(3)	13(4)	27(7)	68(8)	15(4)	50(8)	29(10)	9(3)	27
	ARV	6(3)	22(6)	21(5)	54(7)	26(8)	50(11)	34(9)	14(4)	28
One leg-squats	Peak	8(3)	17(6)	66(9)	41(7)	11(3)	60(8)	25(6)	21(5)	31
	ARV	6(2)	24(8)	33(6)	35(5)	22(7)	53(11)	24(7)	28(5)	28
Straight leg raises	Peak	69(11)	83(18)	90(18)	83(11)	20(4)	50(7)	19(5)	53(7)	58
	ARV	58(16)	90(17)	83(9)	28(10)	19(5)	36(5)	36(9)	46(6)	50
Unweighted squat	Peak	8(2)	15(5)	30(4)	45(7)	11(3)	39(8)	54(12)	44(6)	31
	ARV	6(2)	23(4)	20(3)	41(5)	19(4)	37(9)	48(13)	41(9)	29
Weighted squat	Peak	16(5)	29(6)	30(7)	65(7)	26(4)	46(11)	83(18)	56(10)	44
	ARV	8(5)	28(7)	27(9)	44(9)	28(6)	56(7)	67(14)	48(7)	38
Bar bell Roll-outs	Peak	111(25)	141(26)	97(18)	38(7)	43(7)	39(6)	15(6)	10(3)	62
	ARV	63(16)	88(12)	64(8)	30(6)	40(9)	43(8)	16(5)	17(5)	45
Medicine ball lunge twist	Peak	10(3)	49(7)	86(20)	61(9)	20(5)	69(9)	50(8)	27(6)	47
	ARV	7(4)	33(11)	39(10)	45(7)	28(4)	44(6)	39(5)	30(8)	33
Diagonal pull-down	Peak	17(5)	39(5)	84(8)	32(8)	26(7)	39(8)	34(6)	24(7)	37
	ARV	10(4)	40(7)	64(9)	28(5)	31(10)	44(11)	23(8)	27(4)	33
Diagonal pull-up	Peak	10(5)	31(5)	77(17)	46(7)	45(6)	59(6)	70(12)	4(2)	43
	ARV	7(3)	36(6)	61(8)	43(7)	39(8)	59(7)	47(11)	14(5)	38
Medicine ball sit-twist	Peak	46(10)	118(12)	92(12)	26(8)	18(4)	45(6)	25(6)	62(9)	54
	ARV	35(7)	84(9)	64(11)	29(11)	21(5)	35(7)	22(7)	79(15)	46
Hang leg raise	Peak	95(23)	126(21)	109(15)	64(5)	16(4)	29(4)	40(8)	86(18)	71
	ARV	61(21)	114(23)	89(14)	39(15)	25(7)	28(3)	33(7)	57(12)	56
Average		32	58	63	43	24	45	35	34	32

RA-rectus abdominis, EO- external oblique, IO – internal oblique, MF- multifidus, LD- latissimus dorsi, GM- gluteus maximus, LG- longissimus, RF- rectus femoris



Table 4.3 shows the muscle activations for the eight core muscles during the sixteen core exercises. Each core muscle was activated to a suitable level during the exercises to result in core stability (10-25% MVIC) and/or core strength (>60%) enhancements. The EO and IO muscles did report activation levels of over 100% MVIC during some core exercises. Different activation levels were observed for the same core exercise for the Peak EMG and ARV EMG values.

Table 4.4 shows the sixteen exercises ranked in order of muscular activation level recorded for each core muscle. For some core exercises, Peak EMG and ARV EMG ranked the core exercises differently.

Table 4.4. Ranking of the eight muscles during the core exercises (1 = greatest muscle activation during the sixteen core exercises).

Exercise	EMG	RA	EO	IO	MF	LD	GM	LG	RF	Average
Forward bridge	Peak	5	7	11	16	7	11	13	9	10
	ARV	5	6	10	16	5	14	16	9	10
Side bridge	Peak	8	6	8	8	3	10	7	15	8
	ARV	8	5	3	6	3	9	9	14	7
Bird dog	Peak	15	12	3	7	9	1	4	6	7
	ARV	14	12	14	4	10	5	5	7	9
Bent leg curl-up	Peak	3	5	9	5	13	12	9	12	9
	ARV	4	8	4	14	15	13	14	13	11
Leg extensions	Peak	7	8	13	13	16	6	15	5	10
	ARV	6	7	5	15	16	15	13	3	10
Back extensions	Peak	14	16	16	2	12	5	10	14	11
	ARV	13	16	15	1	8	4	7	15	10
One leg-squats	Peak	16	14	12	11	14	3	12	11	12
	ARV	15	14	12	9	11	3	10	10	11
Straight leg raises	Peak	4	4	5	1	6	7	14	4	6
	ARV	3	2	2	12	13	11	6	5	7
Unweighted squat	Peak	13	15	15	10	15	15	3	7	12
	ARV	16	15	16	7	14	10	2	6	11
Weighted squat	Peak	10	13	14	3	4	8	1	3	7
	ARV	10	13	13	3	6	2	1	4	7
Bar bell Roll-outs	Peak	1	1	2	12	2	14	16	13	8
	ARV	1	3	6	10	1	8	15	12	7
Medicine ball lunge twist	Peak	11	9	6	6	8	2	5	8	7
	ARV	12	11	11	2	7	7	4	8	8
Diagonal pull-down	Peak	9	10	7	14	5	13	8	10	10
	ARV	9	9	7	13	4	6	11	11	9
Diagonal pull-up	Peak	12	11	10	9	1	4	2	16	8
	ARV	11	10	9	5	2	1	3	16	7
Medicine ball sit-twist	Peak	6	3	4	15	10	9	11	2	8
	ARV	7	4	8	11	12	12	12	1	8
Hang leg raise	Peak	2	2	1	4	11	16	6	1	5
	ARV	2	1	1	8	9	6	8	2	5

RA-rectus abdominis, EO- external oblique, IO – internal oblique, MF- multifidus, LD- latissimus dorsi, GM- gluteus maximus, LG- longissimus, RF- rectus femoris

#### 4.4 Discussion

The aim of the Chapter is to quantify the core musculature activity and evaluate the muscular response during a range of core exercises. The findings in the current study supports previous research that suggests that there is not one exercise that activates all of the core muscles maximally [12, 94]. Some of the exercises performed in the current study have been researched before (side bridge and bent leg curl-up [12, 94]) while others have received very little attention (e.g. medicine ball sit-twist exercise). From Tables 4.2 and 4.3 it can be seen that the core muscles were activated to a sufficient level to potentially result in improvements to core ability. Muscular activation of 10 - 25% MVIC have been stated to be sufficient to result in core stability benefits following a period of training [57], while muscular activity of > 60% MVIC can result in muscular strength enhancements [100]. The RA, EO and the RF muscles were found to be activated to over 60% MVIC regularly during the exercises. This highlights the potential importance of these muscles to core strength. The IO, MF, LG, GM and LD muscles were all consistently activated between 10% and 60% MVIC emphasising the potential importance of these muscles to core stability.

The level of muscular activations observed in the current study are in agreement with those observed in previous research, for example, Behm [238] identified that the MF muscle was activated to 66% and 35% during the birddog and side bridge exercises respectively compared to the present studies peak EMG activation levels of 64% and 34% respectively. The EO muscle also shows agreeable values when compared with Juker et al. [103] who found an activation level of 52% during twisting movements compared to the present studies value of 47% (Peak EMG). The LG muscle showed a difference in observed muscle activation when compared with previous research, for example during the birddog and the side bridge exercises, the present studies differ to those of Behm [238] (present study, 53% and 55% Peak EMG compared to Behm [238] 31% and 77% for the side bridge and the birddog respectively). These differences may be due to the large variation seen when analysing this muscle (LG) using sEMG which can be supported by the findings in Chapter 3 where the LG muscles coefficient of variation ranged from 17-66% (Table 3.6) during the core exercises performed. These findings suggest that this muscle may not be suitable for repeatable sEMG analysis.

The overhead squat exercise resulted in the greatest overall muscle activity for four out of the eight muscles (MF, LG, LD and RF) which would be expected as this was the most demanding exercise and would have placed the core musculature under the greatest strain. The RA, GM and RF muscles were found to have the greatest difference in activity between the peak and ARV muscular activity. For example during the bent leg curl-up exercise RA peak EMG activity was 90% MVIC while ARV EMG muscle activity was 44%. This suggests that the muscle is activated in a phasic manner with larger but not consistent contractions occurring during the movement which would concur with the role that this muscle plays in the completion of this exercise (trunk flexion). Furthermore, during the medicine ball sit-twist exercise, peak EMG activity for the RF muscle was 40% while ARV muscle activity was 98% MVIC. This could be due to the muscle being a stabiliser muscle during the exercise which requires a relatively low but consistent muscle activity level throughout the exercise to maintain stability. This is supported by observing the activation levels during the static side bridge exercise when the muscles (for example the GM and RF) are required to be activated for longer but at a sub-maximal level to maintain the static body position.

It was observed that generally the peak EMG activity was greater during the more demanding exercises (seven out of eight muscles had higher activity during the overhead squat exercise), whereas during low threshold exercises, the ARV EMG muscle activity had higher muscle activation levels (three out of eight muscles during the side bridge and birddog exercises). Therefore if both types of exercise (high and low threshold) are being trained and analysed, it is recommended that both EMG measures of muscle activity are reported to provide a more in depth understanding of the true demands of each core stability and core strength exercise.

During the bent leg curl-up and straight hang leg raise, the RA and EO muscles elicited sEMG values of over 100% MVIC in the current study, supporting the high values obtained by Axler and McGill [94] of 105% for the bent leg curl and 110% during the straight hang leg raise exercise for the RA muscle. Konrad et al. [267] also found supra-maximal muscular activity for the EO muscle. %MVIC values of over 100% are common when isometric MVC exercises are used for the normalisation process as these are static exercises which do not have

the added forces and torques on the body that are present when the dynamic exercises are performed [146] and subsequently result in incomplete excitation of the motor-neurons during the static task [267]. Konrad et al. [267] also suggest that this may be due to the changing electrode-to-muscle configuration and distance in dynamic v static contractions. Despite this, MVIC exercises are still commonly used for normalising EMG data as the repeatability of this muscle activation has been found to be higher than using dynamic MVC exercise [235]. Konrad et al. [267] also suggest that because MVIC amplitude normalisation is mainly a rescaling function, the relative (muscle-specific) comparison of EMG activities among several tasks is not affected and should be the main focus of interpretation.

For some of the muscles selected in the current study during the core exercises, the %MVIC value do differ from previous research [12, 94]. For example, in the current study, the straight leg raise exercise resulted in high MVIC values for the RA and EO muscles (>100%), whereas previous research has found MVIC of 55% and 75% respectively [94] and 57% for RA [12]. During the straight hang leg raise, the RF muscle elicited a MVIC of 45% but previous research has shown an MVIC of 110% [94]. These findings may be as a result of different techniques being used, for example during the straight hang leg raise, the focus could be placed more on using the abdominal muscles to stabilise and flex the hips rather than using the hip flexors to raise the legs. Other factors that may have contributed to these differences include; different surface EMG electrode placement, different repetition rates during the exercises (a faster repetition rate or increased resistance would result in a higher %MVIC) and the use of different MVIC exercises to elicit maximum muscle activity. Therefore when comparing muscle activations between studies great care needs to be taken.

As a result of the findings in the current study, it is observed that some exercises may be more effective in resulting in core stability or core strength improvements than others. For example an exercise may bring about a high %MVIC but for only a short period of time during the exercise and therefore may not be the optimum exercise for that muscle to result in core stability improvements but may result in core strength enhancements. This is supported by the current study that found during the bar-bell roll out exercise, the GM reported the second highest peak EMG %MVIC for this muscle (48%) but only the tenth highest ARV EMG

result. Therefore this muscle is only active for a short period of time during the exercise but to a large extent. It may be that to result in core stability or core endurance benefits to this muscle an exercise that produces a longer activation period (for example the diagonal cable pull-down and pull-up exercise) may be more suitable. The information regarding the demands on the core musculature during the different exercises (as outlined here) is essential in formulating and implementing the optimum core training programme that will result in actual sporting performance improvements for athletes.

Establishing which exercise should be preferred for training depends on whether a core strength or core stability enhancement is required. Strength gains have been observed with %MVIC of over 60% [12]. Stability enhancements result from lower (10 - 25% MVIC) [57] but longer phases of muscle activity. From the current study, it can be suggested that exercises such as the straight hang leg raise, overhead weighted squat, bar-bell roll-outs, straight leg raises and the bent leg curl-up would result in strength enhancements in many of the muscles analysed (e.g. RA, EO, IO, MF and RF). Exercises such as the side bridge, bird-dog and back and leg extensions could result in stability enhancements for many of the muscles analysed (e.g. RA, EO, IO, MF, GM, LD and LG).

It is well established that both low and high threshold exercises should be performed in a training programme to improve core stability and core strength [11, 42]. The effect of performing the same exercise (the squat) with and without resistance can be seen in Table 4.3. By introducing a 20 kg weighted bar and making it a high-load exercise, both the peak and ARV %MVIC EMG muscular activations reflect this increased challenge to the core musculature and resulted in a greater ARV EMG and higher peak EMG muscle activity for all the analysed muscles. One exception to this was the MF muscle activity using the ARV EMG measure. This may be due to the increased weight resulting in other lumbar muscles taking over from the MF muscle (e.g. the longissimus muscle). This highlights the importance of performing both low-load and high-load exercises to train all the muscles of the core and not allowing an imbalance to develop and have the global muscles of the core become dominant [48].

#### **4.5 Conclusions**

The current study has been able to establish the muscular activation levels during different types of core exercises. All of the muscles analysed were sufficiently activated to the required level to result in core stability (10 - 25% MVIC) and/or core strength enhancements (>60% MVIC) which could potentially aid sporting performance. It was observed that not one exercise activates all the core musculature to a level required to result in both core stability and core strength improvements. This supports previous research [12] and highlights the need to implement a range of exercises when implementing a core training programme for athletes. These need to be specific, functional and target both stabiliser and globaliser muscles and hence included both low and high threshold exercises [1]. It can also be concluded that the eight core muscles analysed all contribute to an individual's core ability and by reporting both Peak and ARV EMG data a greater understanding of the core musculature recruitment and level of activity can be established. This is due to the different demands that are placed on the core musculature during the different types of exercises that are performed when core stability or core strength is targeted with both maximal and sub-maximal muscular activity taking place.

## **Chapter 5**

### **Short-term Evaluation of a Core Training Programme**

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#### **(Phase I: Development of an Intervention)**



## 5.1 Introduction

Most highly trained swimmers complete pool- and land-based training sessions as part of their weekly training programme [119, 122, 276, 277]. Highly trained and elite level swimmers regularly complete two pool-based sessions a day, covering distances of 5-10 km in a session. This training involves varying swimming speeds and swimming strokes depending on the focus of the session (i.e. lactate threshold session, speed work, endurance set) [6, 73]. It is commonly accepted that all swimmers should support these pool sessions with land-based training [25, 122, 150, 159, 160, 277]. This includes using equipment such as free weights and medicine balls and performing exercises that target and train overall body strength, alongside more specific exercises such as those that target the core musculature to improve core stability, strength and endurance. However it is essential that this land training is specific to swimming and includes the same muscles, in the same movements as the swimming strokes [99]. If this is not the case, any training effect on the muscles may not be transferable into the swimming pool and swimming performance [155]. Therefore it is essential that a specific training programme is implemented for the sports person to maximise their sporting performance [11].

As has been established, the core musculature includes muscles such as the rectus abdominis, external oblique, internal oblique, transverse abdominis, erector spinae, quadratus lumborum, latissimus dorsi and gluteus maximus [6, 19, 20, 37]. These muscles are heavily recruited during core training exercises as seen in unpublished (see Chapter 3 and 4) and published sEMG core musculature studies [79, 80, 101, 125, 135, 172, 192, 199, 225, 282, 283]. Previous literature has also established these core muscles to be heavily involved during the swimming stroke to help maintain body position, transfer forces through the body [78, 80] and optimise swimming technique. As a result it is essential that these muscles are strengthened and trained in swimmers. Training these muscles using functional and sport specific exercises, core stability and core strength may improve and subsequently enhance an individual's swimming performance [116]. Previous research has observed improved performance following a variety of core training programmes in for example, balance and sprint times [186], vertical jump height [105], muscular strength [119] and swimming time [119] (see Table 1.4). For healthy athletes, the type of core exercises performed include; squats,

deadlifts, overhead press and olympic lifts [98, 154]. Devices such as; bar-bells, medicine balls, elastic cords and free weights are used to create external resistance and activate the muscles to an extent that will result in stability and/or strength adaptations [49]. However, many interventions have failed to observe any improvement in swimming performance following a core training programme [117, 155]. This may be due to these studies not designing their training programmes on scientifically based theories which reduce the potential effectiveness. Girolid et al. [118] found no improvement following a dry-land training programme which included barbell press-ups, plyometric jumps and squat exercises. This may be due to these exercises not being suitable to recruit the core musculature in the same manner as during the swimming stroke. For example, performing press-ups using a barbell does not mimic the swimming stroke movement and so would not activate the muscles in the same manner or extent. Due to the lack of muscular activation data during these studies it is not possible to comment on whether these exercises were also not sufficient due to the lack of effectiveness in activating the core or due to their unrepeatability when activating the core musculature.

Findings from this thesis (Chapter 4) highlight the useful information that can be obtained from performing sEMG data analysis during core exercises (Table 4.2 and 4.3). The five core exercises examined in Chapter 4 all activate part of the core musculature to a sufficient level to potentially result in core stability and/or core strength enhancements [100]. Therefore these exercises could be included in a sport specific training programme as they include a variety of movements (static and dynamic), intensities (low to high), positional demands (symmetrical and asymmetrical) and target the whole core musculature (trunk, shoulders and upper leg muscles). The findings from Chapters 3 and 4 also highlight the importance of quantifying both peak and ARV sEMG muscle activity when analysing the core (something which has not been done in previously published literature). Both sEMG measures should be included due to the importance of the sub-maximal muscle activity which is present when performing core stability exercises which is not accounted for when peak EMG muscle activity is solely examined (see Chapter 4). This is important as sub-maximal core muscle activity has been quantified in previous studies during the swimming stroke [72]. Consequently it would be sport-specific to train these muscles at a similar level to that of the sporting movement.

