EMG Measurement of the fatigability of paraspinal muscles of patients with adolescent idiopathic scoliosis

By

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Abstract

This thesis aimed to address two separate questions, 1) Are current exercise approaches to scoliosis based on a strong foundation in the literature? And 2) Do the paraspinal muscles of patients with adolescent idiopathic scoliosis (AIS) differ in endurance properties from controls? The first question was answered through a systematic review of the literature investigating functional muscle properties of the paraspinal muscles and reported a summary of findings as well as recommendations for future research. Results were reported according to 6 objectives: 1) To describe differences in paraspinal muscle functional properties in patients with AIS compared to healthy controls. 2) To describe differences in paraspinal muscle functional properties between concave and convex sides of spinal curvatures in patients with AIS compared to healthy controls. 3) To describe differences in paraspinal muscle functional properties within patients with AIS between concave/convex sides at the end vertebrae and apical vertebra of the spinal curves. 4) To describe differences in paraspinal muscle properties in patients with AIS with different curve types. 5) To describe the correlation between paraspinal muscle properties of patients with AIS with different curve characteristics (Cobb angle, apical translation, and progression). 6) To determine the ability of paraspinal muscle properties to predict curve progression in patients with AIS. The systematic review demonstrated a large amount of variation in methodology and heterogeneity in all outcomes. Some limited evidence supported findings, such as higher activity on the convex side of the curve, overall weakness in patients with scoliosis, and correlations between EMG activity at the lower end vertebrae and progression and prolonged latency and progression. However, due to poor reporting of methodology, small sample sizes, and heterogeneous samples, we concluded that not enough evidence exists to support many of the findings. Only one study was found on muscular endurance. We suggested

that future rigorous research should include sample sizes large enough to allow for sufficient power to detect differences, narrow ranges of Cobb angles, and have a sample size big enough to allow curve type subgroup comparisons. Based on this review, we concluded that while a number of exercise methodologies exist, these approaches are not yet based on a rationale related to knowledge of the muscle imbalances specific to idiopathic scoliosis. Exercise prescription may benefit from a stronger base of knowledge on muscle impairments in scoliosis.

The second question was addressed through a matched case-control study. The endurance properties of the paraspinal muscles were compared between patients with AIS and controls. Subjects performed 6 side planks (3 on each side) as well as a Sorensen test. Subjects held each trial for as long as they could. EMG electrodes were placed at the apex, upper (UEV) and lower (LEV) end vertebrae, as well as, on the medial deltoid on each shoulder. Controls were matched for gender, age, BMI and EMG electrode placement sites. Groups were compared based on their task length as well as the slope of the median frequency of the EMG signal. No significant interactions involving groups were found, however, both groups performed better on convex (mostly right) sided planks than left sided planks. For the side planks, more fatigability was observed using EMG in the control group suggesting a possible difference in muscle activation strategy in patients with scoliosis. Only 14 subjects were tested for the Sorensen task and no group interactions were significant. Significantly more fatigue was noted at the LEV than at the UEV in both groups during the Sorensen test and at the UEV during side planks. This pilot study did not identify significant differences in endurance properties between the scoliosis and control groups. This inability to detect some possibly clinically important differences (effect sizes >0.4-0.66) is partly due to a small sample size, as well as heterogeneity of curve types and severities in our sample. However, this study provides pilot data to guide future research in terms of task selection, sample size estimation, and subject recruitment. This thesis demonstrates that more research is needed on paraspinal muscle impairments in patients with scoliosis to confirm the limited evidence of an association between such impairments and risk of progression.

Preface

This thesis is an original work by Alan Richter. No part of this thesis has yet been previously published. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name “Trunk muscle fatigue and scoliosis”, No. Pro00031256, 02/12/2013.

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List of Symbols and Abbreviations

AIS – Adolescent Idiopathic Scoliosis
Ctrl – Control group
D-PMT – Differences in Premotor time
EMG - Electromyography
Hz - Hertz
IIS – Infantile Idiopathic Scoliosis
IS – Idiopathic Scoliosis
JIS – Juvenile Idiopathic Scoliosis
Lbs - pounds
MF – Median Frequency
MVC – Maximal voluntary contraction
MVIC – Maximal voluntary Isometric contraction
Nm- Newton meters (force)
PMT – Premotor time
Pts – Patients
Reps - Repetitions
RMS – Root mean square
ROM – Range of Motion
Scoli – Overall Scoliosis group
Scoli<x - Cobb angle descriptor
Scolifastprog - fast progressive Scoliosis
Scoli-Nprog - Non progressive Scoliosis
Scolipre-op - preoperative Scoliosis
Scoli-prog - Progressive Scoliosis
Scolislowprog - slow progressive Scoliosis
Sec - Second
sEMG – Surface electromyography
yo= Year old

Chapter 1:
Introduction to Adolescent Idiopathic Scoliosis

Idiopathic Scoliosis

Idiopathic Scoliosis is a deformity of the spine of unknown etiology that occurs in 3 planes: a curve in the frontal plane, hypo or hyper kyphosis in the sagittal plane and rotation in the transverse plane.[2] Idiopathic scoliosis makes up 80-85% of all scoliosis cases in the United States.[3] Other types of scoliosis include congenital scoliosis and neuromuscular scoliosis resulting from neuromuscular or syndromic conditions such as spina bifida or cerebral palsy[3]. Idiopathic scoliosis is subdivided into three age-related categories based on peak periods of onset.[4] A curve detected before the age of three is labeled 'Infantile Idiopathic Scoliosis' (IIS), a curve detected between the ages of five and eight is labeled 'Juvenile Idiopathic Scoliosis' and a curve detected from age ten until the end of growth is labeled 'Adolescent Idiopathic Scoliosis' (AIS).[4] These labels are loosely used, however, as a diagnosis is applied based on the patients age at detection rather than at onset. A curve that arose in the Juvenile age may not be detected until the subject is in the age range to be labeled as an AIS patient. As such there may be an overlap between cases of AIS and JIS when reporting on the prevalence and prognosis of these types of idiopathic scoliosis.

Prevalence

Eighty percent of cases of idiopathic scoliosis fall into the AIS category,[5] and thus, despite some overlap with JIS cases, AIS is the most prevalent type of idiopathic scoliosis. The prevalence rate of AIS ranges from 2 to 9% of the population[2,6], however these rates are very much dependent on curve size cutoffs used for diagnosis. In North America a curvature of 10° is labeled as scoliosis. At this cutoff the prevalence rate is 2-2.5%.[2] The diagnosis of idiopathic scoliosis is one of exclusion and is given once vertebral malformation, neurological disorders, and syndromic disorders have been ruled out.[2]

Etiology

As implied by its name, the etiology of AIS is unclear. There is a strong genetic component to AIS; however, no specific gene has been pinpointed. Metabolic factors such as an abnormal metabolism of melatonin have also been suggested, however, no specific abnormalities have been consistently identified in the literature. Results of studies involving pinealectomies are mixed and other diseases in which melatonin metabolism is affected do not result in scoliosis.[2] Links have also been established between the emergence of small curves and elevated levels of calmodulin, however, the connection between these two factors has not been fully understood.[2,7]

Abnormalities within the paraspinal muscles themselves have been implicated as decreased proportions of type I fibres have been identified as well as impaired function of calcium pumps within the muscles[8], however, no evidence exists to claim these as a cause or a symptom of scoliosis.[2] A variety of other etiology hypotheses and evidence have been presented in the literature[9-11] and since no clear consensus has been reached regarding etiology, this type of scoliosis continues to be labeled as idiopathic.

Measurement

The standard measure for spinal curvature is the Cobb Angle. The Cobb angle is measured by locating the top endplate of the top vertebrae of the curve, which is identified as the vertebrae having a superior surface most tilted towards the curve concavity. The bottom endplate of the bottom vertebra is then located by finding the lowest vertebrae having an inferior surface most tilted towards the concavity. Lines are drawn along the top and bottom of these endplates on the radiographic film. Once these lines are drawn, intersecting perpendicular lines are drawn. The Cobb angle is the resulting angle formed by the perpendicular lines (Fig 1.1).[1]

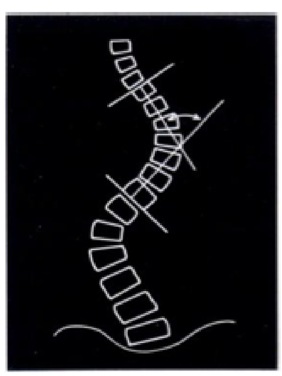

Fig 1.1 Measurement of the Cobb angle[1]

Progression

While the Cobb angle will increase over the lifespan of a person with severe scoliosis (roughly 0.76°-1°/year after skeletal maturity in curves >50°)[12] there are periods when the curve is at a higher risk of progression. Risks factors for progression are: lower age at diagnosis, pre-menarchal status, and a position of the curve apex in the thoracic spine.[13] Curve magnitude is also a factor in curve progression. The larger the Cobb angle, the higher the risk of progression. Curves less than or equal to 30° are at a lower risk of progression, whereas curves greater than 30° are at a higher risk of progression (~30%).[14] This risk of progression increases greatly as the curve further increases in magnitude. Seventy percent of Curves >50° progress at a rate of 0.76-1°/year.[12] In addition, apical vertebrae with 30% rotation and Mehta angle of 20° or more (rib-vertebral angle difference) are at a higher risk of progression.[13] Generally negative consequences of scoliosis begin to manifest themselves when curves exceed 40-50°[2,15]