The potential importance of training the core musculature in swimmers has been outlined in previous chapters and the different methods of training and the effectiveness of different types of exercises on improving sporting performance have been discussed. It has been highlighted that there are many factors that need to be included when designing and implementing a core training programme, and the potential benefits of including sEMG data in the evaluation of such a programme has been suggested. It has been established that by comparing performance measures and sEMG data pre- and post-intervention for a core training group and a control group, it is possible to conclude whether the athletes in the core training group experienced greater adaptations to the training performed during this time. Despite the popularity of core training in competitive swimming programs, to date no studies, as far as the author is aware, have evaluated both swimming performance and changes in core muscle activation concurrently.

Establishing the level of muscular activity during core exercises enables more knowledge to be gained on the demand that each exercise imposes on the core musculature (certain levels of muscular activity are required for stability and strength benefits to occur) [12, 100]. By solely measuring jump height or the strength of a limb pre-post training intervention, it will not be clear whether changes in muscle recruitment have occurred or not during the intervention process as a result of the core training exercises. By measuring individual muscle responses to core training exercises, more information on the training effects on specific muscles can be obtained and conclusions as to how effective certain exercises are in training and to what extent they target the core musculature. More detailed conclusions can then be made regarding the effectiveness of training programmes and improvements made to maximise its effect on improving sporting performance.

### **Aim of Chapter**

To implement a short-term swimming specific core training programme and evaluate performance outcomes in highly trained swimmers.

## 5.2 Methods

### 5.2.1 Subjects

Fifteen highly trained swimmers, eight men ( $15.5 \pm 1.2$  years,  $72.6 \pm 5.6$  kg,  $168.9 \pm 4.3$  cm) and seven women ( $16.2 \pm 1.4$  years,  $70.4 \pm 4.5$  kg,  $165.6 \pm 4.9$  cm) took part in a six week core stability and core strength training programme involving low and high threshold exercises [1] specifically chosen to mimic the demands of the swimming action and target all of the core musculature [8] (details of exercises, Table 5.2). Fifteen highly trained swimmers (nine men;  $17 \pm 2.3$  years,  $73.2 \pm 6.8$  kg,  $168.1 \pm 6.3$  cm, six women;  $16.7 \pm 1.7$  years,  $71.1 \pm 6.3$  kg,  $165.7 \pm 5.4$  cm) served as a control group. Following the reliability analysis conducted in Chapter 3, the required sample size to achieve the recommended statistical power would have been hundreds of subjects (due to the variation observed in the sEMG measurements and the expected smallest worthwhile change being relatively low due to the highly trained nature of the participants). Having small sample sizes is a common occurrence in many sEMG studies (also due to the complex and time-consuming data processing methods required) and it was felt that using a similar sample size to those reported previously in similar sEMG studies (8-15 participants) [31, 90] would be sufficient.

The intervention was a partial randomised experimental design due to the structure at the swimming club being set with the two groups of swimmers already established. However it was found that both of the groups were performing similar weekly mileage (average of 30 kilometers), the same number of swimming sessions in the water per week (eight pool-based sessions), similar types of swimming sessions (made up of recovery, tempo and endurance based sessions) along with a similar number of sprint, middle distance and endurance based swimmers. This was reflected in the pre-performance test scores, where similar pre-training scores were observed (Table 5.5). This therefore formed a ‘controlled before and after’ experimental design. The use of the ANCOVA statistical test for analysis of these performance tests would also remove any potential effect of these initial performance test scores being different as it removes the baseline for both groups in its analysis. During the core training programme it was agreed with the swimming coaches that the pool-based

training continued as normal and that both groups completed similar training sessions (i.e. duration and intensity).

Due to the elaborate and distracting nature of sEMG analysis it was decided to determine if the core muscle programme had performance benefits before undertaking a study requiring all participants to undergo sEMG analysis. Hence surface electromyography (sEMG) analysis was undertaken with three male subjects from the core training group in this study. Since this was the first study of its kind to use sEMG as an indicator of training adaptations during a core training intervention programme using highly trained athletes, it was felt that this sample size would be adequate to provide initial conclusions as to the muscular response of the core muscles to the training and identify if any core muscle activation adaptations took place following training. Future research would then extend these findings by analysing more subjects to expand the knowledge of this area (see Chapter 6).

### **5.2.2 Exercise Details**

One week prior to data collection, each subject was provided with a written explanation for each exercise, shown a demonstration of each exercise and subsequently practised each MVIC exercise (Table 5.1) and core exercise (Table 5.2) at the required repetition rate prior to testing.

#### **5.2.2.1 MVIC Exercises**

The five MVIC exercises to establish each subject's 100% MVIC level were the same as those outlined and utilised in Chapter 3 and shown in Table 3.1. These were performed in a random order for each subject with two minutes rest between each repetition. Each exercise was performed twice for 5 seconds.

#### **5.2.2.2 Core Exercises**

A focus group that consisted of a qualified biomechanist, strength and conditioning coach, swim coach and swimmer reviewed the repeatability (Chapter 3) and muscle activation (Chapter 4) findings in the current thesis and selected seven core exercises that were; i) sufficiently repeatable, ii) recruited the core musculature to sufficient levels, and iii) were specific to the swimming stroke movement. The forward and side bridge exercises both

reported CV values of below 23% (see Table 3.7) and activation levels of over 39% MVIC (see Table 4.3.). The birddog exercise represents a swimming specific asymmetrical movement which was also observed to be repeatable (CV < 23%) and recruit the musculature sufficiently (% MVIC > 31%). The straight leg raise and medicine ball pull-down exercises were included as they are highly swimming specific movements (with them being asymmetrical and rotational movements respectively) and recruited the core musculature to a high level (e.g. straight leg raises 50 - 58% MVIC). The overhead squat and medicine ball sit-twist exercises were also agreed to be included based on their functional movements, repeatability (CV < 24%; Table 3.7) and muscle activation levels (38 - 54%; Table 4.3). Descriptions of the core exercises are shown in Table 4.1.

Both groups continued their normal swimming training in the swimming pool during the six weeks but the core group also performed the core exercises three times a week for 30 - 40 minutes with varying amount of repetitions and sets as the training programme progressed through the six weeks (exercise progression details, see Table 5.1). The focus group established these training levels based on their individual knowledge of the area, previously published successful intervention programmes (see Table 1.4) and physiological muscular adaptation theories that are well reported in the literature. Week 1 and 2 included 60 seconds rest between each set. This rest period was reduced to 30 seconds for the remaining weeks to increase the density of the training sessions, as was agreed by the focus group.

Exercise	Progression	Week 1 - 2		Week 3 - 4		Week 5 - 6	
		Repetitions	Sets	Repetitions	Sets	Repetitions	Sets
Forward bridge	Volume	30sec hold	2	60sec hold	2	90sec hold	2
Side bridge	Volume	30sec hold	2	60 sec hold	2	90sec hold	2
Birddog	Volume	10	3	15	3	20	3
Leg raises	Volume	10	3	15	3	20	3
Medicine ball pull-down	Load	10 left / 10 right	4	10 left / 10 right	4	15 left / 15 right	4
Overhead squat	Load	10 (3kg)	3	10 (5kg)	3	15 (7kg)	3
Sit-twist	Load	15 (3kg)	3	15 (5kg)	3	15 (7kg)	3

### 5.2.2.3 Performance Tests

Performance test measures (Table 5.2) were recorded pre- (0 weeks) and post-training (6 weeks) for both groups to give an indication of core stability, strength and endurance. Each vertical jump was performed twice with the remaining four performance tests being completed once but at a maximal level.

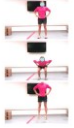






Table 5.2. Performance tests measured pre- (0 weeks) and post-training (6 weeks) for the six week intervention programme.			
Test Performed	Test Description	Process Targeted	Diagram
Countermovement Vertical Jump	Hands placed on hips. Downward movement then upward maximal two footed jump	Upper & lower body strength	
Squat Vertical Jump	Hands placed on hips. Flex knees and hips and hold 'squat' position for 2 seconds then maximal two footed jump		
Shoulder Flexion Strength	Using stacked weight machine, subject stands facing towards machine, with straight elbow down by waist, raise arm to head height, repeat action increasing weight until failure.	Upper body strength	
Shoulder Extension Strength	Same as above but start with straight elbow held above head height in front of body and pull down to vertical position		
Maximum Forward Bridge Hold	Static forward bridge position (forearms and toes in contact with floor). Neutral spine position. Held till quality of technique failed	Static stability / endurance	
Sit-up Bleep Test	Performed to pre-recorded incremental level bleep test on CD. Arms folded across chest and knees bent to 45 degrees. With each bleep subjects complete sit-up movement in either up or down motion and repeated this until fatigue and failure to keep up with the quickening bleeps	Dynamic stability / endurance	

Table 5.2. Performance tests measured pre- (0 weeks) and post-training (6 weeks) for the six week intervention programme.

Test Performed	Test Description	Process Targeted	Diagram
50m Swimming Time	Dive start, 50 m pool, racing each other in groups of 4. Timed with stopwatches	Sporting performance	

### 5.2.3 Data Collection

Surface EMG data was collected from three male subjects ( $16.4 \pm 2.1$  years,  $68.8 \pm 4.8$  kg,  $163.1 \pm 4.2$  cm) from the core training group during the second training session in week 1 (allowing for learning effects in the first session) and again during the second session of week six using a Delsys Wireless Myomonitor III device (sampling rate 1000 Hz) and surface EMG (sEMG) electrodes (details see Chapter 3 section 3.2.3) on six core muscles (see Table 3.3 for electrode placements) to establish any change in muscular activity during the core exercises. These muscles were chosen as they have been found to be heavily involved in the stabilisation and generation of strength from the core musculature [1, 31, 81, 280]. This is also supported by the research outlined in this thesis in Chapters 3 and 4 which highlight that these muscles can produce repeatable sEMG data and are recruited to a sufficient level which is believed to be required to result in core stability or core strength enhancements [100]. Detailed notes and pictures were taken of the electrode placement in week one to reduce the potential variation of electrode placement and subsequent cross talk that may otherwise have taken place when the procedure was repeated in week six.

### 5.2.4 Data Processing

#### 5.2.4.1 MVIC Exercises

The muscle activity in week one and week six during each exercise for each muscle was normalised to 100% MVIC. For both sets of sEMG data (week one and week six) raw sEMG signals for the MVIC and core exercises were processed in the same manner as that stated in Chapter 3 (section 3.2.4). The method for establishing the onset and offset points for each exercise was as stated in Chapter 3 (section 3.2.4). The sEMG data was log-transformed as



stated in Chapter 3 (section 3.2.4). Calculating the Peak EMG and ARV EMG muscle activation levels during the MVIC exercises was also as stated in Chapter 3 (section 3.2.4).

#### **5.2.4.2 Core Exercises**

The sEMG data recorded from the three subjects of the core training group performing the core training exercises were normalised to MVIC muscle activation (see Chapter 3, section 3.2.2). The peak and integrated (ARV) muscular contraction value for each muscle during each exercise were used to obtain a %MVIC activation for peak EMG and ARV EMG during the core training exercises pre- and post-intervention.

#### **5.2.4.3 Performance Tests**

Mean vertical jump height during the squat and countermovement jumps was obtained for each subject based on their two jumps. A group mean was calculated for the performance tests for both the control and core training group for the pre- and post-intervention data collection periods.

#### **5.2.5 Statistical Analysis**

Changes in the performance measures pre-post intervention were analysed using an ANCOVA statistical test. Inspection of the model residuals revealed that the assumptions for the test were met, with symmetrical distribution and constant error variance. An ANCOVA test was used as this removes the baseline of the pre-training scores, allowing for any difference between the initial scores of the two groups (e.g. the 50 m swimming time difference) at the start of the intervention and only takes into account the change in scores during the intervention period.

Effect size (Cohen's *d*) [226] was calculated for the two groups using the groups mean and standard deviations for each performance test using the equation shown below:

$$\text{Effect Size} = \frac{[\text{Mean score experimental group} - \text{Mean score control group}]}{\text{Standard Deviation}} \quad [216]$$

CV and 95% confidence intervals were established for each performance test pre- and post-intervention. A paired samples t-test was performed to establish any significant changes in the peak EMG and ARV EMG levels of activation pre- and post-intervention period for each of the core exercises performed. Statistical significance was set at the  $P < 0.05$  level.

### 5.3 Results

The core training group improved in jump height (leg power), core endurance and 50 m swimming performance to a greater extent than the control group (Table 5.3). However these improvements in the core training group were found to be non-significant improvements except for the improvement in countermovement vertical jump height ( $P < 0.05$ ) (Table 5.4).

Table 5.3. Mean and standard deviations during the performance tests pre- (0 weeks) and post-training (6 weeks) over the six week programme. Also shown are the % performance change and Cohen  $d$  effect size values.

Performance Test	Training Group	Difference % (pre-post)	Pre		Post		Effect Size
			M	SD	M	SD	
Countermovement Vertical Jump (cm)	Core	+9.86	24.7	4.5	27.1	4.9	1.3
	Control	+1.45	27.1	5.91	27.5	5.81	
Squat Vertical Jump (cm)	Core	+6.55	25.7	5.23	27.5	4.50	1.3
	Control	+2.80	27.8	5.41	28.6	5.59	
Shoulder Flexion Strength (kg)	Core	-1.12	9.0	2.05	8.9	2.03	0.3
	Control	+5.88	6.4	3.25	6.8	2.65	
Shoulder Extension Strength (kg)	Core	-2.5	4.1	1.73	4.0	1.63	0.8
	Control	+5	3.8	1.50	4.0	1.40	
Maximum Forward Bridge Hold (seconds)	Core	+11.80	222.1	99.4	248.3	92.2	0.5
	Control	+0.60	168.4	76.40	167.4	72.83	
Sit-up Bleep Test (seconds)	Core	+5.75	394.8	77.4	417.5	89.01	0.7
	Control	+0.66	360.3	145.63	362.7	151.59	
50m Swimming Time (seconds)	Core	-1.37	29.7	1.54	29.3	1.44	0.8
	Control	0	28.9	1.48	28.9	1.47	

The effect size data during the performance tests (Table 5.3) shows that for the maximum endurance forward bridge hold and the shoulder flexion strength test there was a small relationship between the two groups ( $< 0.5$ ). For the other tests (such as the vertical jump height and 50 m swimming time) there was a large effect size between the groups ( $> 0.7$ ) reflecting a similarity in the values between the groups.

Performance Test	Mean Difference	P value	95% CI (lower ; upper)
Countermovement jump (cm)	1.95	0.02 <sup>a</sup>	0.29 ; 3.61
Squat jump (cm)	1.37	0.10	-0.28 ; 3.01
Shoulder flexion (kg)	0.23	0.72	-1.10 ; 1.57
Shoulder extension (kg)	-0.28	0.72	-1.09 ; 0.53
Maximum forward bridge hold (s)	40.19s	0.08	-5.71 ; 86.08
Sit-up bleep test (s)	19.19s	0.13	-6.27 ; 44.67
50 m Swimming time trial (s)	-0.17s	0.29	-0.49 ; 0.15
<sup>a</sup> Significant to $p < 0.05$ level.			

Peak EMG muscle activity was significantly decreased following core training in one or more exercises (medicine ball sit-twist, overhead squat, forward bridge and birddog) for four muscles (EO, GM, MF and RF) ( $P < 0.05$ ) (Table 5.5), while peak EMG significantly increased in one muscle (RA,  $p < 0.05$ ) during the medicine ball sit-twist exercise and remained the same in the LD muscle (Table 5.6). ARV sEMG muscle activity (Table 5.5) was significantly decreased ( $P < 0.05$ ) in one or more exercises (medicine ball sit-twist and pull-down, leg raise, forward and side bridge) for three muscles (MF, GM and RF). ARV sEMG muscular activity was found to significantly increase for the EO muscle during the medicine ball pull-down exercise ( $P < 0.01$ ), while the RA and LD muscles reported no significant differences in ARV muscular activity during the exercises between week one and week six. The sEMG CV values within the EMG training group sample were observed to increase post-intervention for many of the muscles, especially within the ARV sEMG muscle activity.

Table 5.5. Paired samples t-test results for selected muscle activations found to be significantly different post-training (6 weeks) compared to pre-training (0 weeks) (peak and ARV sEMG muscular activity). Significant to  $P < 0.05$ .

Muscle	EMG	Exercise	Mean Difference	P Value	95% CI (lower;upper)
Rectus Abdominis	Peak	Medicine ball sit-twist	26.15	<0.01	25.55 ; 27.07
External Oblique	Peak	Overhead squat	-17.03	<0.05	-32.48 ; -1.58
		Forward bridge	-38.16	<0.01	-51.11 ; -25.21
	ARV	Medicine ball pull-down	57.33	0.001	50.81 ; 63.85
Multifidus	Peak	Birddog	15.92	<0.05	3.52 ; 28.32
		Medicine ball pull-down	-37.77	0.001	-42.58 ; -32.96
		Overhead squat	24.83	0.01	11.68 ; 37.98
	ARV	Overhead squat	-19.89	<0.05	-35.11 ; -4.67
Gluteus Maximus	Peak	Medicine ball pull-down	-11.86	0.01	-17.83 ; -5.89
	ARV	Forward bridge	-16.16	<0.05	-25.92 ; -6.39
		Side bridge	-9.99	<0.05	-15.52 ; -4.47
		Leg raise	-3.17	0.001	-3.65 ; -2.69
		Medicine ball pull-down	-15.29	<0.05	-28.72 ; -1.87
		Medicine ball sit-twist	-18.23	<0.05	-24.52 ; -6.06
Rectus Femoris	Peak	Forward bridge	-1.49	<0.01	-2.04 ; -0.94
	ARV	Side bridge	-2.98	<0.01	-3.20 ; -2.77
		Leg raise	-8.74	<0.05	-15.15 ; -2.33

Table 5.6. Mean sEMG muscle activation (%MVIC) from pre- (0 weeks) and post-training (6 weeks) of the six week training programme for each core exercise and muscle. CV data (peak and ARV sEMG) shown in brackets.