Skeletal maturity is a strong predictor of the potential for curve progression. The farther patients are from skeletal maturity the more at-risk they are for progression. The most commonly used sign to determine skeletal maturity is the Risser sign which divides patients into 5 categories based on the degree of ossification of the illium (0 representing no ossification and a 5 being full ossification). It generally takes two years to reach full ossification from the time ossification begins.[16] Sanders et al proposed an approach dividing skeletal maturity into 8 stages. Stage 1 is the juvenile slow stage in which digital epiphyses of the hand are not yet covered. Stage 2 is the preadolescent slow stage in which the digital epiphyses are covered. Stage 3 is the early adolescent rapid stage in which the second through fifth epiphyses are larger than their metaphyses. Stage 4 is the adolescent rapid late stage in which any distal phalangeal physis is beginning to close. Stage 5 is the adolescent steady early stage in which all distal physes are closed but all others are open. Stage 6 is the late adolescent steady stage in which middle or proximal phalanges are closing. Stage 7 is the early mature stage where only the distal radial physis is open. Stage 8 is the final stage in which the distal radial physis is completely closed.[17,18] Thus skeletal maturity can be determined using radiographs of the hand (Sanders) or pelvis (Risser).[16] Sanders et al found that the Tanner-Whitehouse III RUS Scale strongly predicts the curve acceleration phase (R value of 0.93 $p<0.001$).[17] The juvenile slow and preadolescent slow phases were observed 6 months before the curve acceleration phase. The rapid adolescent phase of growth described in the Tanner-Whitehouse III RUS scale began within 6 months of the curve acceleration phase.[17]

Lonstein and Carlson identified an algorithm to determine the risk of progression using chronological age, the Cobb angle, and the Risser sign. They demonstrated that a progression risk factor can be determined using the formula in figure 1.2 and converted to a percent incidence estimated given the risk factors (fig. 1.2).[19]

$$progression\ factor = \frac{Cobb\ angle - 3 \times Risser\ sign}{chronological\ age}$$

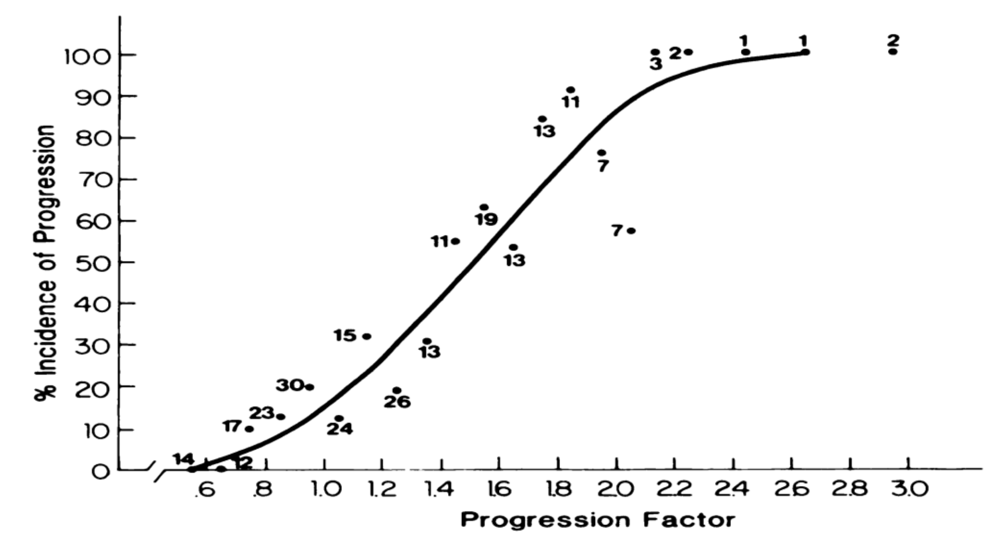

Fig 1.2 Lonstein & Carlson's equation to measure the potential for curve progression. The higher the progression factor, the greater probability of progression.[19]

Treatment of Adolescent Idiopathic Scoliosis

In North America, curves are typically observed until they reach 25-30°, after which a brace is prescribed.[2,20] If curves further progress to 45-50° a surgical intervention is generally recommended.[2,21] Physical therapy is occasionally advised in smaller, non-progressive curves, but little evidence exists in the literature to support such an intervention especially with regards to limiting curve progression.[2,22] However, while European approaches and recommendations for bracing and surgery are similar to North American guidelines, exercises are often recommended in Europe during periods corresponding to the observation and bracing stages of management in North America.[23]

Bracing

The general goal of bracing is to prevent progression of the curve until skeletal maturity is reached.[21] Bracing is the most common non-operative, preventative treatment for idiopathic scoliosis in North America.[21] The most common brace in North America is a rigid thoracolumbosacral orthosis (TLSO) with the goal of stopping the progression of spinal misalignment through external pressure. Practitioners differ in opinion as to the quality of the evidence in favor of bracing.[2] In a recent RCT study of 242 subjects undergoing either bracing or observation, Weinstein et al. noted a significantly decreased incidence of progression in high-risk curves in the braced group. The odds ratio of successful treatment was 1.93 (1.08-3.46). Brace wearing demonstrated a strong dose-response relationship, with longer hours of brace wearing being associated with a greater rate of success. The greatest rate of success was seen in brace-wearers for 17.7 hours a day or more however, bracing may be effective with just 13 hours of wear per day.[21] In contrast, a review by Weiss & Goodall stated the ideal brace wearing time to be 23 hours a day[15] and, in their meta-analysis, Rowe et al suggest that at least 18 hours of brace wearing is necessary.[24]

Surgical intervention

When curves progress to 45-50° surgery is recommended. The spine is fused and held with rods and pedicle screws inserted along the length of the curve through an incision in the back (posterior instrumentation). The primary goals of surgery are to stop progression, allow for maximal permanent correction, improve appearance by balancing the trunk, as well as decreasing both short and long-term complications from scoliosis such as pain and reduced respiratory function.[2] While reported neurological complications from surgery are low (0.49% from 2001-

2003 in patients aged 10-17)[25] surgery is a painful and uncomfortable procedure from which complications such as infection, pseudarthrosis and implant prominence can occur.[13]

Exercise approaches to treatment

While some research has been published exploring the efficacy of various exercise-based approaches to scoliosis management, the overall quality of the research is poor and little evidence exists to support it's use.[2,13,15,22,26,27] This lack of high quality research has kept the clinical use of exercise based physical therapy approaches to a minimum. While specific exercises differ among the many methods, the correction principles and the prescription parameters overlap. Some of the most frequently published approaches to Scoliosis-specific exercise-based management are discussed below.

1) The Schroth Method

Developed and popularized by Katrina Schroth, the primary goal of the Schroth method of exercise treatment is to develop the patients ability to maintain and self-correct their curve independent of visual or therapist feedback.[26] This goal is achieved by thorough patient education of how scoliosis affects each individual subject's spine and torso posture. The Schroth approach consists of scoliosis-specific exercises helping maintain correct posture in daily activities. Schroth exercises focus on endurance and control of postural muscles and aim to improve postural control by employing repetitive corrective movements with progressively less external feedback and passive support from trained therapists. The intensity of the Schroth method ranges from one to two visits a week to an intensive 4-week inpatient program with daily exercises for as many at 7 hours a day.

2) The Scientific Exercise Approach to Scoliosis (SEAS) Method

One of the primary goals of the SEAS method is increasing spinal stability while maintaining auto-correction. This is performed by having patients perform tasks that challenge proper postural alignment while autocorrecting their spinal positioning. Movements are held for 10 seconds. The SEAS method suggests that spinal collapse is related to the inability of the surrounding musculature to maintain spinal alignment against gravity leading, in turn, to skeletal deformity.[28] Thus, muscular activation is a priority in realigning the curve. SEAS also employs in-brace exercises to overcome the side-effects of brace wearing such as the possibility of muscle wasting and breathing impairments. [26]

3) The Dobomed Method

The Dobomed method was introduced in 1979. It focuses on management of the spinal deformity as well as respiratory impairment. The corrective movements focus on spinal flexion (kyphosis) and derotation in the thoracic region. The exercise protocol initially uses many exercises in the quadruped position in an attempt to restore and maintain the vertebrae to their neutral position.[26] Dobomed is administered in a 3-week inpatient setting where patients are monitored and perform exercises daily. After the three weeks they continue the exercises in an outpatient setting.

4) Side Shift & Hitch exercise

The side shift exercise was introduced in 1985. In involves a side shift of the trunk to the concavity of the curve, holding for 10 seconds and returning to the original stance. This movement is repeated 30 times per day. The hitch exercise is used as a treatment for the lumbar curve. Patients lift the heel on the convex side of the curve with the hip and knee straight. This is held for 10 seconds and repeated 30 times per day. The hitch shift exercise is used for double curves in which a combination of the above movements in held for 10 seconds and repeated 30 times per day. This method is recommended in or out of brace.[26]

The physiological mechanisms by which the previous exercise approaches may correct curves are not clearly detailed in publications on Schroth,[22,26] Integrated scoliosis rehabilitation,[29] Dobomed,[26] Side-shift,[30] or on the Scientific Exercise Approach to Scoliosis.[22,26]

Muscle Characteristics

Paraspinal postural muscles are important in maintaining spinal alignment and thus, a deficit in the physiological properties of these muscles could affect the ability of these muscles to maintain proper spinal alignment potentially leading to the collapse of the spinal column.

The Anatomy of Paraspinal Muscles

The deep muscles running alongside the spine are numerous with a variety of origins and insertion points as well as overlap. There are three categories of muscle groupings used to classify spinal muscles, the erector spinae, transversospinalis, and quadratus lumborum muscles.[31]

Erector Spinae- The erector spinae group of muscles is subdivided into three subgroups, known as the illiocostalis group, the longissimus group, and the spinalis group. The three groups flank the vertebral column, with the illiocostalis group located most laterally, the longisimmus group more medially and the spinalis group most medially placed of the three groups. All three groups are responsible for vertebral and neck extension as well as maintenance of posture.

Transversospinalis - This group is subdivided into five categories. The interspinales muscles are responsible for vertebral extension and connect the spinous process of adjacent vertebrae. The intertransversarii are involved in lateral flexion and connect the transverse processes of adjacent vertebrae of each side of the spine. The multifidus muscles are involved in vertebral extension (if contracting bilaterally) as well as rotation (unilaterally) and side bending (unilaterally). The rotatores are also involved in extension and rotation. The final group is the semispinales muscles which are involved in extension of the spinal column and neck as well as lateral flexion and rotation of the neck.

Quadratus Lumborum - This group is involved in the extension and ipsilateral lateral flexion of the lumbar spinal vertebrae.

Interestingly, research does not document adequately how patients with scoliosis differ in terms of paraspinal muscle properties from healthy controls and between curve type and severity subgroups. Documenting such differences is important as they may affect the patient's ability to maintain spinal alignment and stability as well as provide a rationale for selecting specific types and dosages of exercises. Such an understanding is needed to determine appropriate exercise goals, refine the exercises themselves as well as identify important outcomes for assessing their effectiveness.

When studying muscle properties, a number of outcomes are important in measuring function. Strength is the ability of a muscle group to exert force against an object.[32] Flexibility represents the absolute range of motion in a joint or series of joints.[32] Power is defined as the speed at which force can be produced.[32] Endurance is defined as the ability of a muscle or series of muscles to repeatedly exert force against resistance.[32] High performance in these regards represents good overall muscle function.[32]

Endurance is an important outcome when studying spinal musculature and scoliosis. These muscles need to have good endurance properties, as they must constantly maintain spinal alignment during daily activities. Deficiencies in type I fibres (the fibre type necessary to maintain sustained contractions) have been identified in those with scoliosis and as such may affect the ability of those muscles to sustain correct posture.[8] Postural control indeed requires long, low intensity contractions from postural muscles. Dejanovic et al, consistent with this observation, suggest that endurance properties are a better indicator of spinal stability than strength.[33] further highlighting the importance of studying this outcome.

While the aforementioned approaches to exercise, based on our review of how exercises are prescribed, utilize exercise approaches which encourage the improvement of endurance properties (using long holds, static contractions, and multiple repetitions), they do not explicitly suggest that improving this muscle property is a treatment objective. Further, the authors do not justify prescription of exercises at doses likely to improve endurance with an understanding of whether endurance deficiencies exist, and if they do, how they manifest themselves.

Thesis organization

This chapter has provided the reader with an overview of the literature on scoliosis; it's etiology, diagnosis, prognosis, and background on paraspinal musculature adjacent to the spine. This introduction provides the context for the studies included in this master program. A number of methods that can be used to determine the presence of deficits in muscle properties in patients with AIS were presented such as EMG, ultrasound, and strength. Documenting such deficits may provide a rationale for studying and improving exercises prescription parameters when aiming to control curve progression in AIS. The next chapter will therefore systematically review the literature for various methods of assessing functional muscle properties; review the quality of the literature; and determine if differences exist between curve type, severity, and healthy controls. The following chapter will then proceed to report the rationale, methodology and results of a study performed to examine the endurance properties of paraspinal muscles measured through EMG at different levels relative to the curves in patients with AIS and comparing them to controls. This thesis will then conclude with a discussion chapter highlighting the significance of our findings and recommendations for future research.

Chapter 2:
The functional properties of paraspinal muscles in adolescents with idiopathic scoliosis: A systematic review of the literature

Richter, A.; Parent, E.

Abstract

Introduction: Current approaches to scoliosis management in North America consist of observation, bracing, and surgery. Some exercise-based approaches exist; however, it is unclear whether these approaches are based on scientific findings in the literature regarding trunk muscle deficits in scoliosis. The aims of this study were to systematically review the literature to understand the functional muscular properties of paraspinal muscles in AIS to determine: 1) differences in functional outcomes between patients with AIS and controls, 2) differences in functional outcomes between sides (concave and convex) between patients and controls 3) differences between concave and convex sides as well as levels in subjects with AIS, 4) differences in functional outcomes between different curve types. 5) Associations between functional outcomes and curve characteristics, and 6) associations between functional characteristics and progression

Methods: A search was conducted in EMBASE, MEDLINE, SPORTdiscus, CINAHL, SCOPUS, and Web of Science, for keywords describing functional properties of paraspinal muscles and measurement tools including: scoliosis, spinal deformity, spinal muscles, erector, rotatores, longissimus, spinalis, illiocostalis, forse, strength, endurance, fatigability, and muscle fatigue. Two reviewers independently reviewed abstracts and then full-text articles to determine if they met selection criteria. Two reviewers used an extraction form to extract information and appraise the quality during full text review. Levels of evidence were determined for summarized results for each of the 6 objectives.

Results: Our search yielded 316 unique records. Abstract selection inter-reviewer agreement was Kappa = 0.73. Full text review was done for 48 papers and 24 were included. Inter-reviewer Kappa for the full text review was 0.77. A large amount of heterogeneity was in sample studied and assessment methodology. Quality appraisal revealed that no study met a minimum of 50% of the relevant quality criteria. Studies recruited consistently low sample sizes and samples were largely heterogeneous. Limited evidence was noted supporting, prolonged bilateral EMG activation during gait between AIS and controls; elevated homolateral:heterolateral activity ratios during side-bending; overall weakness in those with scoliosis compared to controls; no asymmetry in normalized muscle activity during submaximal isometric contractions; prolonged latencies on the side of the spine opposite of the curve and bilaterally in response to an unloading reflex; strength & muscle volume differences are most commonly pronounced in double curves; Axial rotation of the UEV is correlated with a high convex:concave activity ratio at the LEV; no correlation between latency and curve severity, but a correlation between latency and progression and higher EMG ratios convex:concave and progression, this is pronounced in sitting positions.

Conclusions: Evidence is limited on most objectives due to low quality evidence and lack of research about muscle impairments in scoliosis. Current exercise-based interventions cannot yet be based on a strong understanding of muscle impairments in scoliosis. Research is needed using large, homogenous samples allowing for a comparison between curve types and examining relation to the risk of progression. While many exercise-based programs focus on addressing endurance deficits using high repetitions and long holds, no studies were found on endurance deficits in AIS.

Introduction

Scoliosis is a three-dimensional deformity of the spine occurring in the frontal, transverse, and sagittal planes. Adolescent Idiopathic Scoliosis (AIS) describes patients with an onset of scoliosis from age 10 until the end of growth.[13] The magnitude of the curve is determined by the Cobb angle obtained from two lines drawn on a radiograph, one from the top of the highest most tilted vertebrae and one from the lowest most tilted vertebrae of the curve being measured. Intersecting perpendicular lines emanating from these lines are then drawn and the Cobb angle is the angle between the intersections of these lines.[1]

The etiology of Scoliosis is unclear; while there is a genetic component to scoliosis there is no clear pattern of inheritance.[13] One of the hypotheses is that the deformity may be due to muscular deficiencies and imbalances,[2] however, it is unclear whether the deformity is caused by a preexisting muscle imbalance or whether a muscular imbalance is caused by a preexisting deformity.[2]

Due to the limited knowledge on etiology, scoliosis management emphasizes the prevention of curve progression rather than curve reduction. Curves are 'observed' for progression until they reach 25-30° after which a protocol of bracing is recommended.[13,20] Curves 30° or more are at a higher risk of progression throughout adulthood while smaller curves usually do not progress[14] and therefore a brace is prescribed to prevent such progression. If curves reach 45-50° a surgical intervention is often recommended.[13]

The literature demonstrates that a number of muscular deficits accompany the spinal deformity in AIS. Muscles in the curve concavity have been found to be shorter than the muscles running along the convex side of the curve. Fiber type imbalances have been noted on either side of the curve, with a higher proportion of type I, (endurance) fibers on the side of the curve convexity in scoliosis patients and a higher number of type II (fast fatigable) fibers on both sides of the curve when compared to controls.[8] Studies have also demonstrated higher EMG activity on the convex side of the curve when compared to the concave.[34]

While imbalances in muscle characteristics such as strength, fiber type, and activity differences have been documented in the deformed spine, no exercise-based approach is routinely used nor recommended in North America.[2] This limited use of exercises is due in part to the poor quality of the available research investigating the effect of various exercise-based approaches even though the evidence appears promising.[22,26] Scoliosis-specific, exercise-based approaches aim to restore a balanced posture and prevent curvature progression. Scoliosis-specific approaches use exercises and dosages consistent with improving balance in muscle characteristics across the spine and improve the endurance properties of paraspinal muscles. However, none of these approaches have stated the rationale for their approaches in light of current research into the physiological properties of paraspinal muscles surrounding the deformed spine. [26]

In contrast, studies on low back pain have demonstrated the presence of muscle imbalance and the potential for therapeutic exercises to help restore balance and function to paraspinal muscles.[35] Studies have demonstrated improvement in endurance properties as well as the ability to activate stabilizer muscles through the use of therapeutic exercises.[36,37] Documenting the presence of deficits in paraspinal muscle characteristics and the possibility of correcting deficits through exercises are important if a rationale for exercise interventions in scoliosis is to be developed. The current exercise programs for scoliosis that attempt to correct posture by targeting paraspinal musculature were not specifically developed to address deficits in muscle characteristics. A review of the literature is needed on postural muscle deficits present in AIS.