Exercise	EMG	RA		EO		MF		LD		GM		RF	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Forward bridge	Peak	32 (23)	17 (36)	23 (13)	61 (4)	38 (14)	40 (6)	39 (23)	26 (21)	28 (29)	24 (4)	9 (10)	11 (10)
	ARV	25 (15)	27 (23)	24 (9)	24 (21)	39 (9)	37 (33)	11 (7)	11 (21)	12 (34)	28 (8)	6 (6)	13 (32)
Side bridge	Peak	35 (23)	22 (37)	30 (16)	53 (17)	12 (27)	13 (68)	10 (26)	19 (34)	6 (92)	13 (42)	9 (10)	22 (20)
	ARV	40 (8)	38 (20)	55 (13)	59 (12)	10 (7)	18 (40)	39 (10)	50 (15)	14 (36)	24 (15)	15 (12)	18 (10)
Birddog	Peak	18 (20)	13 (61)	17 (22)	29 (18)	53 (6)	38 (5)	25 (13)	18 (29)	33 (17)	44 (16)	18 (17)	21 (16)
	ARV	25 (10)	22 (16)	24 (22)	16 (23)	39 (20)	35 (32)	20 (5)	17 (14)	37 (12)	29 (14)	17 (7)	21 (26)
Leg raises	Peak	33 (28)	35 (41)	36 (14)	34 (7)	46 (21)	30 (27)	25 (14)	21 (23)	9 (35)	17 (51)	52 (20)	60 (1)
	ARV	25 (13)	24 (28)	19 (15)	32 (10)	31 (13)	41 (20)	18 (18)	9 (40)	10 (30)	13 (21)	41 (1)	50 (5)
Medicine pull-down	Peak	31 (9)	28 (21)	72 (9)	70 (13)	7 (30)	45 (4)	17 (23)	13 (34)	11 (32)	23 (11)	27 (25)	29 (13)
	ARV	49 (4)	57 (8)	76 (3)	18 (14)	10 (7)	24 (24)	21 (16)	19 (23)	15 (17)	31 (19)	53 (5)	55 (13)
Overhead squat	Peak	27 (20)	24 (30)	15 (45)	32 (22)	79 (9)	54 (21)	18 (4)	18 (29)	23 (22)	28 (14)	66 (4)	66 (13)
	ARV	27 (1)	28 (30)	23 (11)	23 (32)	61 (10)	81 (8)	24 (14)	19 (8)	33 (4)	40 (25)	73 (7)	78 (8)
Medicine ball sit-twist	Peak	55 (6)	29 (11)	34 (14)	42 (22)	5 (19)	10 (25)	12 (44)	12 (24)	13 (27)	14 (45)	46 (10)	68 (16)
	ARV	29 (7)	32 (26)	50 (10)	50 (18)	9 (9)	15 (60)	13 (15)	15 (28)	10 (14)	25 (16)	67 (7)	81 (7)

RA-rectus abdominis, EO- external oblique, IO – internal oblique, MF- multifidus, LD- latissimus dorsi, GM- gluteus maximus, LG- longissimus, RF- rectus femoris

## 5.4 Discussion

The aim of this Chapter was to evaluate a swimming specific six week core training programme on core musculature activity and resultant performance measures in highly trained swimmers. The improvements in performances observed here (based on the percentage improvement and 95% confidence intervals) are in agreement with previous findings that have found leg power and swimming speed improvements [199] following a six week core training programme. Strass [119] observed an improved swimming speed over 50 m of 2.1% which is similar to the trend observed in the current study which found an improvement of 1.4%. The control group in the current study demonstrated no improvements in swimming speed following the six weeks of pool-based swimming training. These findings suggest that including core stability and strength training in swimming training programmes has potential benefit. However, like previous studies [117, 155] the improvements in the performance tests were found to be statistical non-significant, except for the improvement in countermovement jump height for the core training group;  $P < 0.05$ ).

Only the countermovement jump pre-post performance measure was found to be significantly different using the ANCOVA statistical test ( $P < 0.05$ ) (Table 5.4) and only a small number of exercises were found to result in significant changes in muscular activity during the six week training programme (Table 5.5). This could partly be due to the length of training programme intervention only being six weeks in duration. Previous studies have found improvements in performance following six week training programmes in swimmers but do not report whether these improvements were statistically significant or not [116, 199]. Therefore it may be that a longer training period is required for these improvements to become significantly improved (e.g. 10 – 12 weeks in duration).

The improvements in jump height (significantly so for the countermovement jump) in the current study (countermovement 9.8% and squat 6.5%) may be suggestive of greater leg power. These improvements are greater than those previously reported by Cressey et al. [151] who found improvements of countermovement jump height of 2.4% following ten weeks of

core training in soccer players. The larger improvement in the current study may be a result of the specificity of the exercises used during the intervention period. Cressey et al. [151] included exercises such as; deadlifts, single leg balance and lunges. These exercises may be less effective in improving jump height ability in footballers than the core training exercises performed in the current study for swimmers. If the exercise movements are the same as the movements required for the performance tests then any improvements in strength or power would be carried over more effectively. Therefore it can be concluded that the exercises used in the current study are specific enough for training adaptations to occur in swimmers. The greater increase in jump height may also be due to the initial lower than typical jump height scores observed pre-intervention, providing a greater room for improvement. The low values observed in the current study may be due to a number of factors; firstly, due to the subjects age range being relatively young (mean age; 16 years), their leg strength and subsequent jump height would be expected to be less than those observed with older subjects, secondly, testing was conducted early in the morning before swimming training, so the individual's muscles would not have been fully warm-up and subject motivation may have been a factor for some individuals. But it was felt that the performance tests needed to be performed before the swimming session as oppose to post-session as fatigue would have been a big hindrance to the performance of maximal tests following a two hour swimming training session.

The observed jump height scores for the core training group also highlight an interesting observation which contradicts that generally seen in previous literature [283]. It is common that countermovement jump height is larger than squat jump height (for example, CMJ, 48cm; SJ, 45cm [283]) due to the beneficial effects of the stretch-shortening cycle in the muscles [284]. However, this study observed higher values for both the core and control groups during the squat jump (e.g. core group; pre 25.7cm, post 27.5cm) rather than the countermovement jump (e.g. core group; pre 24.7cm, post 27.1cm). A possible explanation for these results could be that the squat jump position prior to the vertical jump is more specific to the swimmers starting position which they are highly trained in to produce large forces off the block when starting a swimming race. Being more familiar with this position and type of movement, the force production and subsequent jump height would be greater than during a movement with which the subjects are less familiar with (for example, the countermovement

jump) [71]. Furthermore, swimmers are not regularly trained to perform maximal vertical jumps unlike for example, basketball or volleyball players who are typically used for such research [283].

The lack of significant improvements in performance following the intervention training programme could be due to the magnitude of the change in performance test scores observed. Relatively small magnitudes of change in the performance measures were observed, for example, a 2 cm improvement in jump height over the six weeks. However it is not to say that these small changes are not important changes in strength, stability and performance. For example, a 2 cm increase in jump height (from 25.5 cm to 27.5 cm) is a large improvement in this skill over six weeks of training and represents a 10% improvement. Previous studies have also observed small changes in performance following 6 – 12 week training programmes, for example, Giroid et al. [118] observed a 2.8% (1.05 second) improvement in swimming performance, along with Strass [119] who recorded a 2.1% in 50 m swimming performance. Furthermore, a 0.4 second improvement in 50 m swimming time (1.4%), as seen in the current study, is unlikely to be shown as a statistically significant difference due to the small sample size [260] and large standard deviations of the test scores, however it does reflect a large % improvement in overall swimming performance brought about over a six week training period (1.4% improvement). This improvement could mean the difference in a race of finishing first or finishing much further down the field. For example, at the FINA swimming World Cup in 2010, the swimmers in the men's 50 m freestyle final were only separated by 0.85 of a second. If the winner had swum 0.4 of a second slower he would have been placed down the field in 5<sup>th</sup> place [285].

Hopkins et al. [260] suggest that due to the small sample sizes observed in such studies as the current one and the small changes in performances that are observed, establishing statistical significance is unlikely. This is supported by the study of Madsen et al. [258] who, like the current study, found a non-significant but improved sports performance (cycle time trial; improved 2.9 minutes, 1.8% improvement) following ingestion of glucose supplements. Hopkins et al. [223] propose that using the 95% CI values provides a more accurate representation of the training effect on likely improvements in sporting performance than



statistical significance. For example, in the current study, both maximum forward bridge hold and the sit-up bleep performance tests were found to result in non-significant improvements following the six week training programme, however if the 95% CI intervals are scrutinised, they show that it is likely that an individual would demonstrate an improved performance based on the upper and lower limits in these tests (maximum hold to exhaustion: -5.71 - 86.08 seconds; sit-up bleep test: -6.27 - 44.67 seconds). The high upper limit values for these tests suggest that it is more probably that performances would improve than be reduced. Therefore by reporting 95% CI intervals, further information on the effect of the intervention can be obtained and for studies where small differences and statistically small sample sizes are being used, relying on statistical significance tests may disregard important differences in the data.

The small improvements in some of the performance tests for the core training group are supported by the findings from the sEMG muscle activity data which showed altered muscle activity from week one to week six, for a selection of the analysed muscles (e.g. GM, RF and MF). The significantly decreased muscular activity of the GM and RF (global mobiliser muscles) implies that these two muscles were recruited to a lesser extent during the post-performance tests, which could be explained by the increase in muscular activity of the MF muscle (local stabiliser muscle) during these tests post-intervention. This suggests that the recruitment of the core musculature changed during the intervention programme to be more efficient with the stabiliser muscles becoming more involved, subsequently improving the core stability and strength of the area and potential ability to transfer forces through the body. This is reflected in the significantly improved countermovement jump height score observed for the core training group.

For some of the muscles a significant decrease in %MVIC was observed. For example, the MF peak EMG activity decreased during the medicine ball pull-down exercise and ARV EMG activity decreased during the overhead squat exercise ( $P < 0.05$ ). This could represent a positive enhancement to core stability. Decreasing the peak EMG value of a stabiliser muscle (such as the MF muscle) during an exercise implies that smaller correctional limb positioning movements are taking place, placing the muscle under less strain whilst still being able to carry out the same movement. The LD muscle activity was not different following the

training programme for either peak or ARV EMG muscle activity, implying that the exercises performed did not have a training effect on this muscle. This is supported by the finding that shoulder flexion and extension did not significantly improve for the core training group following the training programme. Further exercises that specifically target the shoulder could be added to the training programme if upper body core stability and strength needs to be improved. Exercises such as, free weight dumbbell shoulder press [3] or the seated row pull [286] could be used to target shoulder strength and stability.

The reduction in % MVIC muscle activations could be explained due to an increase in muscle activation during the MVIC exercises along with a reduction during the core exercises (observed for both Peak and ARV EMG). This would reduce the %MVIC value as the MVIC activation is used as the denominator in the normalisation equation. This increase in muscle activation suggests an increase in muscle strength during the maximal performance tests. The muscle activations during the core exercises were observed to decrease and can be explained by the positive training effect where less muscle activation is required to perform the same movement following a training programme. This theory is supported when the absolute sEMG data are analysed from the MVIC exercises pre and post-training intervention (see Appendix G). This training response is a result of the physiological training responses in the body following a resistance training programme (e.g. enhanced muscle fibre recruitment, synchronisation and distribution).

Between-subject variations were observed in the sEMG muscle activity post-training were greater than that observed pre-training (Table 5.6). This reflects the different training benefits that individuals experience from performing the same set of exercises. This may be as a result of different techniques being used by the subjects, with one of these being more effective for an individual than another. This highlights the importance of specificity of training programmes for individuals [99] and supports the belief that what works for one person does not necessarily work for another. The range of muscular activations observed for the subjects (represented by the CV values) performing the same movements supports the findings reported by Basmajian and De Luca [122] who observed significant variation in EMG activity between individuals performing the same movement. This may reflect a weakness in the

correct recruitment of the core muscles in some individuals which results in poor core stability for those individuals [287].

Based on the findings in the current study which imply a positive effect on performance following the core training programme and changes in the muscular recruitment of the core muscles during the core training exercises, it can be suggested that the extent and type of exercise progression during the six week training programme was sufficient. The length of recovery between exercises was reduced from 60 seconds to 30 seconds following the first week of training, as it was felt by the swimming coach that 60 seconds was too long for the necessary recovery between exercise repetitions. As a result this increased the density of the training sessions and demand on the core musculature which would increase the likelihood of training adaptations being observed. It is recommended that a similar exercise progression format be implemented in future swimming core training programmes.

## **5.5 Conclusions**

The swimming specific training programme resulted in significantly improved countermovement jump height scores and a non-significant trend for improvements in squat jump height, maximal forward bridge hold time, sit-up bleep test time, shoulder strength and a mean 1.4% improvement in 50 m swimming time. It is recommended for future research that a longer training duration could be investigated to establish whether these improvements continue and subsequently increase to significant improvements in performance. It was observed that the training exercises performed did result in changes in the recruitment and level of muscular activity for five of the six core muscles chosen for analysis. By measuring muscular activity changes as well as performances measures, greater knowledge of the strengths and weaknesses that a training programme has on training specific components and parts of the body can be established. It can be concluded that this core training programme may have the potential to significantly improve core strength, stability, endurance and possibly 50 m swimming time in highly trained swimmers when implemented over a longer time period. Future research should establish the training benefits from such a training programme over a longer period of training in highly trained swimmers (Chapter 6).

## **Chapter 6**

# **Long-term Evaluation of a Core Training Programme**

## **(Phase II: An Exploratory Trial)**

## 6.1 Introduction

Chapter 5 has shown that a number of performance improvements can be obtained from a six week core training programme specifically designed for swimmers. These findings support previous studies that have found positive sporting performance improvements following a period of specific core training lasting six weeks [18, 24, 26, 287]. However it was observed following the training programme outlined in Chapter 5 that the improvements in the performance tests (e.g. 50 m swimming time and shoulder strength) were not statistically significant. This may be due to a number of factors (as were discussed in Chapter 5), for example, the large variation (CV values) seen in the response to the training and the possibility that the six week training duration may not be of sufficient length for the core muscles to adapt to the training stimuli significantly [288, 289].

Changes in some of the performance test scores were found to be non-significant statistically, however 95% CI and effect size statistics demonstrated a potentially positive trend in the likelihood of a positive response to training. For example, vertical squat jump height reported 95% CI values of -0.28 to 3.61 cm, suggesting a greater likelihood of an improvement in performance as oppose to a negative effect. An improvement in 50 m swimming time was observed for the core training group by 0.4 seconds (1.4%). It is proposed that by lengthening the core intervention programme a further six weeks may enhance this further and so bring about a bigger (and a statistically significant) improvement in the performance tests. Previous studies have found favorable performance improvements (e.g. balance and jump height scores) over longer training periods involving footballers [151] and athletic females [151, 185]. For example, Cressey et al. [151] observed an improvement in sprint times and countermovement jump height performances following a ten week training programme involving deadlifts, squats and lunging exercises. Myer et al. [185] also observed improved vertical jump performance following a seven week training programme involving plyometric and balance exercises.

During the six week core training programme outlined in Chapter 5, it was concluded that the group's shoulder strength was not improved during the six weeks of training. This may be due to the lack of shoulder strength exercises included in the training programme. Shoulder

strength and stability is an important part of the swimming stroke [73, 80], with the shoulder muscles being used during 92% of the freestyle swimming stroke [7, 131]. Therefore in the core training programme it was decided to include specific shoulder exercises that target and activate the shoulder muscles to a higher level to result in a training adaptation (e.g. increased muscular strength).

sEMG was used on a small number of subjects in the six week training programme outlined in Chapter 5 to examine whether muscle recruitment or activation changes could be detected during the course of a core training programme. The six week programme in Chapter 5 highlighted that muscle activation changes did occur during this training duration with significant changes in the core musculature activations levels being observed for five of the core muscles (RA, EO, MF, GM and RF) during certain core exercises (medicine ball pull-down and sit-twist, forward and side bridge, birddog and leg raise;  $P < 0.05$ ). It is proposed that these, along with other core muscular recruitment changes, would be heightened over a longer training duration. Furthermore, an in-depth analysis on a larger sample of subjects is required to establish whether changes in muscle recruitment can be linked to the changes in performance test scores. Previous studies have identified that following a training programme, a decrease in EMG activity during the same exercise or test represents a positive training effect [290]. This decrease in activity is said to be due to an improved and more efficient motor unit recruitment and synchronisation in the muscles [288, 289]. Equally, an increased muscular activity of the core stabiliser muscles (e.g. multifidus muscle) for example may reflect a positive enhancement in the correct and more efficient recruitment of the core musculature which could then aid performance. However it has been emphasised that sEMG data is not able to provide any reflection on changes in muscle strength or force output [120]. It can only provide an indication of muscle fibre recruitment level within the muscle. Despite this, it remains a popular and successful method of providing a gross measure of the amount of muscle activity changes that may occur as the result of a given stimulus [288, 290].

**Aim of Chapter**

To modify the training protocols implemented in the short-term core training programme (as stated in Chapter 5) and evaluate performance outcomes in highly trained swimmers over a longer-term period.

**6.2 Methods****6.2.1 Subjects**

Ten swimmers (five men,  $16.2 \pm 1.3$  years,  $174.3 \pm 5.6$  cm,  $63.4 \pm 6.4$  kg; five women,  $17.4 \pm 1.5$  years,  $173.2 \pm 4.4$  cm,  $63.8 \pm 4.6$  kg) formed the core training group, with a further ten swimmers (five men,  $17.6 \pm 1.5$  years,  $171.8 \pm 4.2$  cm,  $64.1 \pm 5.5$  kg; five women,  $16.4 \pm 1.8$  years,  $172.6 \pm 3.4$  cm,  $65.9 \pm 4.3$  kg) making up the control group. This sample size was (as stated in Chapter 5) chosen due to the complex and time-consuming nature of the sEMG data processing methods and requirement for subjects who were committed to completing the full 12 week intervention programme. Careful subject selection also ensured no subject dropout during the training programme. The core training group continued with their regular swimming sessions in the swimming pool during the twelve week training programme but also completed the three core training sessions a week. The control group continued their normal swimming training programme in the swimming pool but performed no core training sessions during the twelve week period. Both groups were made up of highly experienced and trained swimmers. As was highlighted in the previous intervention study (Chapter 5), these groups were not totally randomised for this study. A ‘controlled before and after’ experimental design was established for the study. This was achieved by establishing that the two groups both trained in the pool for the same number of times per week, covered a similar weekly mileage in the swimming pool and had a similar make up of sprint, middle distance and endurance swimmers within them.

**6.2.2 Exercise Details**

One week prior to data collection, each subject was provided with a written explanation for each exercise, shown a demonstration of each exercise and subsequently practiced each MVIC

exercise (Table 3.1) and core exercise (Table 3.2) at the required repetition rate prior to testing.

#### **6.2.2.1 MVIC Exercises**

Five MVIC exercises (Table 3.1) were performed targeting each core muscle analysed (Table 3.3). These MVIC exercises were the same as used in the previous chapters of this thesis, as these have been found to provide repeatable estimates of the individual's MVIC of the core muscles (see Chapter 3).

#### **6.2.2.2 Core Exercises**

Based on the findings from the six week intervention training programme outlined in Chapter 5, minor changes were made to the proposed training programme (see Table 6.1 for training programme layout and progression) following a focus group discussion which involved the same members as outlined in Chapter 5 (section 5.2.2.2). To target the shoulders of the swimmers, a new exercise was included; the horizontal shoulder press. This involved the swimmer lying horizontal on the floor with both arms extended above their head positioned flat on the floor. Using a weighted free dumbbell in each hand, the swimmer raised their arm upwards extending the shoulder and returned the dumbbell back to the floor and then repeated this movement with the other arm. This exercise replaced the medicine ball pull-down exercise which was included in the previous training programme as it was felt by the focus group that the horizontal shoulder press exercise was more similar to the movements performed when swimming and so increasing the likelihood of resulting in transferable changes in the recruitment and adaptations of the shoulder muscles. The training programme was also extended to 12 weeks. This allowed for a greater progression of the exercises (either in volume of repetitions or external load) increasing the opportunity for training adaptations to occur within the core musculature. These progressions along with the set, repetition and recovery rates were discussed and agreed using the same focus group as outlined in Chapter 5 (section 5.2.2.2). The remaining six exercises remained the same as those stated and implemented in Chapter 5 (section 5.2.2.2).



The exercise progression of the core exercises used a similar format to the six week programme outlined in Chapter 5 (Table 5.1, section 5.2.2.2) for the initial six weeks of the programme. The same focus group as used to develop the six week training programme felt that this provided a suitable introductory level to training the core musculature. For week six to twelve the exercises increasing in volume or load at the same rate as in weeks one to six, with a progression every two weeks. For example, the forward bridge exercise increased in hold time by 30 seconds and the birddog and leg raise exercises increased by five repetitions (see Table 6.1).

Exercise	Progression	Week 1-2		Week 3-4		Week 5-6	
		Repetitions	Sets	Repetitions	Sets	Repetitions	Sets
Forward bridge	Volume	30 sec hold	2	60 sec hold	2	90 sec hold	2
Side bridge	Volume	30 sec hold	2	60 sec hold	2	90 sec hold	2
Birddog	Volume	10	3	15	3	20	3
Leg raise	Volume	10	3	15	3	20	3
Shoulder press	Volume	10	3	10	4	15	4
Overhead squat	Load	10 (3kg)	3	10 (4kg)	3	15 (5kg)	3
Sit twist	Load	15 (3kg)	3	15 (4kg)	3	15 (5kg)	3
Exercise	Progression	Week 7-8		Week 9-10		Week 11-12	
		Repetitions	Sets	Repetitions	Sets	Repetitions	Sets
Forward bridge	Volume	90 sec hold	3	120 sec hold	2	120 sec hold	3
Side bridge	Volume	90 sec hold	3	120 sec hold	2	120 sec hold	3
Birddog	Volume	25	3	25	4	30	3
Leg raise	Volume	25	3	25	4	30	3
Shoulder press	Volume	20	3	20	4	25	3
Overhead squat	Load	20 (6kg)	3	20 (7kg)	4	25 (7kg)	3
Sit twist	Load	20 (6kg)	3	20 (7kg)	4	25 (7kg)	3

### 6.2.2.3 Performance Tests

The core training and control group performed the five performance tests which were described in Chapter 5 (Table 5.2, section 5.2.2.3). sEMG activity was collected from each subject during the performance tests. For both groups the muscles analysed were the same as those outlined in Chapter 3 (Table 3.3, section 3.2.3). Data collection involved the collection of sEMG activity from one muscle (two muscles for the vertical jump tests) during each of the

tests (this was used as an example of the activation level of one of the main muscles involved in the movement of each performance tests; see Table 5.2 for details of which muscle EMG data was collected during each test). Both groups repeated the five performance tests under identical conditions (e.g. same pieces of gym equipment and time of day) after six weeks and following twelve weeks of training.

### **6.2.3 Data Collection**

sEMG data was collected on both the core training and control groups pre- (0 weeks), mid- (6 weeks) and post- (12 weeks) training periods during the five performance tests and MVIC exercises. The data collection protocol was as outlined in Chapter 5 (section 5.2.3). sEMG data (peak and ARV EMG) for the six core muscles was also collected on the core training group from a core training session during the sixth and twelfth week of the training programme (where they performed the same training exercises with identical external resistance as in the pre-training exercises, see week 1 of the core exercise progression plan, Table 6.1).

### **6.2.4 Data Processing**

#### **6.2.4.1 MVIC Exercises**

sEMG data during the MVIC exercises from the pre-, mid- and post-training periods were used to normalise the sEMG data collected during the performance tests and core exercises using the same data processing method as stated in Chapter 3 (section 3.2.4). Onset and offset values were also calculated using the method and equation as stated in Chapter 3 (section 3.2.4).

#### **6.2.4.2 Core Exercises**

Peak EMG and ARV EMG %MVIC activation during the seven core exercises were calculated using the MVIC data of the core training group (data processing was as stated in Chapter 3, section 3.2.4) for the six core muscles. This was performed on the sEMG data collected pre-, mid- and post-intervention periods.

### 6.2.4.3 Performance Tests

Mean vertical jump height during the squat and countermovement jumps were obtained for each subject based on their two jumps. A group mean was calculated for the performance tests for both the control and core training group for the pre-, mid- and post-data collection periods.

### 6.2.5 Statistical Analysis

An ANCOVA statistical test was used to identify significant differences between the core and the control training groups at the pre-, mid- and post-intervention points for the performance test scores and the sEMG data obtained during these tests. Inspection of the model residuals revealed that the assumptions for the test were met, with symmetrical distribution and constant error variance. An ANCOVA test was used as this removes the baseline of the pre-intervention scores, allowing for any difference between the two groups initial scores at the start of the intervention and only takes into account the change in scores during the intervention period. This was necessary as the experimental design of the current study was not a completely randomised experimental design but a ‘controlled before and after’ experimental design as was used and explained in Chapter 5. Effect size (Cohen’s *d*) [226] was calculated between the two training groups (core and control) using the groups mean and standard deviations from each performance test to establish the effect size pre-mid, mid-post and pre-post intervention periods (see equation Chapter 5, section 5.2.5).

The 95% confidence intervals were established for each performance test and corresponding sEMG data. Paired samples t-tests were performed to establish significant changes in the Peak EMG and ARV EMG levels of activation post-pre and mid-pre intervention period for each of the core exercises performed, for the six core muscles. Statistical significance was set at the  $P < 0.05$  level. The likelihood of a true beneficial effect was calculated using Hopkins et al.’s method [223] based on the 95% confidence intervals and identification of the smallest worthwhile change (typical error of the mean) for each performance test calculated (using the control group mean and standard deviation for each test). This was to identify whether using a magnitude based inference method resulted in clearer conclusions regarding the quantification

of the likelihood of a beneficial effect of the training programme on performance compared to the statistical significance approach that is usually adopted. Hopkins et al. [273] suggest that by establishing these levels it is possible to qualify them with probabilities that reflect the uncertainty in the true value by using the following scale; <0.5% most unlikely, 0.5 - 5% very likely, 5 - 25% unlikely probably not, 25 - 75% possibly, 75 - 95% likely probably, 95 - 99.5% very likely, 99.5> most likely almost certainly [273, 291].

The calculation of the typical error of the mean and the smallest worthwhile change can also be used to establish the signal to error ratio of the measurements. The signal is a reflection of the change in performance test score pre-post training for the core training group, while the error refers to the typical error or variation of the mean observed for the control group for each performance test [223].

### 6.3 Results

Table 6.2 represents the signal to error relationship between the typical error of the measurement and the smallest worthwhile change observed during the performance tests. It can be observed that the signal was greater than the error measured during each of the performance tests.

Table 6.2. Typical variation of the mean (%) (control group) and performance test change (%) (pre-post) during the performance tests (core group).						
Measure	Counter-movement Jump	Squat Vertical Jump	Shoulder Strength	Maximum Forward Bridge	Abdominal Sit-up Bleep Test	50 m Swimming Time
Change in Performance Score (%)	7.6	7.7	17.7	10.7	11.1	-2.4
Typical Variation of Mean (%)	1.1	1.6	6	7.2	6.9	-0.6
NB. Negative value for swimming time reflects a faster swimming time						

The core training group resulted in the larger mean improvements during all six performance tests compared with the control training group (see % difference pre-post) over the 12 week training programme (Table 6.3). The core training group showed at least a 7.6% improvement in performance test scores for the land-based performance tests and a 2.4% improvement in performance for the 50 m swimming time trial.

Table 6.3. Performance test values pre- (0 weeks), mid- (6 weeks) and post- (12 weeks) training programme for core and control group (means $\pm$ standard deviations). Performance change (%) between pre- (0 weeks) and post-training (12 weeks) are shown. Effect sizes are shown for pre-, mid- and post-training.								
Performance Test	Training Group	% Difference (pre-post)	Pre	ES Pre-mid	Mid	ES Mid-post	Post	ES Post
Countermovement Vertical Jump (cm)	Core	+7.6	23.4 $\pm$ 2.07	0.8	24.2 $\pm$ 2.05	1.2	24.5 $\pm$ 2	1.3
	Control	+2.2	23.6 $\pm$ 1.1		23.8 $\pm$ 1.1		23.9 $\pm$ 1.2	
Squat Vertical Jump (cm)	Core	+7.7	23.2 $\pm$ 2.18	1.6	24.1 $\pm$ 1.81	0.7	24.3 $\pm$ 1.88	1.1
	Control	+3.1	22.6 $\pm$ 1.4		22.8 $\pm$ 1.5		23 $\pm$ 1.4	
Shoulder Flexion Strength (kg)	Core	+17.7	8.4 $\pm$ 2.51	1	9.8 $\pm$ 2.25	0.5	10.2 $\pm$ 1.98	1.4
	Control	+3.5	8.4 $\pm$ 2.4		8.6 $\pm$ 2.3		8.7 $\pm$ 2.2	
Maximum Forward Bridge Hold (second)	Core	+10.7	223.1 $\pm$ 77.27	0.6	235.7 $\pm$ 76.92	1.4	249.8 $\pm$ 75.07	0.5
	Control	+2.1	221.1 $\pm$ 92.5		224.3 $\pm$ 82.7		225.8 $\pm$ 81.3	
Sit-up Bleep Test (second)	Core	+11.1	218.3 $\pm$ 54.14	0.1	228.5 $\pm$ 53.89	0.6	245.5 $\pm$ 47.86	0.3
	Control	+8.3	221.3 $\pm$ 71.3		231.6 $\pm$ 63.3		241.2 $\pm$ 58.2	
50m Swimming Time (second)	Core	-2.4	29.5 $\pm$ 1.96	0.6	29 $\pm$ 1.67	0.7	28.8 $\pm$ 1.61	0.8
	Control	-0.7	28 $\pm$ 1.9		27.9 $\pm$ 1.9		27.8 $\pm$ 1.9	
The minus 50 m swimming time % difference represents a quicker 50 m swimming time. ES – Effect Size								

Four of the six performance tests resulted in a significant improvement in performance for the core training group following the 12 week core training intervention programme ( $P < 0.05$ ) (Table 6.4). Three of the six performance tests resulted in a significant improvement in performance after six week of training, with these improvements then increasing further in the additional six weeks of training. The maximum bridge hold test was found to result in a significant improvement in performance following six weeks of core training only.

Table 6.4. ANCOVA findings for the performance test values comparing post-pre and mid-pre training intervention.

Performance test	Post-Pre					Mid-Pre				
	Mean Difference	95% CI Lower	95% CI Upper	P value	% Change	Mean Difference	95% CI Lower	95% CI Upper	P value	% Change
Countermovement Jump (cm)	0.78	0.35	1.215	0.001	5.77	0.61	0.09	1.13	0.024	4.5
Squat Jump (cm)	0.69	0.13	1.25	0.018	5.34	0.77	0.28	1.26	0.004	5.96
Shoulder Flexion (kg)	1.5	0.73	2.25	0.001	17.86	1.17	0.3	2.0	0.01	13.93
Maximum Bridge Hold (s)	22.2	8.1	36.4	0.004	9.99	9.55	-7.6	26.7	0.26	4.3 <sup>b</sup>
Sit-up Bleep Test (s)	6.75	-8.5	21.99	0.366	3.07 <sup>b</sup>	-0.45	-19.99	19.1	0.96	-0.2 <sup>b</sup>
50m Swimming time (s)	-0.3 <sup>a</sup>	-0.95	0.347	0.341	-1.04 <sup>b</sup>	-0.18 <sup>a</sup>	-0.83	0.471	0.57	-0.62 <sup>b</sup>

<sup>a</sup> - value indicates improved swimming time, <sup>b</sup> - not significant to p < 0.05 level.

The muscular activation observed during the performance tests show that they result in a range of levels during the movements (Table 6.5), with some resulting in low levels of activity (e.g. countermovement jump for the GM muscle, % MVIC <25%) and others high levels of activity (e.g. countermovement jump for the RF muscle, % MVIC >60%).

Table 6.5. % MVIC muscular activation (peak and ARV EMG) during the performance tests. Comparison of the core training and control groups pre- (0 weeks), mid- (6 weeks) and post-training (12 weeks) for the six muscles.

Training Group	EMG	Pre								Mid								Post															
		SB		CMJ		SJ		SF		BH		SB		CMJ		SJ		SF		BH		SB		CMJ		SJ		SF		BH			
		RA	EO	GM	RF	GM	RF	LD	MF	RA	EO	GM	RF	GM	RF	LD	MF	RA	EO	GM	RF	GM	RF	LD	MF	RA	EO	GM	RF	GM	RF	LD	MF
Core	Peak	55	33	14	86	70	64	83	90	60	30	16	80	57	54	80	86	62	32	16	81	63	59	79	84								
	ARV	55	38	20	87	66	60	84	86	58	41	24	90	67	58	82	84	59	41	22	90	65	56	82	83								
Control	Peak	24	22	18	65	57	51	44	45	20	21	18	60	56	51	37	37	20	22	20	57	53	51	36	39								
	ARV	25	24	17	72	55	38	36	30	25	26	19	73	55	40	33	28	25	25	19	73	56	43	34	29								

RA ,EO– sit-up bleep test, MF– maximum bridge hold , LD- shoulder flexion , GM, RF– countermovement and squat vertical jump. SB– Sit-up bleep, CMJ– countermovement jump, SJ– squat jump, SF–shoulder flexion, BH–Maximum bridge hold

The majority of the muscles during the performance tests resulted in a decrease in muscular activity for the core training group compared to the control group (Tables 6.5 and 6.6). Comparing the mid-pre and post-pre values it can be observed that generally the decrease in muscle activity observed was greater after the 12 weeks compared to after 6 weeks of core training. Seven sEMG measures (six ARV EMG, one peak EMG) during the performance tests were found to be not significantly different after six weeks of training. After 12 weeks of training, six sEMG measures (four ARV EMG, two peak EMG) remained non-significant.

Table 6.6. ANCOVA results for the sEMG values (peak and ARV EMG) for the core muscles during the performance test where they are a dominant muscle. A comparison of the core training and control groups post-pre and mid-pre training.

Exercise	Muscle	EMG variable	Post-pre					Mid-pre				
			Mean Difference	95% CI - Lower	95% CI - Upper	P value	% Change	Mean Difference	95% CI - Lower	95% CI - Upper	P value	% Change
Countermovement Jump (cm)	Gluteus Maximus	Peak	-2.99	-6.26	0.27	0.07	-4.3	-11.95	-15.48	-8.43	<0.01	-17.35
		ARV	-4.27	-7.55	-0.98	0.014	-8.0	-1.83	-3.85	0.20	0.07 <sup>a</sup>	-3.4
	Rectus Femoris	Peak	0.68	-2.66	4.01	0.68 <sup>a</sup>	0.8	-0.12	-2.59	2.34	0.92 <sup>a</sup>	-0.1
		ARV	-2.03	-4.40	0.34	0.089 <sup>a</sup>	-5.2	-0.62	-3.2	1.97	0.62 <sup>a</sup>	-1.6
Squat Jump (cm)	Gluteus Maximus	Peak	-4.49	-8.19	-0.79	0.02	-7.6	-7.71	-11.08	-4.33	<0.01	-13
		ARV	-2.99	-5.98	0.002	0.05	-7.1	-0.91	-3.22	1.41	0.42 <sup>a</sup>	-2.2
	Rectus Femoris	Peak	-3.83	-6.75	-0.91	0.01	-4.5	-3.54	-6.49	-0.59	0.02	-4.2
		ARV	2.43	-0.73	5.59	0.12 <sup>a</sup>	6.4	3.06	-1.10	7.23	0.14 <sup>a</sup>	8.1
Shoulder Flexion (kg)	Latissimus Dorsi	Peak	-5.03	-9.72	-0.33	0.04	-5.9	-6.63	-10.19	-3.06	<0.01	-7.8
		ARV	-11.18	-15.12	-7.24	<0.01	-16.5	-6.70	-10.89	-2.51	0.004	-9.9
Maximum Bridge Hold (s)	Multifidus	Peak	-2.85	-5.01	-0.70	0.01	-16.7	-3.47	-6.26	-0.68	0.02	-20.3
		ARV	0.311	-1.56	2.18	0.729 <sup>a</sup>	1.7	-1.21	-2.64	0.22	0.09 <sup>a</sup>	-6.9
Sit-up Bleep Test (s)	External Oblique	Peak	-2.60	-5.1	-0.09	0.04	-7.1	-5.45	-7.61	-3.29	<0.01	-14.9
		ARV	-4.28	-1.88	-0.79	0.40 <sup>a</sup>	-2.3	-2.25	-3.24	-1.26	<0.01	-15.2
	Rectus Femoris	Peak	2.52	-2.99	8.03	0.35 <sup>a</sup>	4.5	1.35	-4.94	7.65	0.66 <sup>a</sup>	2.4
		ARV	0.55	-5.56	-3.00	<0.01	-17.6	-3.69	-4.75	-2.63	<0.01	-9.5

Negative value indicates a decreased level of sEMG muscle activity. <sup>a</sup> – not significant at p < 0.05 level. S – Significance

Table 6.7. Percentage of MVIC muscle activation for the core muscles during the core exercises. A comparison of pre-, mid- and post-training programme (coefficient of variation shown in brackets).