There are numerous ways to document muscle function. Strength measurements are a useful measure of function and commonly obtained using dynamometry.[38] Electromyography (EMG) is a useful and versatile tool that can be used to measure muscle latency, activity, as well as endurance.[39] Imaging can be used to measure muscle thickness at rest and during contractions. Many of these tools have been employed in studies of muscle function in AIS. There are reviews of the literature reporting promising effects of exercise-based interventions on outcomes other than muscle characteristics.[22,26,27] However, to provide a rationale for exercise based approaches and possibly inform how to improve exercise prescription, the literature surrounding various muscular imbalances in AIS that could be targeted by exercises needs to be studied and reviewed as well.

Objectives

The general study objective was to systematically review the existing literature exploring functional muscle properties such as activity, latency, strength, and fatigability documented using EMG, imaging and dynamometry in people with Adolescent Idiopathic Scoliosis (AIS). The specific aims, if literature was sufficiently rich to address them, were:

1) To describe differences in paraspinal muscle functional properties in patients with AIS compared to healthy controls.
2) To describe differences in paraspinal muscle functional properties between concave and convex sides of spinal curvatures in patients with AIS compared to healthy controls
3) To describe differences in paraspinal muscle functional properties within patients with AIS between concave/convex sides at the end vertebrae and apical vertebrae of the spinal curves
4) To describe differences in paraspinal muscle properties in patients with AIS with different curve types
5) To describe the correlation between paraspinal muscle properties of patients with AIS with different curve characteristics (cobb angle, apical translation, and progression)
6) To determine the ability of paraspinal muscle properties to predict curve progression in patients with AIS.

Hypothesis

As a result of our a priori knowledge of the literature, we expected this review to find studies highlighting the effects of the aforementioned imbalances. We hypothesized that we would find:

1) Differences in overall EMG activity, endurance, latency, and strength between patients with AIS and healthy controls. Higher EMG activity, lower endurance, longer latencies and decreased strength in the paraspinals is expected in the AIS group.
2) Differences in the overall EMG activity, endurance, latency, and strength between convex and concave sides of the curve in patients with AIS vs healthy controls. With greater balance of these outcomes across the spine in the healthy group compared to the AIS group.
3) Differences in the overall EMG activity, endurance, latency, and strength between convex and concave sides of the curve as well as between levels of the curve in patients with AIS. We expected greater activity and latency times on the convex side of the curve, and shorter latency

times and lower strength on the concave side of the curve. Higher EMG activity was expected at the endpoints of the deformity compared to the apex.

4) Differences in the overall EMG activity, endurance, latency, and strength between different curve types and severity with greater imbalances in the musculature surrounding more severe curves and different patterns of imbalance in multiple curves compared to single curves.

5) Significant correlations between higher muscle activity, endurance, latency and strength and Cobb angle, apical translation, and progression.

6) We expected the muscle activity and strength to be able to predict curve progression in AIS.

Methods

A comprehensive literature search was conducted in April 2013 in EMBASE (1974 – April 2013), MEDLINE (1946 to April 2013), SPORTdiscus (1975 – April 2013), CINAHL (1937 – April 2013) SCOPUS, and Web of science (1899 – April 2013) for a set of predetermined indexed and free text keyword terms describing various functional properties and measurement tools for paraspinal muscles in AIS. No date limits were applied to the search.

The keywords included in the search were: Scoliosis, spinal deformity, spinal muscles, spinal musculature, erector, rotatores, longissimus, spinalis, illiocostalis, force, strength, endurance, fatigability, and muscle fatigue.

The full search strategies for each database were developed with the help of a librarian and can be found in appendix A

Inclusion criteria

Studies were included if the patient population had AIS, were aged 10-18 years old (with at least 75% within the age bracket). Included studies focused on paraspinal stabilizer muscles, functional muscle properties, and conservative management of scoliosis. Studies were included in the following languages: English, Hebrew, and French based on the fluencies of the reviewers. Randomized controlled trials, cohort studies, case-control, case series, and prospective controlled studies were included.

Exclusion Criteria

Studies were excluded if their main outcome was bio molecular analysis as opposed to functional parameters, if the patient population was post-surgical, had any other type of scoliosis diagnosis (such as congenital scoliosis), or had scoliosis due to a traumatic incident. Case studies, studies involving less than 10 subjects, or studies that were non-experimental in nature were excluded.

Screening Process

Once the search was completed, the reference lists from each database were exported to Refworks. Duplicates were removed using the duplicate removal function in Refworks and two evaluators assessed the list of titles and abstracts to determine if they met inclusion criteria. Articles selected by either evaluator were compiled into a final list to be retrieved for full text review. If disagreement occurred the full texts of the articles were retrieved for further clarification. Full texts of the articles were obtained. Identifying information (title and author) were removed by an independent research assistant, and both reviewers used a standard extraction form to review the blinded full-text version of the papers.

Extraction form

The extraction form was divided into a number of sections. A checklist of study selection criteria was completed to confirm study eligibility before extraction took place. Study design, objectives, subject inclusion or exclusion criteria, and follow up details were then recorded. Characteristics of each subgroup were extracted including sample size, maturity indicators and curve characteristics. The exercise task used to appraise muscle function, sets/reps, measurement tool, and outcome variables were recorded as well as any information regarding normative data referred to in the paper.

Study quality was then assessed. Questions relevant to the present study based on COSMIN criteria[40] were used including questions such as justification of sample size, blinding of researchers, and procedure replication (Table 1). Each study was given a score for each item based on the COSMIN criteria relevant to each study. The quality of reporting of EMG study was assessed using the International Society of Electrophysiology and Kinesiology (ISEK) checklist (Table 2).[41]

Results of differences between groups, sides and levels were also extracted along with the statistical methods used in difference testing. Estimates of associations and variables tested were also extracted along with the statistical methods used to estimate associations. An extraction form was prepared based on those used in similar reviews and modified to suit the needs of this review.[42] The first reviewer compared extractions performed by both reviewers and consensus discussions were used to resolve differences.

Reviewer agreement

Agreement between reviewers was determined by comparing the include/exclude recommendations for the title/abstract and the full-text reviews as well as the rating of the quality appraisal criteria. A Kappa statistic was calculated to determine a coefficient of agreement between reviewers and the percent agreement was calculated.

Data Summaries

From the extracted data, summary tables were prepared. A table was prepared to describe the groups and subgroups as well as inclusion & exclusion criteria of the respective papers. Another table reports the EMG reporting quality as per the ISEK checklist. The scoring criteria are listed in table 2. Another table summarizing the quality of the papers as determined by the COSMIN criteria was prepared. Six different tables were assembled summarizing study results for each of the six different objectives.

The summary paragraphs for each objective were divided based on measurement tools and methodology. For each paragraph, results were reported in alphabetical order. The measurement tools found in the literature and relevant to this review were dynamometry, imaging, and EMG methodologies. These tools were subdivided into outcomes variables. Imaging was restricted to muscle thickness measurement, and EMG-related outcomes were divided into latency, fatigue measurement, and activity.

No meta-analysis was planned in the present study because of the anticipated heterogeneity in research methodologies. The level of evidence for conclusions related to each objective was therefore assessed using the criteria adopted in previous prognostic research.[43] The level of evidence (strong, moderate, limited, no, and conflicting evidence) was classified based on the quality appraisal of the studies and the consistency of the research findings (Table 3). A high quality study in the present review was defined as a study for which >50% of quality criteria deemed applicable were met. If $\geq$75% of all the included studies reported a factor that showed a uniform association in the same direction, the evidence was considered consistent.[43]

Results

The PRISMA flowchart summarizing this study's selection strategy and results are presented in figure 2.1. Web of Science and Scopus returned the most hits. The Kappa coefficient representing reviewer agreement during abstract review was 0.725. After abstract review a total of 48 articles were selected for full-text review. A total of 20 articles were included after the full-text review stage. Kappa coefficient of agreement for full text inclusion before consensus discussion was 0.768. Full EMG methodologies can be found in table 4. The samples and subgroups examined in each of the studies are described in table 5.

The study quality assessments can be seen in table 12. Overall study quality was poor as no studies met greater than 50% of the applicable COSMIN criteria. Out of 25 criteria, 14 criteria were met by 5 or less studies. These criteria were whether a representative sample and/or examiners was used (20% & 4% of studies respectively); whether examiners were blinded to clinical information or other task related information (0% for all four examiner blinding related criteria); whether consecutive sample of patients were enrolled (20% of studies); what percentage of missing data was reported (12% of studies) and how this data was handled (12% of studies).

The most commonly met quality criteria were: adequate study design (met by 88% of studies); reporting demographic characteristics (met by 64% of studies); and the ability to replicate the testing methodology (met by 60% of studies). The results of EMG reporting analysis based on the ISEK criteria can be found in table 13. Criteria that were not reported by any study were excluded from the list of items. Criteria that were not listed in this table were: amplification type, impedance, & crosstalk. Only one study reached 80% EMG reporting quality. Six studies out of 15 reached 60% quality, and eleven out of fifteen reached 50% quality.

Findings related to the six objectives

Objective 1: To describe differences in paraspinal muscle functional properties in patients with AIS compared to healthy controls.

Eight papers summarizing 8 unique studies addressed objective 1 (Table 6). Six studies employed EMG methodologies and four employed strength testing through either dynamometry or manual muscle testing.

EMG Methodologies

Those with fast progressive scoliosis demonstrated a longer latency than slow progressive scoliosis, pelvic tilt scoliosis and controls and less unloading reflex cycles at T8.[44] Subjects with AIS demonstrated higher activity measured using RMS on the heterolateral side of the spine during side bending compared to controls. These increases in heterolateral to homolateral ratios in patients compared to controls were more pronounced in left bending tasks than in right bending specifically at T10, L1, and L3 (Apical sites) and abdominal sites.[45] During a lateral step test, among 4 EMG and 10 ground reaction force discriminating variables considered, the right and left erector spinae muscles, right gluteus maximus, as well as the latero-lateral ground reaction force had stronger correlations with the discriminating function correctly classifying 78% of patients with AIS and controls.[46] In addition, one study reported a significant difference in RMS of muscle activity across the spine between patients and controls.[47] Muscle activity duration during gait was significantly prolonged in patients with AIS than controls for the Erector spinae & Quadratus lumborum.[48,49] In contrast, Oliveira et al found no difference in overall normalized RMS between patients and controls during contraction in extension at 40, 60 and 80% MVIC.[50]

Due to the heterogeneity of study methodology, evidence is limited (one low quality study for each variable) suggesting prolonged EMG activation during gait, increased heterolateral to homolateral activity ratios during side bending tasks, unique EMG response during lateral step tests and the absence of a difference during extension contractions at different intensity of contractions in patients with AIS compared to controls. There were no EMG studies comparing fatigability in patients with AIS to controls.

Dynamometry

Decreased bilateral and unilateral strength measurements were noted for tests of arm/shoulder muscles in patients with scoliosis compared to healthy controls using tests suggested to be challenging for the transverse spinal musculature.[47] Overall patients with AIS demonstrated marked deficiencies in isokinetic torso extension and flexion peak torque, total work at 90^{o}/sec and more significant at 120^{o}/sec when compared to controls.[51] In contrast, no differences in maximum voluntary isometric contraction torque in extension was observed by deOliveira et al between patients and controls.[50] Patients had lower flexion mean power than

CTRL at both 90 and 120^{O}/sec. Patients with AIS also has slower flexion acceleration times and faster deceleration times in flexion and extension at both 60 and 90^{O}/sec speeds.[51] In contrast, patients with AIS exhibited shorter times to extension at both speed and to flexion peak torque at 90^{o}/sec.[51]

Manual muscle testing

Mahaudens et al. used manual muscle testing but found no differences in median scores between groups for erector spinae and both gluteus muscles. However, a strength deficit was noted in the abdominal muscles of the scoliosis group.[48]

Three out of four studies of muscle strength found consistent deficiencies in muscular strength of the abdominal or paraspinal muscles in AIS. However, due to heterogeneous methodologies (task, outcome, and measurement site) limited evidence exists to support the conclusion that subjects with AIS demonstrate overall weakness in trunk muscles when compared to controls.

Objective 2: Differences in functional properties convex:concave in AIS vs controls.

Four papers addressed objective two (Table 7). All four studies employed EMG methodologies.

EMG Methodologies

Dobosiewicz et al noted symmetrical reflex response in scoliosis and control groups, however, found prolonged latencies on the side opposite the curve in progressive scoliosis during unloading of either extremity.[44] Feipel et al measured the activity on the heterolateral and homolateral sides of the spine during various unilateral bending tasks and found larger activity at the T10, L1 and L3 sites on the heterolateral side of the curve (relative to the bending direction) during one-way side-bending. This asymmetric activity (heterolateral/ homolateral RMS ratio) was not as large during the same tasks in the control group.[45] In contrast, no differences were found in corresponding normalized muscle activities between controls and subjects with AIS during submaximal isometric spinal extension.[50] Nevertheless, significantly elevated activity was noted on the convex side of the spine only at L5 (not T8 or L2) during trunk extension only at 80% of MVIC (not 40 or 60%) in subjects with AIS. Similarly, controls had a significantly elevated RMS on the left side of the spine only at L5 during extension at 80% MVIC.[50]

Tsai et al did not statistically compare the magnitude of differences between sides observed in patients with scoliosis to differences observed in controls but tested separately in each group differences between sides during concentric and eccentric isokinetic extension contractions at 30 and 90°/sec.[52] They found no difference between sides in thoracic medial and lateral paraspinal muscles activations in both controls and patients with small curves. In contrast, the AIS group with a Cobb angle between 20-50° demonstrated elevated RMS in medial thoracic paraspinals on the non-dominant side during concentric (30 and 90°/sec) and eccentric torso extension contractions (at 90°/sec).[52] Controls had higher lumbar paraspinal activity on the dominant side during all tests. Both controls and patients with small curves had more lumbar medial paraspinal activity on the dominant side during the eccentric contraction at 90°/sec, and during concentric contraction at both speeds. Both groups had higher lumbar lateral paraspinal activity during concentric contraction at 90°/sec. In contrast, patients with larger scoliosis curves did not have significant differences in lumbar paraspinal activity between sides for any task.[52]

Limited evidence exists to support the conclusions that subjects with AIS exhibit the following compared to controls:

- Increased heterolateral activity during side-bending tasks,
- No differences in the amount of asymmetry in normalized muscles activity during submaximal isometric contractions
- Different patterns of asymmetry during isokinetic contractions of the paraspinals in patients, which are more important in patients with larger curves.
- Prolonged latencies on the side of the spine opposite the curve.

Objective 3: Differences in functional properties within AIS patients between sides and levels

This objective yielded the largest number of included studies with 12 relevant studies (Table 8) of which, 11 employed EMG methodologies, 2 addressed strength measurements, and one employed imaging methodologies.

EMG Methodologies

Alexander et al, using needle EMG in paraspinal muscles found muscles at the apex were generally silent bilaterally when subjects lay prone. Higher activity was observed on the convex side (2/3) or balanced (1/3) during standing.[53] Cheung et al reported findings in three studies in which the same subjects were partially used. They subdivided the curves of patients with AIS into progressive and non-progressive groups and found a higher asymmetry in activity overall in subjects with progressive AIS[54] and more pronounced convex/concave activity ratios at the upper and lower end vertebrae depending on whether the patients are tested lying supine, sitting or standing.[34,55] Non-progressive curves had higher ratios at the apex of the curve while ratios at the upper and lower end vertebrae were not consistently significantly elevated.[34,54,55] Only progressive curves demonstrated increased asymmetry at the LEV (dominant convex).[34,54,55] Gram et al tested the muscles in different positions including standing, sitting erect sitting, and writing. Higher activity on the convex side was noted in the multifidus but not the iliocostalis in all positions at L1 & L3. Significantly higher activity on the convex side was noted in the thoracic spine at T6 only during erect sitting.[56]

Mooney et al reported asymmetries in side-to-side paraspinal muscle activities without indicating the dominant side. Mooney et al also reported imbalances between paraspinal (lower) and oblique muscles activities (higher) on the weaker side but did not quantify the differences.[57] Dobosiewitz et al demonstrated a prolonged unloading reflex latency in the concave side of the curve during sudden unloading using a trapdoor platform tilting to either side in the progressive AIS group.[44] Feipel et al found greater RMS on the left side during right bending.[45] Similarly, in Shimode's work on EMG latency, they found D-PMT ratios significantly different from 0 at the apex and lower end vertebrae.[58]

Finally, no difference in duration of activation expressed as a percentage of the gait cycle for the erector spinae, quadratum lumborum or gluteus medius between the concave and convex side of the curve was noted in gait analysis.[48] Similarly, no difference in activation durations during gait were found within each of 3 curve severity categories.[49]

There is conflicting evidence to support the following observations:

- Higher activity on the convexity of the curve during postural task
- More pronounced activity on the convex side at the UEV, LEV and Apex of the curve.

- More pronounced activity on the convex side at the LEV only in progressive curves with only activity at the apex elevated in non-progressive curves.

Limited evidence exists to support the following findings in the research:

- Prolonged latency to unloading reflex and
- The absence of prolonged activation duration between sides during walking.

Strength Measurements

Two studies measured the asymmetry in rotation strength measurements. [57,59] Mooney et al. reported strength differences ranging between 12 and 47% with a majority of subjects with AIS exhibiting weaker paraspinals on the concave side. In contrast, McIntire et al did not find differences between corresponding rotation strength measurements either towards the midline or outwards from different pre-rotated positions.[59]

There is a conflicting level of evidence regarding differences in strength measurements between the convex and concave side of the spine with some evidence pointing to no differences between sides in rotational strength and other evidence suggesting weaker paraspinal muscles on the concave side.

Imaging

MRI measurements indicated no significant differences in overall muscle volume obtained at rest between the concave and convex side of the curve.[60] The percentages of the sample with mean volume difference index values indicating larger volume on both the concave and convex side. These were similar over each third of the curve on the concave side (14.3-15.3%) and more important at the apex (12.1) than above or below (9-9.9%) the apex on the convex side.

Therefore, there is limited evidence about whether paraspinal muscles volumes at rest differ between the convex and the concave side of the curve. This depends on the measurement definition used, with evidence pointing to either no difference between side (overall volume) or to larger proportion of patients with a larger volume on the concave side especially at the upper and lower third of the curve.[60]

Objective 4: Differences in Muscle properties in patients with AIS between different curve types

Three studies were included in this category (Table 9) two of which employed strength measurement, and one used MRI imaging.

Strength measurements

Peak Torque

No difference in peak torque was found between different postural (kyphotic, lordotic or equivalent) or curve types (Thoracic, Thoracolumbar).[61]

Time to Peak Torque

Time to peak torque differed between curve severity subgroups. Those with larger curves demonstrated longer time to peak torque in extension in sitting at 90°/sec. The discriminant function demonstrated longer time to peak torque in flexion in sitting at 60°/sec as well as extension to 120°/sec in semi-sitting in those with a lordotic posture followed by kyphotic posture, and then equivalent.[61]

Acceleration time

No difference was found in acceleration time between posture, or curve types, in all positions and velocities.[61]

Deceleration time

Those with thoracolumbar curves demonstrated a shorter deceleration time than those with thoracic curves in sitting at 120°/s while those with thoracic curves demonstrated a shorter deceleration time than thoracolumbar curves in sitting flexion at 60°/s. All other variables and outcomes were not significant when analyzed through the discriminant function.[61]

Mooney et al determined weakness on the convex side of the spine in 2/12 subjects. Both had double curves.[57]

Due to the low number of studies in this objective using strength as an outcome, and the relative heterogeneity of findings and outcomes evidence to support the findings of strength differences based on curve type is limited.