Exercise	EMG	Rectus Abdominis			External Oblique			Multifidus			Latissimus Dorsi			Gluteus Maximus			Rectus Femoris		
		pre	mid	post	pre	mid	post	pre	mid	post	pre	mid	post	pre	mid	post	pre	mid	post
Forward bridge	Peak	64(3)	58(2)	57(3)	24(12)	22(11)	22(10)	44(10)	39(12)	39(9)	61(2)	55(3)	56(3)	20(7)	19(8)	18(7)	25(12)	23(12)	22(9)
	ARV	74(4)	68(4)	67(3)	40(3)	38(3)	38(3)	75(2)	81(7)	78(4)	39(1)	37(1)	35(3)	12(6)	12(6)	11(8)	74(4)	73(11)	69(11)
Side bridge	Peak	37(7)	34(6)	36(8)	30(5)	27(5)	27(3)	47(4)	40(3)	39(4)	63(1)	57(1)	58(3)	26(13)	23(14)	22(12)	22(12)	20(11)	19(8)
	ARV	68(2)	62(2)	62(2)	63(1)	61(1)	58(1)	52(5)	51(4)	48(5)	52(6)	48(7)	45(7)	30(6)	29(6)	27(7)	25(6)	22(6)	19(2)
Birddog	Peak	36(11)	34(8)	32(6)	30(11)	29(9)	28(12)	82(6)	70(7)	67(6)	51(3)	47(4)	47(4)	31(14)	29(12)	27(14)	54(7)	51(7)	49(7)
	ARV	18(3)	16(4)	16(4)	36(3)	34(3)	32(4)	43(3)	41(3)	42(3)	31(6)	28(7)	26(5)	45(7)	43(5)	41(6)	18(8)	17(5)	15(6)
Leg raises	Peak	71(2)	69(1)	65(2)	42(5)	40(11)	39(4)	36(7)	30(4)	29(6)	24(11)	23(12)	23(10)	53(2)	51(2)	48(2)	52(6)	50(4)	48(4)
	ARV	61(1)	57(1)	56(1)	78(7)	76(6)	74(6)	38(5)	38(3)	38(4)	39(6)	36(5)	33(6)	55(7)	55(6)	53(6)	35(5)	32(5)	30(7)
Shoulder raises	Peak	29(5)	27(8)	27(7)	44(5)	42(5)	39(5)	90(3)	79(3)	74(2)	61(4)	56(3)	59(4)	36(6)	35(5)	33(4)	36(5)	32(4)	31(6)
	ARV	14(4)	12(4)	12(3)	47(4)	45(4)	42(5)	65(3)	62(3)	60(3)	63(3)	58(4)	55(4)	43(3)	42(4)	40(4)	16(11)	15(10)	14(10)
Overhead Squat	Peak	26(15)	26(17)	26(14)	50(8)	48(9)	46(9)	89(3)	77(3)	74(4)	31(6)	29(6)	30(6)	46(10)	44(10)	41(9)	36(12)	34(10)	33(7)
	ARV	24(7)	22(6)	22(6)	34(2)	33(3)	31(1)	72(5)	69(5)	69(4)	55(3)	51(3)	48(3)	43(5)	40(6)	37(7)	37(2)	34(3)	32(4)
Sit-twist	Peak	91(4)	91(3)	89(3)	40(5)	39(6)	37(6)	84(5)	75(4)	74(4)	28(8)	27(6)	27(6)	46(8)	43(8)	40(7)	46(6)	43(6)	43(5)
	ARV	58(4)	54(5)	53(6)	45(6)	43(6)	40(6)	42(6)	40(5)	40(5)	40(4)	37(6)	34(6)	38(7)	35(7)	34(6)	37(4)	35(3)	33(3)



The % MVIC activation levels show that for the six core muscles there was a decrease in muscular activity during most of the core exercises over the 12 weeks of core training (Table 6.7). This is represented in both the Peak and ARV EMG data.

Tables 6.8 – 6.13 show the sEMG activity of the six core muscles comparing the post-pre and mid-pre training values for each of the seven core training exercises and reports whether the muscular activation levels recorded were significantly different ( $P < 0.05$ ). The ARV EMG data shows that all the core exercises reported a decrease in muscular activity of the RA muscle after 6 weeks and 12 weeks of core training (Table 6.8). The peak EMG data reports that all of the core exercises also showed a decrease in RA peak muscular activity except during the overhead squat and sit-twist exercises (after 6 weeks).

Table 6.8. Paired t-test results for sEMG activity of the rectus abdominis muscle during the core exercises. A comparison of post-pre (0 – 12 weeks) and mid-pre (0 – 6 weeks) values.

Exercise	EMG	Post – Pre				Mid - Pre			
		Mean	95% CI lower	95% CI upper	P value	Mean	95% CI lower	95% CI upper	P value
Forward bridge	Peak	-5.33	-7.20	-3.46	<0.01	-3.97	-5.89	-2.03	0.001
	ARV	-6.45	-7.85	-5.84	<0.01	-6.06	-7.50	-4.63	<0.01
Side bridge	Peak	-1.90	-3.67	-0.14	0.037	-2.61	-3.50	-1.72	<0.01
	ARV	-6.27	-7.50	-5.04	<0.01	-5.98	-7.35	-4.60	<0.01
Birddog	Peak	-4.60	-6.24	-2.95	<0.01	-2.42	-3.99	-0.85	0.007
	ARV	-1.59	-2.11	-1.07	<0.01	-1.65	-1.95	-1.35	<0.01
Leg raises	Peak	-7.40	-8.85	-5.95	<0.01	-3.86	-5.36	-2.34	<0.01
	ARV	-6.20	-7.43	-4.98	<0.01	-5.14	-5.80	-4.48	<0.01
Shoulder raises	Peak	-2.25	-3.24	-1.27	0.001	-2.01	-3.10	-1.03	0.001
	ARV	-1.42	-1.71	-1.13	<0.01	-1.24	-1.41	-1.06	<0.01
Overhead Squat	Peak	-2.41	-4.57	-0.23	0.033	-1.05	-2.63	0.54	0.170 <sup>a</sup>
	ARV	-1.64	-2.02	-1.27	<0.01	-1.87	-2.26	-1.48	<0.01
Sit-twist	Peak	-4.33	-7.36	-1.30	0.010	-1.97	-4.31	0.38	0.091 <sup>a</sup>
	ARV	-3.49	-5.70	-1.27	0.006	-3.99	-4.77	-3.22	<0.01

<sup>a</sup> - indicates not significant,  $p = 0.05$ . Negative value indicates a decrease of EMG muscle activity.

All the core exercises reported a decrease in ARV EMG muscle activity of the EO muscle after six weeks and 12 weeks of core training (Table 6.9). Peak EMG data shows that all the core exercises resulted in a decrease in EO muscle activity after 6 weeks and 12 weeks of training.

Table 6.9. Paired t-test results for sEMG activity of the external oblique muscle during the core exercises. A comparison of post-pre (0 – 12 weeks) and mid-pre (0 – 6 weeks) values.									
Exercise	EMG	Post – Pre				Mid – Pre			
		Mean	95% CI lower	95% CI upper	P value	Mean	95% CI lower	95% CI upper	P value
Forward bridge	Peak	-2.67	-3.92	-1.41	0.001	-2.15	-3.09	-1.21	0.001
	ARV	-3.91	-4.67	-3.15	<0.01	-2.09	-2.29	-1.89	<0.01
Side bridge	Peak	-3.02	-3.80	-2.24	<0.01	-1.92	-2.32	-1.50	<0.01
	ARV	-4.95	-5.51	-4.38	<0.01	-1.66	-2.26	-1.06	<0.01
Birddog	Peak	-2.45	-3.52	-1.37	0.001	-1.07	-1.91	-0.24	0.017
	ARV	-2.95	-3.54	-2.35	<0.01	-1.11	-1.31	-0.90	<0.01
Leg raises	Peak	-2.33	-3.47	-1.18	0.001	-1.87	-3.13	-0.59	0.009
	ARV	-8.75	-12.57	-4.92	0.001	-4.99	-7.67	-2.32	0.002
Shoulder raises	Peak	-4.74	-5.46	-4.01	<0.01	-2.45	-2.91	-1.98	<0.01
	ARV	-4.54	-5.21	-3.86	<0.01	-1.30	-1.56	-1.03	<0.01
Overhead Squat	Peak	-4.28	-5.40	-3.16	<0.01	-2.47	-3.64	-1.31	0.001
	ARV	-2.23	-2.82	-1.63	<0.01	-0.96	-1.19	-0.72	<0.01
Sit-twist	Peak	-3.02	-4.32	-1.71	0.001	-1.39	-2.29	-0.49	0.007
	ARV	-4.69	-5.26	-4.11	<0.01	-1.66	-2.03	-1.28	<0.01

<sup>a</sup> - indicates not significant, p = 0.05. Negative value indicates a decrease of EMG muscle activity.

All the core exercises showed a decrease in ARV EMG muscular activity of the MF muscle except during the forward bridge and leg raise exercises after 12 weeks of training (Table 6.10). Peak EMG data shows that all the core exercises resulted in a significant decrease in MF muscular activity except during the forward bridge following six weeks and 12 weeks of training.

Table 6.10. Paired t-test results for sEMG activity of the multifidus muscle during the core exercises. A comparison of post-pre (0 – 12 weeks) and mid-pre (0 – 6 weeks) values.

Exercise	EMG	Post – Pre				Mid - Pre			
		Mean	95% CI lower	95% CI upper	P value	Mean	95% CI lower	95% CI upper	P value
Forward bridge	Peak	-3.59	-8.53	1.35	0.135 <sup>a</sup>	-2.64	-7.08	1.78	0.210 <sup>a</sup>
	ARV	-0.32	-4.25	3.62	0.86 <sup>a</sup>	2.63	-1.29	6.55	0.164 <sup>a</sup>
Side bridge	Peak	-8.66	-9.95	-7.36	<0.01	-6.77	-7.83	-5.72	<0.01
	ARV	-4.65	-5.86	-3.44	<0.01	-1.60	-2.23	-0.94	<0.01
Birddog	Peak	-13.62	-14.79	-12.45	<0.01	-10.01	-11.49	-8.64	<0.01
	ARV	-1.56	-2.01	-1.03	<0.01	-1.71	-1.86	-1.56	<0.01
Leg raises	Peak	-7.06	-8.65	-5.47	<0.01	-4.89	-5.88	-3.90	<0.01
	ARV	-1.22	-2.66	0.21	0.086 <sup>a</sup>	-0.33	-0.66	0.01	0.054 <sup>a</sup>
Shoulder raises	Peak	-16.33	-18.03	-14.63	<0.01	-10.12	-12.02	-8.21	<0.01
	ARV	-4.12	-4.68	-3.55	<0.01	-2.15	-2.84	-1.45	<0.01
Overhead Squat	Peak	-15.80	-16.97	-14.62	<0.01	-11.44	-13.30	-9.58	<0.01
	ARV	-3.32	-4.07	-2.57	<0.01	-2.46	-3.32	-1.60	<0.01
Sit-twist	Peak	-12.51	-14.95	-10.06	<0.01	-9.54	-11.69	-7.39	<0.01
	ARV	-2.36	-3.11	-1.62	<0.01	-1.58	-2.11	-1.04	<0.01

<sup>a</sup> - indicates not significant, p = 0.05. Negative value indicates a decrease of EMG muscle activity.

All the core exercises significantly reduced the muscular activity of the LD muscle after 12 weeks of training for the ARV and Peak EMG variable (Table 6.11). These changes were also all found to be significantly reduced after six weeks of training ( $P < 0.05$ ).

Table 6.11. Paired t-test results for sEMG activity of the latissimus dorsi muscle during the core exercises. A comparison of post-pre (0 – 12 weeks) and mid-pre (0 - 6 weeks) values.

Exercise	EMG	Post – Pre				Mid - Pre			
		Mean	95% CI lower	95% CI upper	P value	Mean	95% CI lower	95% CI upper	P value
Forward bridge	Peak	-5.17	-6.57	-3.76	<0.01	-5.21	-6.29	-4.13	<0.01
	ARV	-4.25	-5.07	-3.43	<0.01	-2.35	-2.58	-2.11	<0.01
Side bridge	Peak	-5.44	-7.19	-3.70	<0.01	-5.39	-5.90	4.88	<0.01
	ARV	-8.10	-9.21	-6.99	<0.01	-4.48	-5.05	-3.91	<0.01
Birddog	Peak	-4.03	-4.69	-3.36	<0.01	-4.17	-4.64	-3.69	<0.01
	ARV	-4.83	-5.21	-4.44	<0.01	-2.72	-2.96	-2.48	<0.01
Leg raises	Peak	-2.25	-3.31	-1.18	0.001	-1.37	-1.82	-0.91	<0.01
	ARV	-7.36	-8.88	-5.84	<0.01	-4.47	-5.58	-3.35	<0.01
Shoulder raises	Peak	-3.79	-6.36	-1.22	0.009	-4.84	-5.72	-3.95	<0.01
	ARV	-8.26	-9.26	-7.26	<0.01	-4.71	-5.14	-4.27	<0.01
Overhead Squat	Peak	-1.74	-2.55	-0.92	0.001	-2.23	-2.71	-1.75	<0.01
	ARV	-7.76	-8.82	-6.69	<0.01	-4.61	-5.20	-4.02	<0.01
Sit-twist	Peak	-1.86	-3.26	-0.46	0.015	-1.87	-2.44	-1.30	<0.01
	ARV	-5.76	-6.67	-4.83	<0.01	-3.35	-4.06	-2.65	<0.01

<sup>a</sup> - indicates not significant, p = 0.05. Negative value indicates a decrease of EMG muscle activity.

All the core exercises significantly reduced the muscular activity of the GM muscle after 12 weeks of core training for the ARV and Peak EMG variable (Table 6.12). These changes were also all found to be significantly reduced following six weeks of training ( $P < 0.05$ ).

Table 6.12. Paired t-test results for sEMG activity of the gluteus maximus muscle during the core exercises. A comparison of post-pre (0 – 12 weeks) and mid-pre (0 – 6 weeks) values.									
Exercise	EMG	Post – Pre				Mid - Pre			
		Mean	95% CI lower	95% CI upper	P value	Mean	95% CI lower	95% CI upper	P value
Forward bridge	Peak	-2.56	-3.04	-2.06	<0.01	-1.45	-1.72	-1.18	<0.01
	ARV	-1.56	-1.89	-1.23	<0.01	-0.43	-0.54	-0.34	<0.01
Side bridge	Peak	-4.00	-5.44	-2.56	<0.01	-2.74	-3.69	-1.80	<0.01
	ARV	-3.20	-3.69	-2.70	<0.01	-0.71	-0.97	-0.43	<0.01
Birddog	Peak	-4.62	-5.78	-3.46	<0.01	-2.46	-3.32	-1.59	<0.01
	ARV	-3.57	-4.19	-2.94	<0.01	-1.34	-1.85	-0.83	<0.01
Leg raises	Peak	-5.49	-6.61	-4.36	<0.01	-2.64	-3.43	-1.84	<0.01
	ARV	-3.15	-4.53	-1.77	0.001	-0.62	-1.19	-0.6	0.035
Shoulder raises	Peak	-4.17	-5.40	-2.93	<0.01	-1.89	-2.39	-1.40	<0.01
	ARV	-4.75	-5.18	-3.69	<0.01	-1.73	-2.47	-0.99	<0.01
Overhead Squat	Peak	-4.95	-6.32	-3.56	<0.01	-2.02	-2.90	-1.14	0.001
	ARV	-4.60	-5.42	-3.77	<0.01	-1.82	-2.57	-1.06	<0.01
Sit-twist	Peak	-5.07	-7.00	-3.13	<0.01	-2.73	-3.76	-1.70	<0.01
	ARV	-4.32	-4.94	-3.69	<0.01	-2.38	-2.93	-1.83	<0.01

<sup>a</sup> - indicates not significant, p = 0.05. Negative value indicates a decrease of EMG muscle activity.

All the core exercises significantly reduced the ARV EMG muscular activity of the RF muscle following 12 weeks of core training, although the forward bridge exercise did report a non-significant difference in muscular activity after six weeks of training (Table 6.13). For the peak EMG values, all the core exercises significantly reduced the muscular activity of this muscle (RF) after 12 weeks of training and these changes were found to be significantly reduced after six weeks of training ( $P < 0.05$ ).

Table 6.13. Paired t-test results for sEMG activity of the rectus femoris muscle during the core exercises. A comparison of post-pre (0 – 12 weeks) and mid-pre (0 – 6 weeks) values.

Exercise	EMG	Post – Pre				Mid - Pre			
		Mean	95% CI lower	95% CI upper	P value	Mean	95% CI lower	95% CI upper	P value
Forward bridge	Peak	-3.47	-4.41	-2.52	<0.01	-2.34	-2.76	-1.91	<0.01
	ARV	-5.97	-11.40	-0.54	0.034	-4.26	-9.91	1.39	0.122 <sup>a</sup>
Side bridge	Peak	-2.79	-3.64	-1.93	<0.01	-1.90	-2.46	-1.32	<0.01
	ARV	-5.87	-6.77	-4.95	<0.01	-2.71	-3.21	-2.20	<0.01
Birddog	Peak	-4.67	-5.87	-3.45	<0.01	-3.29	-4.03	-2.54	<0.01
	ARV	-2.47	-2.79	-2.14	<0.01	-1.33	-1.71	-0.94	<0.01
Leg raises	Peak	-4.39	-5.95	-2.82	<0.01	-2.92	-4.37	-1.47	0.001
	ARV	-6.26	-7.54	-4.98	<0.01	-3.68	4.17	-3.19	<0.01
Shoulder raises	Peak	-4.31	-5.14	-3.46	<0.01	-3.50	-4.16	-2.84	<0.01
	ARV	-2.03	-2.31	-1.74	<0.01	-1.07	-1.31	-0.84	<0.01
Overhead Squat	Peak	-3.83	-5.16	-2.50	<0.01	-2.90	-3.96	-1.83	<0.01
	ARV	-5.20	-5.78	-4.60	<0.01	-3.23	-3.71	-2.74	<0.01
Sit-twist	Peak	-3.94	-4.79	-3.09	<0.01	-3.13	-3.99	-2.26	<0.01
	ARV	-4.63	-5.10	-4.17	<0.01	-2.71	-3.08	-2.34	<0.01

<sup>a</sup> - indicates not significant, p = 0.05. Negative value indicates a decrease of EMG muscle activity.

## 6.4 Discussion

The aim of the Chapter is to modify the training protocols implemented in the short-term (6 week) core training programme (as stated in Chapter 5) and evaluate these in terms of performance outcomes in highly trained swimmers over a longer (12 week) period.

It is important to establish whether the performance enhancements observed in the intervention study following the core training programme are true improvements or whether these differences in activations and performance are due to noise in the sEMG signal. The findings for these measures can be seen in Table 6.2. It is important that the change in the signal is greater than the potential error so that conclusions can be made regarding the potential benefits of the change in performance. If the error is greater than the signal then it is

impossible to make any clear observations regarding the true effect of the intervention on the subsequent performance. It can be observed from Table 6.2 that the performance enhancements observed following the twelve week core training programme are larger than the typical error of the tests. Therefore it can be suggested that the signal to error ratio is at an acceptable level for the changes in performance to be deemed valid and true and not due to unacceptable levels of error in the data. For example, the countermovement vertical jump test resulted in an improvement of 7.6% following the twelve weeks of core training, while a typical variation of 1.1% was observed, therefore the signal is clearly greater than the potential error. Therefore it can be concluded that the change in performance score observed for this performance test is a true change in performance. The low typical error values observed during the performance tests also support the setting of the 26% CV acceptability limit in Chapter 3. The typical error values observed during the performance tests of the twelve week intervention programme range from 0.6 - 7.2%. This may be due to a number of factors, such as, the subject's adequate familiarisation with the performance tests and their subsequent ability to perform the exercises in a similar manner pre- and post-training programme.

The six core muscles analysed showed a decreased muscular activity following the twelve week core training programme. The decrease in %MVIC values observed following the 12 week training programme can (as was discussed in Chapter 5) be explained by the increase in muscle activations during the MVIC exercises and a decrease during the core exercises (Peak and ARV EMG) post-training (absolute sEMG values can be seen in Appendix G). This suggests that when core stability and core strength are improved, muscle fibre activation in these muscles is reduced while still maintaining or improving performance. This could be a result of improved motor unit firing synchronisation and more efficient recruitment of the motor units within the muscle with more fast twitch type II fibres being activated which provide a faster and stronger contraction than type I fibres [289]. The change in muscle recruitment is believed to be due to changes in motor unit recruitment and improved synchronisation initially with minimal adaptations to the muscle hypertrophy at first [289, 292] with this following after a prolonged period of training.

It was observed that there was no statistically significant improvement in 50 m swimming time for the core training group (Table 6.4) after the 12 weeks of core training despite a 2.4% improvement in time over the 12 weeks (Table 6.3). However as stated in Chapter 5, due to only small changes taking place (a result of the highly trained nature of the subjects) the probability of finding a significant difference is unlikely. However the 2.4% improvement in swimming time could still be an important improvement, as improving swimming time by 2% could mean the difference between first and fourth when split seconds divide the swim field during a race (for example, the 50 m men's freestyle final at the 2010 World Cup when the swimming field was split by 0.85 of a second and the top five by 0.4 of a second) [285]. It was found in Chapter 5 that following six weeks of core training, a 1.4% improvement was observed. The 2.4% improvement observed here might suggest that by extending this period of core training to 12 weeks, improvements to performance can be extenuated.

It has been suggested by Hopkins et al. [273] that the 95% confidence intervals provide a better understanding of the possible beneficial effect on performance (for example, 50 m swimming time  $-0.9 \pm 0.4$  seconds) than by calculating the statistical significance. Based on Hopkins et al. [257] this proposal the 50 m swimming time performance change score resulted in a 46.1% beneficial, 39.2% trivial and 14.6% harmful ratio. Therefore there is an 85.3% chance that the core training programme resulted in either a trivial or beneficial improvement in swimming performance. This implies that there is only a small chance of harm on performance which would be appealing for a swimming coach as they can implement the training programme knowing that there is high likelihood of some benefit to performance occurring. The remaining performance tests also showed potential beneficial improvements to performance for the core training group and these will be summarised below.

The countermovement jump test resulted in a 75.4% beneficial, 6.8% trivial and 17.7% harmful ratio while the squat jump test resulted in a 70.8% beneficial, 12% trivial and 17.3% harmful ratio for the core training group. These high beneficial scores are supported by the countermovement and squat vertical jump tests also resulting in a statistically significant increase in performance following the 12 weeks of training (5.8% and 5.3% increase in performance respectively) ( $P < 0.05$ ) for the core training group compared to the control



group. This improvement in performance can be explained to some extent by the sEMG results observed during these performance tests for the core training group. The sEMG results suggest that this improvement is due to a significant change ( $P < 0.05$ ) in the recruitment of the GM muscle during the two vertical jump tests following the first six weeks of core training and not due to changes in the recruitment of the RF muscle (as this was found to be not significantly different in recruitment during the countermovement jump test for peak and ARV EMG or ARV EMG activity during the squat jump). As was observed in Chapter 5, the countermovement jump height was the same as the squat jump height both pre and post-training (Table 6.3). Possible explanations for this non-typical finding were outlined in Chapter 5 and can be extended to this Chapter which provides further evidence for the possible explanations.

The maximum forward bridge hold test resulted in significant improvements in performance for the core training group ( $P < 0.05$ ) between the sixth week and twelfth week of training, but not following the first six weeks of training, with a potential likelihood of benefit of 68.4% beneficial, 0.3% trivial and 31.4% harmful. It was also observed during the maximal forward bridge hold performance test for the core training group that there was a significant decrease in peak EMG muscle activity of the MF muscle but the ARV EMG of this muscle stayed the same ( $P > 0.05$ ). This suggests that there were fewer balance corrections taking place during the test and implies that the subjects were more balanced, more efficient and were able to hold the position for longer without having to make large correctional body positional changes (which would have increased or maintained the peak EMG value measured). With the changes in muscular activity and performance only being observed following twelve weeks of training and not six weeks, it can be concluded that this exercise needs to be performed for at least six weeks before training benefits can be observed. This suggests that core endurance ability of an individual may take longer to train than core stability or core strength ability. Previous research has also suggested that neural adaptations to muscles depends on the intensity of the training itself and the complexity of the movement being performed [288, 293]. Tal-Akabi et al. [293] suggested that high intensity strength and task-specific training resulted in greater neural adaptations to muscles than low intensity training. This supports the finding above from the current study as the maximal forward bridge hold test (although it was

a maximal duration hold) is a low intensity exercise which as suggested may require a longer time period for neural adaptations to occur in the core muscles involved in this movement.

The core training group reported a significant improvement in performance ( $P < 0.05$ ) during the shoulder flexion test and a high likelihood of performance benefit (83.6% beneficial, 7.3% trivial and 9.1% harmful) which implies that there was an improvement in shoulder muscle strength. This conclusion is supported by a significant decrease in peak and ARV EMG activity of the latissimus dorsi muscle ( $P < 0.05$ ). This implies that there may have been an improvement of strength in this muscle (due to improved motor unit recruitment and synchronisation within the muscle) [289] as it is able to contract while resisting more weight but with less muscle recruitment / activity taking place. This has important injury reduction benefits as the muscle can perform to a higher level while stressing the muscle to a lesser extent, reducing the possibility of overloading and injuring the muscle.

During the sit-up bleep test no significant improvement in performance was observed but a positive ratio of likely benefit was observed (58.6% beneficial, 0.6% trivial and 40.8% harmful). The larger likelihood of harm seen in this test as opposed to other performance tests (e.g. shoulder strength, 9.1% and 50 m swimming time, 14.6%) may be due to varying levels of motivation during the test (this is supported by the larger harmful likelihood during the maximum forward bridge hold performance test, 31.4%). During these two endurance tests, performance depends greatly on the motivation of the individual to maximally exert themselves. It may be that some subjects were not as motivated to continue the test following the training programme as they were when they performed the test prior to the training programme. Alternatively, this finding may again be linked to core endurance taking longer to train than core stability or core strength and that low intensity exercises like this require a longer time period for neural adaptations to be observed in the muscles used to perform these exercises. The sit-up bleep test being an endurance test which puts the muscles under low levels of stress but requires good endurance to maintain the contractions for as long as possible. The sEMG muscular activity during the sit-up bleep test shows that the RA muscle activity had no significant decrease in peak EMG activity, but there was a significant decrease in EO peak muscle activity. This may represent a change in the muscle recruitment preference

during this exercise by recruiting the larger RA muscle more (this is supported by the significant increase in RA ARV EMG activity). The RA muscle is a larger, stronger and more efficient muscle which is less susceptible to injury. It is also harder to overload, which may be a further reason why performance was not improved on the sit-up bleep test.

Both peak and ARV EMG muscle activity were calculated in the current study. As has been stated earlier, it was observed that during the majority of the performance tests, the activity of the six core muscles decreased over the twelve weeks of core training. This trend agrees with previous research that has observed a decreased in sEMG activity following specific sports training programmes [293]. Peak EMG activity during the performance tests resulted in more significantly improved test scores ( $P < 0.05$ , Table 6.6) compared to ARV EMG performance test scores for both training groups. This implies that the peak muscular activity values were reduced to a greater extent than the overall muscular activity levels seen during a full repetition of an exercise (the integrated measure). This suggests that the subject's core stability and strength has been improved during the training period as the subjects were able to improve their performance test scores while displaying reduced muscular activity. The improvements observed during the performance tests can therefore to some extent be explained by the changes in sEMG activity (reduced muscular activity) observed for the six core muscles during the core exercises which formed the twelve week core training programme.

The reduction in muscular activity observed during the performance tests are supported by the sEMG activity results observed during the core exercises at the pre- (0 weeks), mid- (6 weeks) and post- (12 weeks) periods of the core training programme. From the seven core training exercises, the birddog exercise resulted in the minimal amount of training improvements over the twelve week programme. It was found that many of the core muscles did not report a significant difference in muscular recruitment following six weeks of core training. However some core muscles did subsequently result in a significant difference in muscular activity ( $p < 0.05$ ) following the full twelve week training programme. This implies that for training enhancements using this exercise (the birddog), it needs to be performed for at least six weeks before training advantages can be observed. This may be due to the low threshold nature of

the exercise on the core muscles and subsequently the core stability demand on the body being less as has been suggested earlier and in previous studies [288]. This is supported by the high threshold exercises showing a greater reduction in muscle activity during the twelve weeks of core training for the analysed core muscles (e.g. the overhead squat and sit-twist exercises, Table 6.7). It has also been suggested that the complexity of the movement being performed has an impact on the speed of neural changes occurring in the muscles (due to the multi-joint nature of the more complex movements and the need to coordinate many different muscles which need to adapt before improvements can be identified) [289, 292]. Chilibeck et al. [289] observed a prolonged neural adaptation for more complex movements such as the bench press and leg press movements compared to movements such as the arm curl.

## **6.5 Conclusions**

The twelve week core training programme resulted in significant improvements ( $P < 0.05$ ) in a number of sport performance tests (e.g. countermovement and squat vertical jump height, shoulder flexion strength, maximum forward bridge hold) for the core training group. In addition a high likelihood of benefit ratio was observed for the six performance tests with the beneficial likelihood value ranged from 46.1% (50 m swimming time) to 75.4% (countermovement vertical jump height). This resulted in a low potential likelihood of harm for many of the performance tests following the training programme (e.g. 50 m swimming time, 14.6%). Some of the significant improvements observed during the performance tests occurred within the first six weeks of training, while others took longer to be improved and occurred following twelve weeks of core training. Significant reductions in core muscular activity were observed for the analysed core muscles ( $P < 0.05$ ) during the performance tests and the core exercises. It can be implied therefore that core training results in a decrease in muscular activity of selected core muscles (due to changes in the muscles motor unit recruitment and synchronisation being enhanced) and subsequently the muscle can be recruited and worked to a lesser extent to perform the same movement. This theoretically reduces the potential injury risk to the muscles and may improve overall sporting performance. The neural adaptation to muscles during a training programme is believed to be largely influenced by the complexity of the movements being performed with higher intensity

exercises resulting in the greater training adaptations initially with lower intensity exercises resulting in improvements after a longer period of training. The core training programme targeted core exercises specifically for swimmers and subsequently improved sporting performance (e.g. vertical jump height, shoulder strength, 50 m swimming time) and changed the muscle recruitment of the core musculature. Therefore this core training programme can be recommended for swimmers to implement in their swimming training to improve individual core stability, core strength and core endurance to help improve their swimming performance.

## **Chapter 7**

# **Development of a Theoretical Model to Design Core Training Programmes for Highly Trained Athletes**

## **7.1 Introduction**

The concept of training an athlete's core stability and core strength has become increasingly popular due to the potential benefits in improving their resultant sporting performance [59, 186]. However much of the supporting evidence for the success of core ability training is based on research performed in the rehabilitation sector on rehabilitating the general population following injuries and achieving normal functioning movements again by stabilising and strengthening the core musculature [87, 172, 290] rather than on healthy, trained athletes. There is a dearth of published sport specific research which focuses on the more demanding nature of the movement athletes experience and subsequently the more demanding training exercises that need to be performed to result in sporting enhancements. This thesis has highlighted some innovative methods which can be used to analyse core musculature activation during different types of core training exercises. For example, calculating the ARV EMG value provides more in-depth understanding of the sub-maximal levels of muscular recruitment during core exercises. Subsequently conclusions regarding which exercises may be optimal to result in core stability and core strength benefits to the athlete can be more accurately established. The most effective core training programme for an athlete can then be designed which result in physiological adaptations to the core musculoskeletal system leading to an improved core ability and resultant sporting performance. The many methodological and experimental variables which affect this successful implementation of training (e.g. progression levels, duration of programme, exercises to be performed) depend on the background of the athlete in question (e.g. their current core ability). Coaches and athletes would benefit from a theoretical model which outlines these variables and provides them with a guide to designing an effective core training programme.

### **Aim of Chapter**

To develop a theoretical model outlining how to structure an effective core training programme for elite and sub-elite athletes.

## **7.2 Established Theories Regarding Core Training**

This thesis has established a repeatable method for collecting sEMG data on the core musculature and has designed and implemented an effective 12 week core training programme for the highly trained swimmer which results in an improvement in swimming performance. This is a result of the individual's core ability being enhanced (by the physiological adaptations as a result of the core training) which subsequently makes their sporting performance more effective. As the swimmer has no base of support to help produce force through the water during the swimming stroke, the individual's ability to produce and transfer force within the body is essential and this is achieved and maximised by having a strong and stable core [119, 155]. Therefore core training can be viewed as an essential part of a swimmer's training programme [155].

This thesis has utilised sEMG methods to establish the effectiveness of core training exercises to recruit the core musculature and subsequently measure an individual's core ability (stability, strength and endurance). Due to a significant lack of published research, there are many unanswered questions regarding the level of musculature activation brought about during different types of core training exercises and how effective these exercises are in improving an individual's core ability. A reason for this deficit may be the difficult nature of reliably measuring the core muscles and their level of activation during dynamic movements. This thesis has outlined a suitable method for collecting repeatable sEMG data on the core musculature as long as the researcher incorporates sufficient planning, data processing and analysis into their study.

Based on the findings of previous studies that have measured core stability and core strength using surface EMG on the core musculature [12, 159, 198, 235, 238], along with the current thesis, it can be concluded that due to the orientation and positioning of certain core muscles (e.g. IO and LG muscles), only superficially positioned core muscles can be repeatedly measured and analysed. By measuring this musculature activity of the core muscles and establishing a %MVIC activation level for these muscles, it is possible to evaluate the



different types of core exercises and assess how effective these exercises are in activating the core muscles and to what extent [94]. This is due to the level of muscular activation influencing whether core stability and/or core strength improvements are trained [195, 196]. However it is important to stress that by measuring sEMG muscle activity this does not represent or provide any conclusions on changes in the muscle strength or force output [121]. It can only provide an indication of the muscle fibre recruitment level and highlight any potential changes in the activation of these muscles over time or between different types of movements. Despite this, establishing the level of muscle activation still provides useful information for the researcher as this helps explain and understand any improvements in performance by establishing changes in the muscle recruitment patterns during the same set of exercises or movements for the core muscles. Subsequently this enables conclusions to be made regarding the effectiveness of the training programme to target and train specific core muscles.

### **7.2.1 Implications for the Elite Athlete**

When designing training programmes for an athlete, there are many factors that need to be considered; functionality, progression, periodisation, and the level of overload on the muscles [99]. These processes need to be carefully worked into a training program to make sure that it is effective in improving the athlete's sporting performance.

This thesis has shown that a core training programme of twelve weeks resulted in positive improvements to a group of swimmers core ability. During these twelve weeks it is essential that exercise progression is built into the training programme [52]. It has been shown (in Chapters 5 and 6) that by incorporating progression into the exercises every two weeks, either by increasing the external load or by increasing the volume of repetitions during the exercises, has an effective training benefit. The core training programme outlined in Chapters 5 and 6 included core exercises that targeted the whole body, not just what is traditionally termed as the core (i.e. the abdominal region). For example, the upper legs and shoulders muscles were also targeted which resulted in positive enhancements to shoulder strength and vertical jump height ability. Therefore it is important that a complete range of

core exercises that target the whole body in a sport specific manner are included in the training programme.

Chapter 4 established that different core stability and strength exercises activate the core muscles to differing extents. Therefore supporting previous research that suggests that there is not one exercise that can be performed that activates the whole core musculature to the required level to result in core stability and core strength enhancements [12, 19, 56, 94]. The Chapter also highlights that different types of core exercises can be used to target different levels of core training. For example, the high threshold exercises resulted in higher levels of activation for many of the core muscles, which can be used for core strength gains. While the low threshold exercises resulting in lower levels of activation, subsequently targeting core stability muscles and their development. Previous research has established that muscle activation levels of  $> 10\%$  are required to result in core stability enhancements [196] while activations of above 60% maximum are required to result in core strength enhancements [11, 195]. This implies that by activating a muscle above 60% of its maximum could result in core strength and stability improvements, suggesting that elite athletes looking for core strength improvements should only perform exercises that activate the muscles above this level. However there are training implications which may prevent this from being as beneficial as it appears, these are outlined below.