Imaging findings

Zoabli et al found the largest muscle volume difference in double curves.[60]

Limited evidence exists to support the finding that double curves exhibit the greatest muscle volume difference. Only one study with a small samples size supports this finding.

Objective 5: Association between muscle properties of patients with AIS and different curve characteristics (location, severity)

Seven studies were included in this category with five studies employing EMG methodology and two employing strength measurement.

EMG Methodology

Cheung et al identified a correlation between axial rotation at the upper end vertebrae and a convex:concave activity ratio at the lower end vertebrae. Higher activity at the LEV is correlated with lower axial rotation at the UEV.[34] Discriminative analysis did not demonstrate any association between curve severity and EMG results in lateral step tests to either side.[46] However, Odermatt et al did find a linear correlation between the lumbar Cobb angle and lumbar EMG asymmetry during resisted flexion.[62] Finally, Tsai et al did not find any correlation between RMS on each side of the curve and curve severity.[52] Shimode et al did not find a correlation between D-PMT latency values and curve severity.[58]

The research is:

- Limited that axial rotation at the UEV is correlated with high convex/concave ratio at the LEV.
- Limited that there is no correlation between latency and curve severity.
- Conflicting (2 out of 3 studies) in suggesting that there is no correlation between RMS findings and curve severity.

Strength Methodology

Anwajler et al found peak torque during extension at 60°/sec was higher in those with more severe curves (31-60°) than those with smaller curves (0-30°). Those with lordotic postures demonstrated a higher normalized peak torque at flexion at 120°/s.[61] Longer time to peak torque was observed in those with thoracic curves compared to thoracolumbar curves in both flexion and extension at 60° in sitting.[61] In contrast, Mooney et al did not find any correlations between strength differences between sides and curve severity.[57]

Conflicting evidence exists between two studies regarding the association between strength differences and curve severity with differences observed in the isokinetic testing in the sagittal plane but not during testing in the axial plane.

Objective 6: To determine the ability of muscle properties to predict curve progression.
Four studies were included in this category all employing EMG methodologies.

EMG Methodology:
In two studies of a partially similar sample, Cheung et al demonstrated that larger convex/concave EMG activity ratios at the LEV predicted Cobb angle progression.[34] These correlations were even more pronounced in sitting posture.[34] Dobosiewicz et al found that changes in latency can predict progression, however these latency differences were not correlated with age.[44] These results are further supported by the work of Shimode et al who also found a correlation between latency values (D-PMT) and progression at the LEV.[58]

Limited evidence exists to support findings that

- Larger convex:concave activity ratios can predict curve progression
- These correlations are more pronounced in sitting postures
- Prolonged latency can predict progression

EMG Reporting quality

Eleven out of thirteen studies reported 50% of ISEK criteria, 6/16 reported 60%, and 1/16 studies reported 80% of criteria. The results and reporting criteria can be found in tables 3, 13, and 14.

Discussion

To our knowledge this is the first systematic review surveying the literature on functional muscle properties of torso muscles in patients with AIS. Our results highlight the need for well-designed research in this area of study as the reviewed studies met at best 50% of the quality criteria in our appraisal. The small sample sizes, unclear methodology and heterogeneity in measurement methods and tasks used throughout the 21 papers surveyed indicate that there is a quality issue within this literature on AIS. After summarizing the most common topic addressed in the literature and justifying why a meta-analysis was not possible, key findings of this review are listed by objectives.

There are important gaps in the literature as only a few studies were found studying endurance (isokinetic approaches[51]) and none quantified fatigue by EMG methods. Imaging studies were rare[60] and no studies were found specifically on muscle length/flexibility (reports on global range of motion were not included as a key finding as such studies were not specific to the muscles of interest). In addition, even though many studies recorded EMG activity from multiple trunk muscles, a very limited number of studies analyzed the magnitude and timing of co-activations of postural trunk muscles beyond the reporting of EMG ratios between the convex-concave sides of the spine.[49,57] The latter may be relevant to provide a rationale for exercise programs focused on improving the motor control of postural muscles with a scoliosis-specific program.

Measurement tools:

Overall, 13 studies out of the 21 included in this review used EMG methodology, seven studies examined strength, and one study used imaging. Thus the overwhelming majority of studies examining paraspinal (rotatores, spinalis, longissimus, illiocostalis) functional muscular properties employ EMG as a method of documenting outcomes.

Metanalysis not possible:

While EMG is the most prevalent measurement tool, the EMG outcome variables reported are quite diverse. We were unable to find two studies homogenous enough in terms of methodology employed, variable analyzed, or task studied to attempt meta-analysis. Many studies analyzed EMG ‘activity,’ however, post-processing of the raw signal varied. Some papers only looked at raw signal,[53,56,57] while some papers calculated the Root Mean Squared over various task durations[50,52] (a method of smoothing where the amplitudes are squared, averaged and then the square root is calculated). Others measured imbalance across the spine by calculating ratios of the RMS obtained on each side of the curvature.[34,45,52,55,62,63] Studies exploring latency and duration of muscle activation during walking added further heterogeneity in the outcomes.[44,48,49,58]

The variation in EMG analysis was matched by a large heterogeneity in task. Four EMG studies examined subjects lying in prone or supine.[34,53-55] One study assessed subjects as they engaged in basic sitting or writing tasks. [56]

Six studies had subjects engaging in resisted strength testing tasks, but again, high variation was observed in both the challenging tasks tested and the parameters analyzed. Some used dynamic movements (rotation, flexion, extension, neck extension, overhead push and pull, walking)[47,51,61] some isometric (rotation, flexion, extension) [50,57,59], unilateral (rotation)[57], and bilateral tasks (flexion, extension, overhead push and pull)[47,50,51,59,61]. Parameters tested included overall strength (lbs lifted)[47], total work & power output[51], acceleration & deceleration time[51,61], peak torque & normalized peak torque (normalized to body weight) [51,59,64],and time to peak torque.[51,61] The large variation seen in tasks was also met by a large variation in task duration, load, and repetitions. These parameters were often not specified.

Two studies employed walking tasks.[48,65] Latency tasks involved perturbations in standing through a trapdoor with a release mechanism as well as neck extension at the sound of a cue.[44,58]

Due to the variety and inconsistency found in the results, it is difficult to isolate which tasks and outcomes were most effective at detecting differences within subjects with AIS and between subjects and controls. However, consistent results were noted for dynamic strength measurement demonstrating weakness in patients with scoliosis.[47,51,57,61] In addition to overall weakness, one study found greater weakness on the convex side.[57] Isometric strength measurement was rather inconsistent within the literature as 2/3 studies did not demonstrate significant results.[50,57,59]

EMG results were also quite varied making it difficult to recommend specific protocols for future research, however, the tasks demonstrating the most consistent results were measuring duration of activation in walking[48,49] as well as postural static tasks such as standing, sitting, lying, and writing.[34,54-56] latency findings were noted when using postural pertubations[44] as well as response to an external stimulus.[58]

Since only one study employing imaging was used[60], no recommendations for imaging type, or positioning can be made.

Summary of findings

Objective 1: Differences in functional muscle properties between patients with AIS and controls

Due to the heterogeneity of study methodology, evidence is limited regarding findings of prolonged EMG activation during gait; increased heterolateral to homolateral activity ratios during side bending tasks; unique EMG response during lateral step tests; and the absence of a difference during extension contractions at different intensity of contractions in patients with AIS compared to controls. Subgroups with sample sizes as low as 10 were common within the papers included[45] and Cobb angles included ranged from as low as 11°[48] all the way up to 56°.[45] There were no EMG studies comparing fatigability in patients with AIS to Controls. Differences between AIS and control were noted in both EMG and strength outcomes. Only one study examined muscular co-activation.[48] AIS subjects demonstrated higher convex/concave EMG muscle activity asymmetry ratios during side-bending tasks[45] and longer activation durations during gait than controls.[48] The increase in activity of convex sided muscles during lateral bending to the concave side may be the result of reflex stabilization, suggesting that the activity may be attributed to the deformity.[45] DeOlivieria et al did not find any significant differences in normalized muscle activity between groups at any percent of MVIC tested.[50] Filipovic et al found differences between scoliosis and controls with the use of a discriminant function[46], however, the results are difficult to interpret as the outcome variable is not defined.

Latency findings suggested that those with scoliosis demonstrate a longer time to respond to an unloading reflex than controls.[44] Patients with scoliosis demonstrated prolonged muscle activation during walking than controls.[49] Mahaudens et al suggested that the prolonged duration could be a reaction and compensation of muscles to the movement of a deformed spine and misaligned pelvis, and/or there may be an unknown motor control issue associated with AIS.[49]

Strength outcomes produced conflicting results, in that some studies found significant differences between AIS and controls while others found no differences. Two studies found that the erector spinae in subjects with AIS demonstrate overall weakness when compared to those of controls in both unilateral and bilateral movements[66] but a faster time to peak torque.[47,51] Faster time to peak torque is generally associated with muscular efficiency, higher in the scoliosis group, however, despite this; the girls still exhibited strength deficits. It is not possible to conclude whether the weakness observed is a causal factor or symptom of the curve. By affecting the length-tension relationship of paraspinal muscles the spinal deformity may limit the strength output of the muscles.[67,68] Elongated musculature is found on the convexity side and shortened muscles on the concavity, abdominal muscles tend to be tight.[68]

While some studies did compare the AIS groups to controls they were not discussed in objectives 1 & 2 if the control sample did not meet our inclusion criteria (<10 subjects, or out of the age range 10-18).

Objective 2: Differences in convex-concave side measurements between AIS and controls

Reported activity differences between groups were varied between papers however, limited evidence exist that subjects with AIS exhibit the following compared to controls: increased heterolateral activity during sidebending tasks[45], no differences in the amount of asymmetry in normalized activity during submaximal isometric contractions[50], different patterns of asymmetry during isokinetic contractions, which are more important in patients with larger curves[52]. The conflicting evidence that was found may be attributed to small sample size as well as methodological reasons. Feipel et al used surface electrodes for dynamic tasks, which can often interfere with the signal as electrodes may create signal artifact when they move relative to the skin.[39] The increased activity ratio was especially pronounced around the curve apex[45] and even more so in the lumbar spine.[50] A number of explanations have been given for this, including, greater need for muscle activation in the scoliosis groups as their muscles struggle to maintain alignment.[69] In addition Riddle et al suggest that differences seen are a result of stronger musculature on the convexity of the curve in the AIS group.[67] Despite these trends, the large heterogeneity in measurement sites, results, and sample limits the ability to draw more generalized conclusions. Better quality research is required to confirm these findings.

Investigations into latency did not yield any significant differences between unloading tests to the left or the right sides when comparing AIS to controls. In patients with scoliosis the latency of the reflex response was prolonged on the side opposite to the curve.[44] Cobb angles tended to be more homogenous than in Objective 1, however sample size was still low (3 out of 4 studies test subgroups with less than 15 subjects)[45,50,52]

Objective 3: Differences in functional properties within AIS patients between sides and levels.

The presence of higher activity on the side of the convexity of the curve was further observed in papers addressing this objective.[34,53-56] All sites on the curve (UEV, APEX, & LEV) demonstrated significantly higher EMG ratios on the convexity compared to the concavity in progressive AIS curves whereas this ratio was only elevated at the APEX in non-progressive AIS curves.[34,55] A number of explanations are proposed in the literature. Cheung et al suggest that the high levels of activation seen on the convexity are the result of musculature trying to maintain alignment against gravity. This imbalance would be further elevated at the most severely deviated part of the curve (the apex). Due to the need to constantly maintain alignment, muscles would contract more strongly resulting in an elevated EMG signal.[54] Feipel et al agree with Cheung et al's rationale for elevated signals representing the heightened need for postural alignment when discussing the rationale for their findings of high RMS ratios on the heterolateral side during right-side (convex) bending.[45] However, Zoabli et al propose two other suggestions based on their MRI findings. They suggest that EMG activity on the convexity of the curve could be a result of 1) greater neural feedback in muscles that are stretched (as suggested by the MRI findings) or 2) closer proximity of the stretched convex muscles to the surface leading to a smaller skinfold thickness, resulting in greater sEMG signal.[60] Zoabli et al suggest further research combining MRI imaging and EMG to determine whether the elevated EMG signal is due to a more superficial position of the muscles and therefore an artificial finding, or one resulting from increased neural feedback due to stretched muscles[60]. The absence of differences using normalized EMG to MVIC provides indirect evidence in support of Zoabli's hypothesis.[50]

Reflex responses tended to be symmetrical on both sides of the spine in side bending, however the time from stimulus to unloading reflex was prolonged on the side opposite the curve in progressive scoliosis.[44] Similarly, latency differences across the spine were significantly different from 0 at the apex and lower end vertebrae reflecting longer latencies on the concave side in response to neck extension.[58] Dobociewicz et al explain that there may be a deficiency in the functioning of muscle spindles, but do not elaborate on how the deficiency expresses itself. In contrast, during gait no differences in duration of activation were noted by Mahaudens et al between sides in the scoliosis group.[48,65] They propose that the prolonged duration of activation observed is a co-contraction of concave and convex muscles in an attempt to stabilize the spine and pelvis.

Conflicting study findings were observed regarding rotation strength asymmetries relative to the curve direction with some evidence pointing to no differences between sides[59] and other evidence suggesting weaker paraspinal muscles on the concave side.[57] Nevertheless, studies under objective 1 suggested an overall weakness in the erector spinae muscles of the scoliosis group and thus it would be important for further research to address how weakness manifests itself along the curve at transition sites and between the convex and concave sides. This would help pinpoint the movements to include in an exercise program to improve strength of the paraspinal muscles. Both Mooney et al and Mcintire et al were able to reduce weakness with their rotation-based strengthening programs.[57,59] The conflicting findings may be due to a small sample size(<20), insufficient power and a lack of homogeneity in curve type (ranging from 10-60° in some cases) and direction among the patients tested.

The only imaging study demonstrated more patients with increased muscle volume on the concavity of the curve.[60] This imbalance would be expected due to compression on the concave side and stretching on the convex as a result of the geometry of the spinal deformity. [60]. However, the concave:convex differences were not tested for significance making it difficult to draw conclusions from this paper.

This is the objective with the largest number of included papers; however, it is difficult to draw conclusions about whether these characteristics are unique to patients with scoliosis as no comparisons to controls were performed. More comparisons between scoliosis subgroups would also be informative as very few papers grouped subjects by progressiveness, curve severity, or location.

Objective 4: Differences in muscle properties in patients with AIS between different curve types

While different curve types are likely to exhibit different imbalances in functional muscle properties there is a gap in the literature addressing this question with only 3 studies reporting related evidence.[57,60,61] In addition, sample sizes of subgroups were as low as 10 in one study.[61] Examples of curve types possibly impacting the length, activity and strength of the surrounding musculature could include curve direction, location, and number of curves. While not present in their final analysis, many studies acknowledge the relevance of curve type to muscle properties by limiting their recruitment to specific curve types. Six studies specifically recruited individual curve types ranging from left thoracolumbar or lumbar curves[49], single right curves[58], as well as one study which listed left thoracic curves as an exclusion criteria.[59] If feasible, studies should aim to recruit single curve types or have sufficient sample size to allow for comparisons of sufficiently large subgroups of curve types.

Limited evidence exists to support findings regarding muscle properties in different curve types. Very few studies exist and outcomes and methodology are heterogenous. Of the three studies addressing objective 4, no study used EMG methodologies, one study analyzed peak torque,[61] one studied isometric rotational strength,[57] and one used imaging finding the largest muscle volume differences between sides in double curves.[60] Of the two studies employing strength as an outcome the different curve types analyzed were heterogeneous. Mooney et al reported on curve number, reporting weakness in double curves on the convexity.[57] Anwajler et al focused on curve location and reported thoracic curves as demonstrating the lowest peak torque and longest time to peak torque.[61] However, further evidence is needed to understand how paraspinal muscles differ in functional properties based on location and number of curves. Anwajler et al suggest that differences in the biomechanical nature of the spine in various curve types will cause a difference in muscle properties. For example shorter time to reach peak torque in extension and a corresponding longer time to reach peak torque in flexion in primary thoracic curves may be explained by increases in the tone of the spinal extensors due to a larger lordosis, often associated with primary thoracic curves. This increased tone in the extensors would be met with decreased activation of the flexors.[61] This example highlights the differences that exist in muscle properties between curve types, and the importance of understanding the muscle properties of each curve.

Curve type is an important factor to consider when studying muscle properties, as muscles will behave differently based on the curve. The musculature on the convex and concave side differs in both activity and fibre type. Thus, the direction of the curve must be taken into account when analyzing the musculature. The number of curves adds complexity because with multiple convexities identifying the convex vs concave side at transitional vertebrae is an issue. In a double curve the muscles on the convexity of the thoracic curve at the lower end vertebrae would also be classified as being on the concavity of the upper endpoint of the lower curve. The current literature does not provide sufficient evidence to understand how muscles are affected by their positions within multiple curves. It is also too early to understand how imbalance in muscle properties within different curve types could inform exercise interventions for all patients with AIS. One important characteristic of scoliosis-specific exercise prescription is the fact that specific auto correction exercises are prescribed depending on curve types. Providing evidence that muscle characteristics differ at baseline, and possibly respond differently to exercises, between curves types therefore appears important.

Objective 5: Correlation between muscle properties of patients with AIS and different curve characteristics

Limited EMG findings suggest a negative correlation between axial rotation at the UEV and muscle activity at the LEV.[34] In addition, Odermatt et al found a linear correlation between EMG imbalance in the lumbar spine and Cobb angle severity, implying greater asymmetry in more severe lumbar curves.[62] However, two other studies did not find any correlations therefore the level of evidence on this question is conflicting. Tsai et al did not find any such correlation when analyzing paraspinal EMG on each side of the spine during concentric an eccentric extension contractions.[52] Filipovic et al did not find any correlation between EMG activity during a step test and curve severity, although their specific EMG outcome is unclear. Similarly, strength did not correlate with curve severity[57] and no correlation between latency ratios and curve severity were noted by Shimode et al.[58] No explanation for this lack of correlation between curve severity and latency ratios was given in the literature. The evidence related to correlations between strength or latencies and curves severity is thus limited. This lack of correlation may be due to samples with a very broad range of severities (10-60°)[54], small sample sizes (as low as 10 in some subgroups)[61], and high variability due to not controlling for curve type.

Objective 6: To determine the ability of muscle properties to predict curve progression.