### **7.2.2 Benefits of Sub-Maximal and Maximal Training**

Core stability can be improved by activating a muscle to 10% of its maximal contraction [11, 196]. However, many strength and conditioning coaches would argue for training this muscle to 100% and bringing about strength enhancements too. They would propose that there could be stability improvements as well as strength improvements if training this way. Therefore suggesting that core strength exercises target core stability as well (just at a higher level of activation) and subsequently stabilises and strengthens the core. Many training exercises that strength and conditioning coaches recommend traditionally involve one repetition maximums and working the muscles of the body maximally [195]. During muscular strength training the bias is on developing the type II fibres of the muscles, which

have less endurance capacity but greater strength [294]. These fibres do not have the capability of being able to stabilise the core for long periods of time. It is the local stabiliser muscles (which are mostly made up of type I fibres) which provide the stabilisation during sporting movements [295]. Therefore, strength training increases the size and proportion of type II fibres in muscles and so potentially reduces the individual's core stability ability if these muscles (local stabilisers) and fibres (type I) are not trained alongside the strength training [295].

Furthermore, when performing high threshold exercises, a greater strain is placed on the core muscles (due to the higher activation levels observed) subsequently placing these muscles under an increased injury risk [296]. This would limit how many exercises and repetitions the individual would be able to perform due to fatigue and tiredness and as a result may affect the effectiveness of the training programme on improving the individual's core ability. The success of the training programme also depends on it being tailored specifically for that individual so that it is sport specific and targets the individual's weakness in their core ability. Many sporting movements do not activate the muscles maximally therefore these muscles do not need to be trained and stressed to a maximal, highly intense level. Instead the muscles are often subject to lower levels of stress and it is important that they are trained to be able to activate and stabilise the body effectively at these times to prevent injury and optimise effective force transfer through the body.

Only activating the muscles maximally fails to train the smaller local stabiliser muscles of the core which help in injury prevention during sporting movements. This is due to the proposal that during high threshold exercises and high demanding movements, the bigger mobiliser muscles tend to take over from the smaller stabilising muscles [42]. As a result this could create a weakness in the individual's core stability by reducing activation of the smaller muscles which are essential in maintaining fitness and posture during sporting movements. Therefore it is essential that both low and high threshold exercises are trained and included in a core training programme. This supports the theory and research carried out by Comerford and Mottram [1, 42].

### **7.3 Theoretical Model for Core Training of Elite Athletes**

This thesis has outlined different processes that need to be considered in order to be able to implement an effective core stability and core strength training programme. The theoretical model outlined in Figure 7.1 has been designed based on the findings from the previous chapters of this thesis regarding the measurement of core muscular activation, establishing an individual's core stability and core strength ability, effectively training the core musculature and evaluating subsequent sporting enhancements. The purpose of establishing this theoretical model is to provide a clear format for the trained athlete and coach to implement an effective core training programme which results in an improvement in sporting performance.

#### **7.3.1 Optimising Core Training Using the Model**

It is essential to establish the background of the athlete with which the training programme is being designed for. It is also important that the training programme is sport specific to replicate the same demands on the body during the training exercises as those experienced during the sporting movement [99]. This is so any training adaptations to the core musculature are transferable and functional to the sporting environment. Prior to the training programme being developed, it is important that the athlete's strengths and weaknesses in the area are established so that the programme can be tailored to target and correct any underlying weaknesses effectively [48]. When assessing the core ability of an individual it is important that core strength, core stability and core endurance are assessed during specific performance tests (e.g. vertical jumps, sprint times). As most sports involve low (e.g. balance) and high (e.g. force resistance) threshold demands on the body, the initial assessment exercises need to include both threshold levels of exercises too. These movements need to include; static and dynamic, asymmetrical and symmetrical movements, with and without external loads / resistance, while incorporating multiple limbs to perform the exercise. By doing this, it is possible to replicate similar movements to that of the sporting movement so providing an accurate reflection of the athlete's core ability. Ideally,

prior to a training programme being implemented, sEMG data should be collected during the sporting movement to establish the level of core musculature activity experienced so that sufficient levels of activation can be brought about during the training programme to mimic and overload these levels to optimise the possibility of a training benefit (in the current thesis, this was done by using previously collected sEMG data on swimmers during the freestyle swimming stroke) [7, 72].

To establish repeatable values for core ability, it is necessary to record the assessment exercises using video and collect data using a quantitative method (e.g. sEMG, ultrasound). Due to the limitations of using ultrasound during highly dynamic movements (which need to be performed when assessing an elite athlete) sEMG provides a more suitable method of establishing an individual's core musculature activation levels during the different movements. This thesis has established that it is not only peak muscle activation levels (which have mostly been reported in the past) but also an integrated measure of muscle activity that is needed when analysing the core musculature. This is because peak EMG values do not represent the length of time of activation in the muscle and/or a measure of sub-maximal muscle activity. During core exercises where balance corrections are common and are of sub-maximal activation levels it has been shown, in this thesis, that a measure such as ARV EMG is a useful indicator of this type of muscular contraction as it provides a greater understanding of the demands that the different types of core exercises place on the body. Chapters 3 and 4 highlight the potentially large variation in sEMG data that can be recorded from some of the core musculature (CV observed between 5 - 75%). However this variation can be reduced by following good practise in the collection of EMG data [297].

This thesis has established that it is important to analyse a number of different muscles from the core musculature which includes muscles outside of what is generally referred to as 'the core' (hip and abdominal region) [19]. The upper leg muscles and shoulder stabiliser muscles are also important in core stability and core strength as they play an essential role in force transfer through the body during most sporting movements [155]. Therefore a range of muscles should be analysed and these should include both stabiliser and mobiliser muscles. However, it has been highlighted that some core muscles are not able to be

accurately measured using sEMG due to their location and orientation in the body [120]. This is due to high levels of cross talk from the surrounding muscles and difficult repeatable electrode placement for some muscles (e.g. LG and IO muscles).

To be able to establish the muscle activation levels in the athlete it is necessary to normalise the data using MVIC exercises [239]. Chapter 3 of this thesis established that it is possible to collect repeatable MVIC data on the core musculature during five exercises (side bridge, birddog, bent leg curl-up, overhead squat and medicine ball sit-twist). It is recommended that the athlete performs at least three different MVIC exercises to increase the likelihood of bringing about a 100% activation of the muscles being analysed [233]. Subsequently it is then possible to compare individual muscle activation levels and establish any exceptionally high peak EMG muscle activities (for example during low threshold exercises when muscle activity should be low) and any low ARV EMG muscle activities (for example during highly dynamic exercises when that muscle should theoretical be active and involved in the movement) during the assessment exercises and subsequently establish these inconsistencies as weaknesses for that individual. The weaker muscles can then be targeted when designing the individual's core training programme. It is essential that these weaknesses are identified and corrected as they can increase the injury risk of the athlete, by relying and overusing other muscles (usually the global muscles) and so maintaining a lack of strength in the stabiliser muscles which should be responsible for stabilising limbs and joints [1]. This could have a large impact on the athletes sporting performance by reducing the effective force transfer through the body due to poor stability or in the development of force in the muscles due to poor strength. Chapters 4 to 6 highlighted the range of muscular activation levels that different core training exercises result in (e.g. 0 - 110% MVIC). It should be expected that a range of levels will be observed for the core musculature depending on the type of training movements being performed.

Once the weaknesses in an individual's core ability have been identified it is possible to design a sport and individual specific core training programme targeting those areas. Chapters 5 and 6 of this thesis, along with previous studies [118, 151], have identified that a core training programme of 10 - 12 weeks is optimal for performance enhancements to be

established. Based on the successful training programme outlined in this thesis and previous studies [298] further recommendations can be made regarding the development of an effective core training programme. Firstly, the core training sessions should take place three times per week and be 30 - 40 minutes in duration [105, 161, 186]. Secondly, each session should include sport specific multi-limb movements of both low- and high-load intensity [42] and it is recommended that a number of different core exercises are performed to make sure that all the core muscles are trained and that each type of exercise is performed [60].

The training programme should begin at a suitable level so that the athlete can perform each exercise comfortably and confidently. After the initial familiarisation of the exercises, exercise progression should take place [11, 52]. This should be either an increase in the external load or demand during the exercise (e.g. increase the weight of medicine ball or free dumbbell weights) or an increase in the number of repetitions or sets of the exercise (e.g. from two sets of ten repetitions to three sets of eight repetitions). This progression should be manageable for the individual but still provide extra stress on the body to establish the overload principle in the muscles. It is recommended that a progression should be introduced every few weeks during the training programme [101] (supported by the findings in Chapters 5 and 6 of this thesis). This allows for muscular adaptation to occur at each progression to cope with the increase in demand on the body before overloading the muscles again. It is believed that by utilising the overload principle and implementing progressions of the exercise that this results in greater muscle hypertrophy which leads to greater improved force generation due to the advantageous changes in the muscle fibres [52]. The high and low threshold training is also believed to result in improvements in CNS control, improve motor unit recruitment and the synchronisation of motor unit firing within the muscles [1]. These adaptations result in improved muscle stability, strength and endurance which can then be transferred and utilised during an athlete's sporting performance. The training programme should be carried out alongside any other normal training programme, for example, swimmers continue to do their normal pool-based training. This maintains the aerobic fitness levels of the athlete and also encourages the muscles to train in a similar way during the pool-based and land-based training sessions, potentially making the improvements more transferrable.

Following the core training programme it is essential that the athlete is re-assessed to evaluate the effectiveness of the training programme and identify any changes in sporting performance and their core ability (stability, strength and endurance). Core stability, core strength and core endurance must be re-assessed using the same exercises and performance tests used during the initial assessment so that the body is experiencing the same demands. As a result, any performance changes which have occurred during the intervention period can be clearly identified. The current thesis recommends video and sEMG analysis of the same muscles, with peak and ARV EMG muscle activation levels being re-established for each exercise and core muscle investigated. These values can then be compared to the pre-training values. Changes in the level of muscular activation could reflect improvements in muscle strength, stability and/or endurance. Positive training adaptations could also be reflected in the performance tests by observing an improved time or distance covered. This could reflect an improvement in for example, endurance (maximum forward bridge hold test), power (leg strength), speed (time trial) and/or agility (interval tests). Subsequently if changes in muscle activation and improved performance levels have been observed it can be concluded that the core training programme has been effective in improving performance by altering the muscle activation parameters of the core musculature.

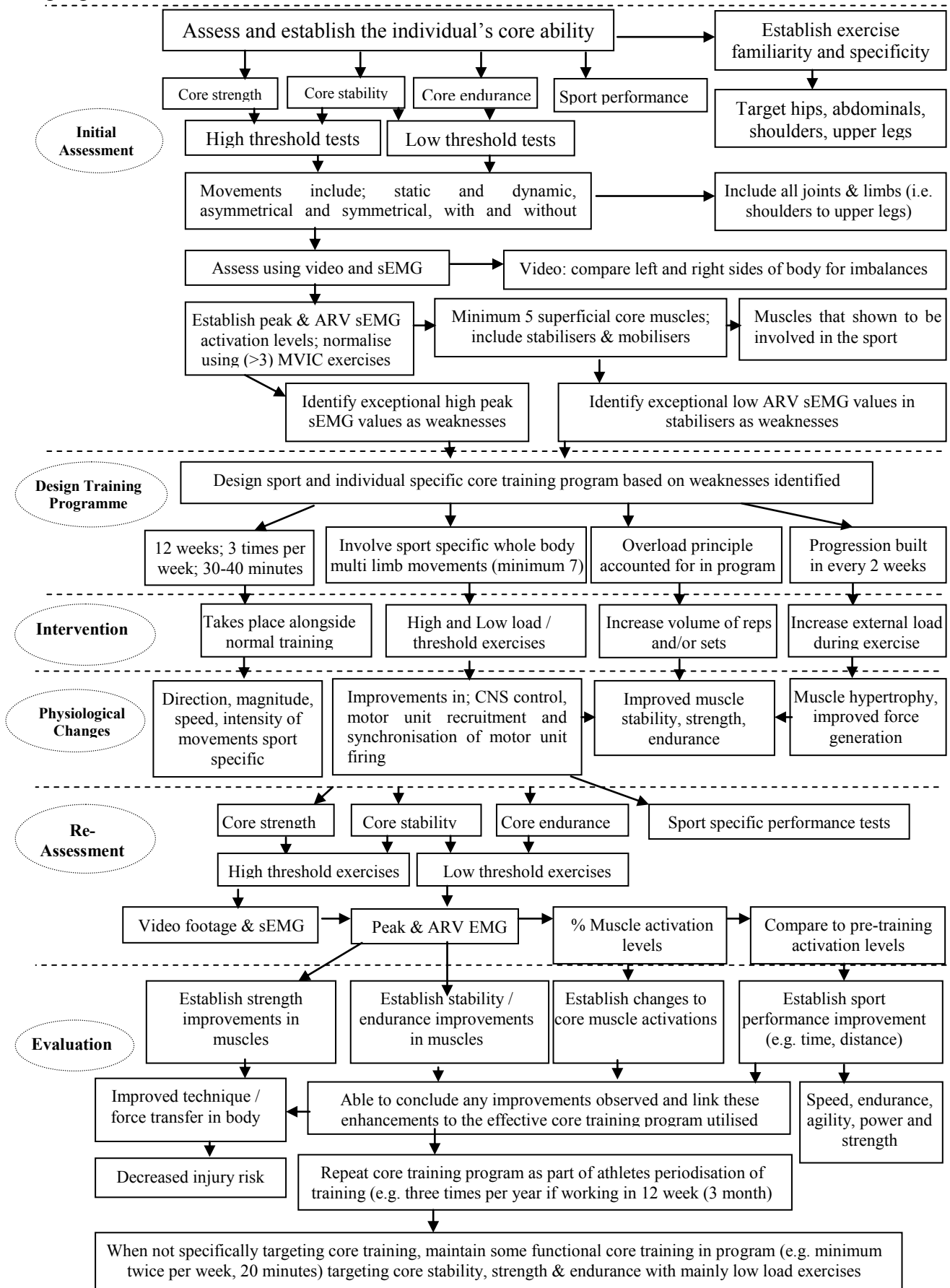
Athlete's training programmes often utilise a rigid periodisation structure of their training. For example, certain months will focus on strength or speed, while others may have a focus on endurance [99]. It is recommended that core ability training be included into one of these periodisations as the main focus of training (while it is maintained at a lower emphasis in the remaining periods). Therefore if each periodisation is a 12 week block (three months), an athlete will have four main periods of training in a year. It is recommended, based on current training theories [101], that each period of training should have a different main training focus, where the athlete concentrates on one aspect of training, for example, core training. The other training components (e.g. speed, strength, endurance) remain but at a lesser extent (i.e. training volume and intensity). This remains for one three month period then the emphasis shifts to another component of training for the following period. This approach enables the body to fully recover between training periods to help prevent overuse



and overtraining of the muscles which could increase the injury risk to the athlete [99]. By following this training structure to develop core ability, it will help develop the core musculature of the individual providing them with a solid base to structure their other training around. Due to the high importance of good core stability and core strength in highly trained athletes to perform optimally (as we have established in the current thesis and previous studies [119, 155]) it is recommended that even during the non-core training focused periods that a minimal level of core training is performed each week to maintain the muscle recruitment patterns and prevent any weaknesses from developing. For example, functional sport specific core training could take place for 20 minutes twice a week during the other three month periods, with the focus remaining on low threshold exercises to maintain their current ability while other physiological process and adaptations are targeted with specific training (e.g. aerobic, anaerobic or lactate systems).

In Chapters 1 and 5 it has been emphasised that training a swimmer's core ability may impact on swimming performance [119, 199]. Based on the results outlined in Chapter 6, it can be suggested that improvements in core ability following a 12 week training programme leads to a likely (85.3%) improvement in 50 m swimming performance, along with beneficial improvements in other strength and stability performance skills (for example, a 75.4% likelihood of improvement in countermovement vertical jump height and a 68.4% likelihood of improvement in forward bridge maximum hold endurance test performance were also observed). Therefore swimmers and coaches that implement the core training model outlined in Figure 7.1 could increase the likelihood of positive enhancements from core stability and core strength training which result in true performance enhancements for the swimmer.

Figure 7.1. A theoretical model to aid in the development and evaluation of a core training programme for the elite level athlete.



### **7.3.2 Theoretical Examples Using the Model**

To explain how the ‘core training model’ outlined in Figure 7.1 can be used by a coach or athlete to develop a specific core training programme, two case study examples have been outlined showing how the ‘model’ would be affected by differing athlete circumstances. The first case study (Figure 7.2) is a swimmer who has not performed any specific core stability or core strength training to date.

#### **7.3.2.1 Case Study 1 – Swimmer with No Previous Core Training**

The model would begin by establishing the individual’s current core ability by performing a range of high and low threshold performance tests. These tests would include; the sit-up bleep test, strength tests of the shoulders and legs (high threshold), maximum forward bridge hold and balance tests (low threshold). For this theoretical situation, the performance tests would highlight a weakness, in potentially, all of the performance tests due to the lack of specific training of the core musculature to date. This would be represented by poor strength, lack of balance and by the swimmer being able to only perform the sit-up bleep test and hold the forward bridge static position for a short period of time (e.g. under two minutes and one minute respectively). Subsequently, a training programme to target these areas can be developed. For this swimmer, the training programme would focus on training core stability and core endurance which would develop the stabiliser muscles of the core to establish efficient recruitment of these muscles. This would take place prior to introducing any core strength training of the larger mobiliser muscles of the core. This follows the suggested training approach outlined in previous studies [47] which progresses from establishing efficient recruitment of the stabiliser muscles, to low intensity functional stabilisation exercises, progressing to a continuum of exercises involving the control of body weight in all planes of movement, moving onto controlling high intensity functional movements with external forces and loads on the body [192].

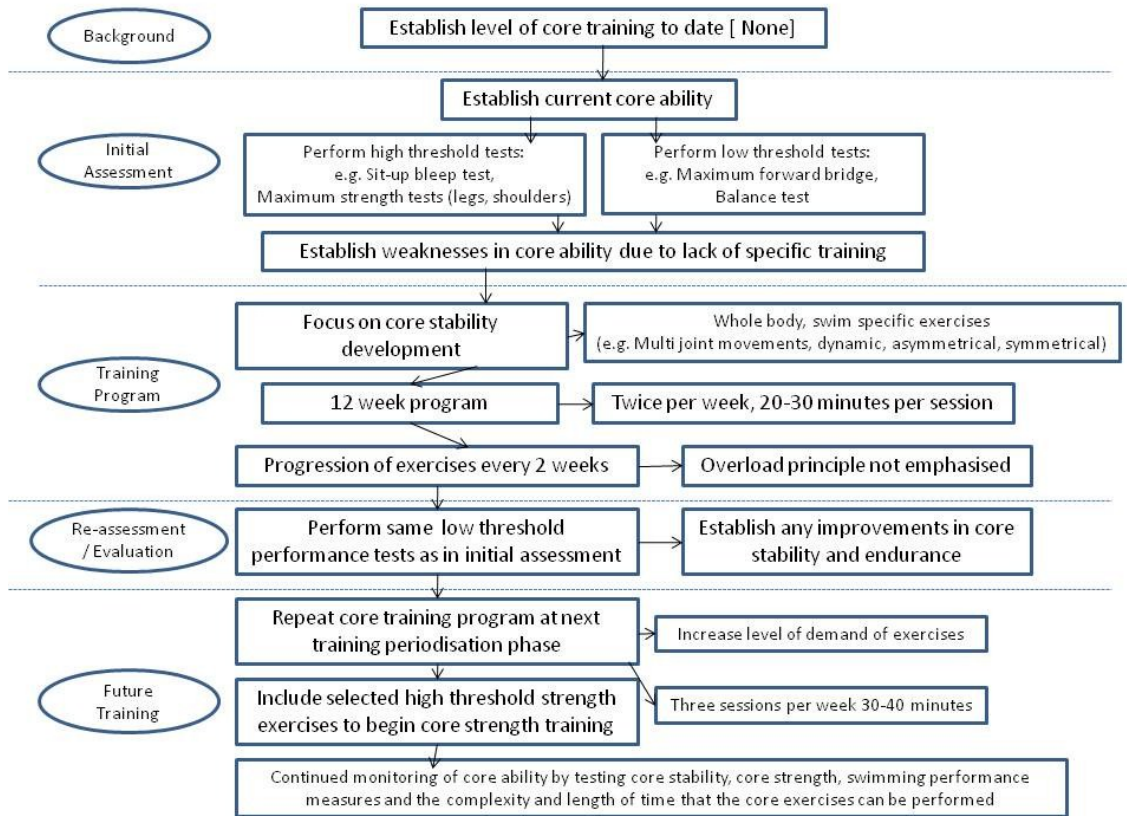


Figure 7.2. A theoretical case study of a core training model for a swimmer with no previous core training experience.

A twelve week programme of two sessions per week (20 - 30 minutes in duration) would be recommended, with an exercise progression to occur every two weeks. Two sessions a week would be suggested due to the level of experience of the swimmer being a beginner when performing core stability training so not to strain the muscles too much. Previous studies have found positive improvements in core stability following two sessions of specific core training a week [118, 161, 199]. A two week progression of the exercise complexity would be advised as this was found in the current thesis (Chapters 5 and 6) to provide a sufficient period of time to overload the muscles and allow the muscles to physiologically adapt before the next increase in intensity (volume of repetitions performed or resistance load during the exercise) of the exercise takes place. The training programme would begin at an introductory level due to the individual's body having to learn new movements and recruiting muscles which perhaps have not been used to this extent in the past (it is

important that the body is not overloaded too greatly as this could result in injury). However it is still likely that improvements would be observed within the first six weeks of training due to the greater scope for improvement in these areas due to the naive starting point.

Following the twelve weeks of training, the low threshold tests would be repeated (i.e. maximum forward bridge hold and balance tests) to establish if any improvements have occurred in the individual's core stability or endurance (in the example tests outlined above, this would be represented as an improved balance score and a longer time for which the forward bridge position can be held for). The high threshold tests would not need to be repeated at this stage as core strength was not targeted and so no improvements in strength would be expected. Future training for this individual would include repeating the core training programme in the subsequent periodisation phase where there would be an increase in the demands of the exercises (e.g. extra number of repetitions or sets) and an increase in the volume of training (e.g. three sessions per week of 30 minutes). These progressions are based on the positive effects observed on performance in the core training intervention outlined in Chapter 6. The introduction of some core strength exercises (high threshold exercises) such as, weighted squats and bar bell roll-out exercises would be included to begin core strength development. Continued monitoring of the athlete would take place following each training phase by evaluating core stability, core strength, swimming performance and the level / demand of the core exercises being able to be performed by the individual. This could be done by performing sEMG data collection on the specific core muscles (as have been outlined in Chapters 3 - 6) and monitoring the activation levels of these during the core exercises and following the period of core training. As observed in Chapters 5 and 6, it would be expected that the activation of the core stabiliser muscles (for example, MF) would be increased as a result of the core training (activation levels of approximately 30 - 60% MVIC, based on Chapter 6 findings). Subsequently, it may be observed that the level of muscular activation of the global mobiliser muscles (for example, GM and RF muscles; which may have been used instead of the stabiliser muscles previously) is decreased (activation levels of approximately 20 - 50% MVIC, based on Chapter 6 findings). Changes in level of muscular activation over the twelve weeks could be

expected to be up to 15% (based on the results following the twelve week core training programme outlined in Chapter 6).

### **7.3.2.2 Case Study 2 – Swimmer with Previous Core Strength Training**

The second case study (Figure 7.3) outlines how the model would be altered for a swimmer who has performed a large amount of weight training but no specific core stability or core endurance training. As with case study 1, it is important to establish with the athlete their background and current level of experience regarding any specific stability or strength training. Following this discussion, the initial assessment would, as with case study 1, consist of high and low threshold performance tests to establish the athlete's strengths and weaknesses in their core ability. For this individual, the performance tests may highlight poor core stability and core endurance in the low threshold tests due to the lack of previous training in these areas and the subsequent lack of recruitment of the stabiliser muscles (due to the more dominant globaliser muscles used during strength training 'taking over'). The high threshold tests would expect to show good performances as these are dependant more on muscle strength which this athlete has previously had specific training in. Collecting sEMG data during these tests would provide the objective data to determine this and quantify the extent of the imbalance between the activation of the stabiliser and mobiliser muscles. Based on these measurements and identification of an imbalance or lack of core stability ability, a training programme could be devised focusing on core stability and core endurance. The duration of which would be twelve weeks, with sessions completed three times a week for 20 - 30 minutes per session (based on findings in Chapter 6). The twelve week training programme duration is recommended for this individual due to the findings observed in Chapter 5 of the current thesis where core endurance ability appeared to take longer than six weeks to be enhanced.

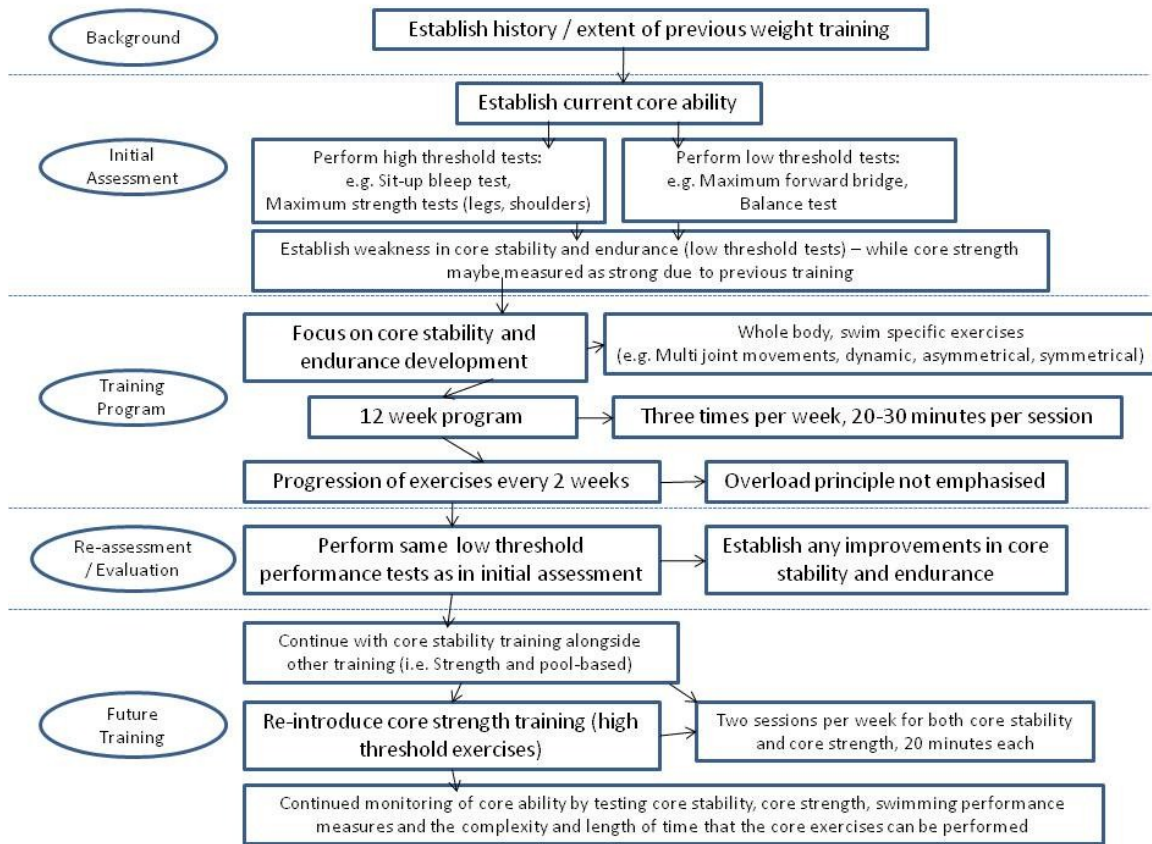


Figure 7.3. A theoretical case study of a core training model for a swimmer with previous core strength training but no specific core stability or core endurance training experience.

As outlined with case study 1, progression of the exercises every two weeks would be emphasised (for example, an increase in the number of repetitions and/or sets of exercises). However, the overload principle would not be emphasised as core strength is not being targeted for this individual during this phase. The training focus remains on establishing the correct and efficient recruitment of the core muscles during the exercises to develop stability in the core musculature. Following the core training programme, re-assessment using the same low threshold tests as used in the initial assessment would be performed. As with case study 1, high threshold tests would not need to be performed as core strength has not been specifically trained. Any improvements in core stability and/or endurance would be established by comparing the performance tests before and after the training programme. Future training for this swimmer would involve continued core stability and endurance training with a progression in complexity of the exercises. This would take place alongside

their regular pool-based training and also the re-introduction of specific strength training. The re-introduction of strength exercises would be at a higher level than that for the swimmer in case study 1, as this athlete has previous exercise familiarity with strength exercises and a suitable level of muscular strength already established to build upon. The swimmer would be monitored every six to twelve weeks for improvements in core ability and sporting performance to evaluate the effectiveness of the core training programme and enable sufficient progressions of the core training exercise demands to take place. As with case study 1, sEMG measurements of the activation levels of the core musculature during the training weeks would provide the objective data needed to enable conclusions to be made regarding the training intensity and establish any muscular recruitment changes during the core exercises which would come about as a result of training these muscles. For example, greater recruitment of the stabiliser muscles would be expected, along with a decrease in some of the global mobiliser muscle activation levels (as was observed in Chapter 6). It could be expected that these muscles may, over the twelve weeks, show a change in activation level of up to 18% MVIC (as was observed in Chapter 6 following twelve weeks of core training).



## **Chapter 8**

### **General Conclusions**

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## **8.1 Overall Conclusions**

The aim of this thesis was to establish a repeatable method of analysis to develop a methodologically sound core training programme and evaluate the effect of this core training intervention over a 12 week period on a group of trained swimmers. Subsequently a repeatable method of collecting sEMG data from the core musculature was established (with peak and ARV EMG data being quantified) to provide an understanding of the muscular activation during different types of core exercises. This knowledge was implemented in a six week and a twelve week core training programme which resulted in core musculature activation level changes, positive enhancements in core stability and core strength of sub-elite swimmers and improved test performances, which included 50 m swimming time.

These findings have important implications for the athlete and coach. It provides a training programme which results in an improved sporting performance by improving an athlete's core stability and core strength, highlighting the importance of core training for the elite athlete. It also has important implications for researchers analysing the core musculature. The thesis has established the importance of including sEMG data of the integrated signal (ARV EMG) alongside the peak EMG signal when analysing core training exercises. The thesis has provided new and important information regarding some of the many unanswered questions currently in the rehabilitation and sporting environments regarding core training (for example, establishing which core exercises are best to target core stability and in turn core strength and how to reliably analyse the core musculature). However the thesis has also created further questions and recommendations for future research which will help continue to increase researcher understanding and knowledge of the processes involved in training the core musculature which can benefit both the sporting and rehabilitation sectors.

## **8.2 Limitations**

This thesis has managed to quantify the reliability of measuring core muscle activation levels during MVIC and core training exercises, which have previously been largely

unreported. This may be due to the complex positioning and orientation of some core muscles as well as the quasi-random nature of the activation of muscle fibres in the body when performing repeated muscular contractions. Subsequently, as this thesis has shown (Chapter 3), some of these muscles result in poor reliability of the sEMG muscle activation signal (e.g. LG and IO). As a result, only a selection of muscles can be analysed using the sEMG method.

The sample sizes used in the current thesis range from 5 to 30 subjects (total from the training and control groups). These sample sizes are typical when sEMG research is performed. However they are below the recommended required sample size required to obtain sufficient statistical power based on sample size calculations using standard deviation or coefficient measurements. The required sample size needed to meet the recommended level would be in the hundreds due to the large variations observed between subjects when sEMG data is collected (as was observed in Chapter 3) and due to the potentially small, but worthwhile, performance changes that could be expected. Clearly, recruiting this number of highly-trained swimmers is unrealistic and would be extremely difficult to monitor every individual's completion of the training intervention programme and collecting of the required sEMG data and performance testing. Equally, the time that would be required to process, analyse and collate the sEMG data would be too great for this thesis' time frame. As a result, it was felt that the sample sizes selected for the research in this thesis were suitable and are in agreement with previous research studies in this area.

Due to the small sample sizes, typically larger than traditional variation in the data (compared to non-EMG studies) and small performance changes being identified, statistical significance ( $P < 0.05$ ) is unlikely to be shown in many cases. This may result in a false negative conclusion being made when actually the difference in the measurements is a true enhancement. This may have occurred in Chapter 5 following the 6 week intervention programme where small performance and muscle activation differences were observed. Chapter 6 attempted to establish whether this was the case by increasing the intervention programme to 12 weeks and seeing whether the differences continued to increase and subsequently whether they then became significantly different. This limitation was partially

overcome in Chapter 6 where the likelihood of benefit score (which is believed to be a more effective method of analysing such data when small differences are being sort using small sample sizes) was calculated.

### **8.3 Future Research**

The latter chapters of this thesis have focused on swimming where the demands on the body are very different from other sports (for example, those where movements are performed vertically and where the body is in contact with a stable base of support). It has been highlighted that it is important that the training programme is sport specific so the athletes are training and moving in a similar manner to that of the sporting movement so that any potential training benefit can be transferred to sporting performance. As a result it is important that researchers develop and analyse sport specific training methods to identify which types of exercises are the most efficient at reproducing these environments for the athletes to maximise potential performance enhancement. Future research needs to focus on establishing sport specific effective core training programmes to determine what the training effect on sporting performance is following a core training intervention programme (for example, the footballer, gymnast or golfer).

It would be beneficial if future research would implement the core training model developed in this thesis with athletes, other than swimmers, to establish whether there are any differences in the trainability of different sportsmen and women to the same stimuli due to their differing sporting requirements. This would enable conclusions to be made regarding whether the same performance benefits are observed for the different types of athletes. It may be that the swimmers experience less of a training impact and resultant improvement in performance due to the harder task of trying to transfer the improvements into the performance in the water due to the lack of base of support when swimming.

The outlined training programme in Chapters 5 and 6 could be instigated with further analysis taking place, during and following the training programme. Data collected on the

individual's swimming stroke technique could be established to assess whether there are changes in stroke technique and other biomechanical factors as a result of the core training programme. For example, does the swimming stroke effectiveness change (stroke rate and stroke length) and does the start technique change due to the improvements in core ability. It may be that the improvements observed in 50 m time were achieved during the dive, the tumble turn, during the free swimming with changes in technique effectiveness or from a combination of these variables. Further analysis would enable more precise conclusions to be made regarding how the core training improves sporting performance and specifically which areas of the sporting performance are improved.

The thesis has implemented new methods of analysing data collected from the core musculature and during a range of sporting performance tests. For example, the introduction of using the ARV EMG variable for a more in-depth understanding of the demands on the core musculature activation during different core training exercises. Also new methods for reporting data collected on the highly trained athlete when small changes in performance are observed have been outlined. Traditional statistical significance tests are more likely to find the changes in scores from highly trained athletes non-significant due to the magnitude of the changes observed being small and due to the, sometimes large, standard deviations observed in such a population when using data collection methods such as sEMG. Therefore methods such as using the 95% limits of agreement and magnitude-based inferences of the data (the likelihood of a beneficial, trivial, harmful effect on performance) have been found to be more useful in the subsequent analysis of results [223, 299]. Future research needs to report findings using these methods rather than the traditional statistical significance levels which may result in misleading conclusions.

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## **Appendix A – Sports Medicine Journal Published paper**

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This is the article which was accepted for publication into the Sports Medicine Journal in 2008. It forms part of the literature review which is written up in Chapter 1 of the current thesis.

## **Appendix B – Journal of Electromyography and Kinesiology Published Paper**

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This is the article which was accepted for publication into the Journal of Electromyography and Kinesiology in 2011. It forms the repeatability data collection and analysis which is written up in Chapter 3 of the current thesis.

## **Appendix C – Core Training Programme Medical Questionnaire**

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## **Appendix D – Core Training Programme Participant Information Sheet**

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## **Appendix E – Core Training Programme Subject Informed Consent Form**

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## **Appendix F – Example Teesside University Ethics Form**

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**Appendix G – Absolute sEMG muscle activations  
(Peak and ARV EMG) during the MVIC and core  
exercises performed during the 6 week (Chapter 5)  
and 12 week (Chapter 6) intervention programmes**

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