Due to the low quality of studies but consistent findings among the studies on this topic, there is limited evidence of a correlation between EMG activity asymmetry and progression. Cheung et al found correlations between increased convex/concave EMG ratio at the lower end vertebrae and progression.[34] They also found higher EMG ratios in the progressive group at all sites (UEV, Apex, LEV) compared to the non-progressive group which only demonstrated elevated EMG activity at the apical vertebrae.[54,55] Cheung et al also created a nomogram suggesting that a spine growth velocity of more than 15mm/year and an EMG activity ratio of greater than 2 has an 89% chance of progression.[54] The correlation between progression, spine growth velocity, and EMG activity was not explained in the literature.

Further, there is conflicting evidence of correlations between increased latency and progression. Dobosciewicz et al reported that latency changes correlate with disease progression without providing correlation estimates.[44] They suggest that this is due to defects within the muscle spindles, however, do not elaborate on the mechanism behind these defects. In contrast, Shimode et al found a correlation between the differences in latency across the spine and progression at the lower end vertebrae (0.432).[58] However, as in previous objectives, this objective included studies with small sample sizes (n=11 in one subgroup)[34] and a wide variety of curve severities.[34]

These differences may imply that inherent markers of progression may be present in at-risk curves. However, most studies do not propose a mechanism or explanation for these differences. Cheung et al discuss the importance of recognizing that elevated EMG at the lower end vertebrae is in no way a prognostic factor, but may present a potential risk factor for more intense supervision.[55] In addition to a risk factor to inform observation, differences in muscle function associated with curve progression may be used to identify exercise priorities for curves exhibiting greater risk of progression if those specific risk factors (higher activity at the LEV, longer latency) can be modified with specific movements. There is a gap in the literature regarding whether many of the muscle impairments considered under previous objectives exhibit an association with curve progression.

Study quality

Overall, the quality of the included studies was poor. A number of quality issues plagued the research. Small sample sizes were insufficient to power studies to detect possibly clinically important differences (14/24 studies had less than 20 subjects). Studies were prone to type 2 errors, and may have limited external generalizability. Study methodology was often unclear, making it difficult to reproduce protocols and adequately judge quality. In the future, to ensure that studies on muscle properties can inform treatment, methodologies must be clearly outlined and sample sizes of sufficient sizes must be recruited to detect differences. For this review we used applicable criteria of the COSMIN checklist to evaluate what percentage of quality criteria were met by each study.[40] Out of the 25 criteria for quality papers included in the study 14 criteria were met by ≤5/20 papers (Table 2.12). The most common criteria missed related to blinding of examiners to patient data, to comparator tests results, and to previous muscle measurements. No studies reported information to meet these criteria. It is possible that examiners were blinded, but this must be reported in order to give the reader confidence in the methodology. The criteria fulfilled by the most number of papers related to appropriate study design and reporting of demographic information in which criteria were met on 92% and 67% of occasions respectively. The COSMIN checklist was compiled in 2005 meaning that 14 of our included studies preceded its publication. While it does not change the ability to rely on poorly reported methodologies, it is important to note that no methodological guidelines had been published to allow for better quality reporting in these studies. Future researchers could use the relevant sections of the COSMIN criteria based on their study objectives as a guide when designing and reporting research. EMG studies should use the ISEK criteria to assist with the design and with preparing complete and adequate reporting of results of EMG studies.[41] However, it is possible that some high quality studies may rank poorly due to poor reporting of methodologies as the criteria are based on whether key elements are adequately reported.

Implications for treatment prescription

While some significant impairments were noted in paraspinal muscle characteristics between patients and controls and between different curve types or muscles sites, since the etiology of scoliosis is unclear, it is not sufficiently clear whether the differences arise as an adaptation to the curve or whether they play a causal role in the development and progression of scoliosis. These noted impairments include higher EMG activity at the apex of the curve on the convexity, higher EMG activity asymmetry in progressive curves, prolonged latency in patients with AIS, and overall weakness in the extensors of patient with AIS. These observations provide a list of potential treatment goals. However, before making any specific treatment recommendations, research should clarify whether differences arise as an adaptation to the curvature or whether they play a causal role in the development and progression of scoliosis. Very few studies have demonstrated that purposefully targeting a specific muscle imbalance can change the natural progression of scoliosis[57,59] and very few longitudinal studies have demonstrated that some muscle impairment variables are predictive of progression.

The effects of strengthening, modifying activation balance, modifying timing of activation or the length of the muscles surrounding the curve could alternatively potentially exacerbate the problem. For example, the increased activation ratio on the convex side may be a biomechanical adaptation to prevent further bending of the spine to occur under the influence of gravity. Further activation of muscles on the concave side may in fact lead to increased curvature if the origin and insertion of muscles on the concave side get pulled closer during contraction. Future exercise studies should monitor how torso muscles are influenced by exercise programs as well as the effect of exercises on curvatures. Such measurements would allow for the determination of a relationship between the effects of targeted exercises on musculature as well as the effects on curvatures. This data could lead to refining exercise prescription to maximize treatment effects. Improving the curve through addressing muscle imbalance has been attempted in the past. A number of studies found promising results through the use of muscle stimulation.[70,71] However, much like current exercise approaches to scoliosis management, these stimulation programs were developed without a good knowledge of underlying muscle properties. In a meta-analysis by Rowe et al, bracing was identified as having a better success rate than observation and muscle stimulation. There was no statistical difference for treatment success between muscle stimulation and observation.[24] This highlights the need for a strong base of knowledge when discussing interventions for scoliosis management that target muscular imbalances.

That being said, despite the poor quality, and gap in the literature, certain consistent observations do exist within the research. Imbalances between curve sides and between groups were fairly consistent and may be adequate targets to be investigated for therapy programs aiming to limit curve progression.

Other exercise related outcomes

Only one paper found during our full text review measured fatigability. This paper did not meet our inclusion criteria as it only involved 6 subjects (n<10).[72] Skrzek et al analyzed endurance parameters, but did not find any differences in peak torque between 10 repetitions at 120° and 20 repetitions at 120° for all four tasks. However, this difference was not tested statistically and he did not compare the subjects with scoliosis to controls or between sides. Therefore his findings did not fit into our objectives.[51] Another important study goal would be measuring a correlation between endurance and progression. If the paraspinal musculature is lacking in endurance and is therefore unable to support the spine effectively throughout daily activities, this may be a factor to consider when determining methods to prevent further progression. Thus fatigability needs to be studied as a potential therapy goal.

In addition, in studies that measured EMG and/or strength methodology, physical activity levels and types were not taken into account in either group, possibly explaining the differences observed. The identification of an existing weakness in the paraspinal muscles of patients with AIS suggests the existence of an important clinical goal. However, further research needs to identify the most effective exercise prescription (duration, sets, and repetitions) to address weaknesses. In addition further research can help determine whether correcting differences observed in muscle characteristics relative to controls can lead to improvement in curve characteristics or prevent curve progression.

Future research recommendations

This review has identified gaps in the research needing to be addressed in order to gain a full understanding of paraspinal muscle characteristics in scoliosis. Exercise approaches consider curve types during exercise prescription, however, the exact characteristics of paraspinal musculature and the effect of curve type needs to be understood to guide concrete recommendations related to curve types. Thus research must focus either on a homogeneous curve type, or recruit sample sizes big enough to allow for subgroups comparisons.

Endurance is a strong predictor of spinal stability within the field of low back pain[33] and therefore the endurance properties of paraspinal musculature must be understood in order to understand whether there are deficits that must be addressed, and if so, whether these deficits manifest themselves differently on the concavity, convexity, or vertebral levels in various curve types.

Muscle characteristics with implications for motor control such as muscle co-activation and latency need to be studied as well in order to guide exercise prescription targeting muscular recruitment and coordination. If therapists have knowledge of muscle recruitment patterns in patients with scoliosis that are associated with progression, they can focus on correct muscle recruitment as a treatment goal.

Imaging techniques are often used in studying muscle properties and back pain.[42,73,74] Outcomes like muscle thickness and volume are useful in understanding the characteristics of paraspinal musculature. Our review only identified one paper using imaging as an outcome. This is an area in need of further study.

The tasks used in the majority of studies were shorter duration tasks. The role of paraspinal musculature is to constantly maintain alignment in all positions during long periods. Research should be done to investigate how the paraspinal musculature responds to long-term tasks, mimicking the real-world role of these muscles. The cumulative findings of this review provide the therapist with an understanding of the current state of literature regarding the physiology of paraspinal muscles and orients the researcher for further research.

Strengths & Limitations

Strengths

This systematic review maintained a high standard for quality appraisal and relied on the agreement of 2 reviewers. The agreement between the reviewers was high (0.77). This review effectively highlights gaps in the research and demonstrates a deficiency in the pool of research relating to paraspinal muscle properties in AIS. This review suggests that current exercise-based interventions cannot yet be based on quality scientific inquiry and stresses that a larger pool of research is necessary before the rationale for using exercises is based on objective documentation of muscle impairments.

Limitations

This systematic review only focused on adolescent idiopathic scoliosis and excluded any paper in which 25% of the sample was over the age of 18 or under the age of 10. This limited the scope of the paper, however, it was justified in light of the fact that the rapid growth phase seen in adolescent is critical to curve progression[55] and thus this age range is a population at risk. It may be worth looking at a population no longer at risk of progression in order to understand muscle characteristics when the curve has stabilized. Only English and French papers were included, limiting the scope of the review. As exercise interventions are more commonly used in Europe, it would have been beneficial to include other languages. However, given the added cost, limited resources, and often-poor translation quality it was not feasible to expand our search strategy. With a large heterogeneity in methodology and outcomes, meta-analysis was not possible.

Conclusion

The quality of research into functional characteristics of paraspinal musculature is poor as none of the studies met 50% of our quality criteria. Despite quality issues and relative heterogeneity in findings and methodology some key findings were observed. Overall, higher RMS ratio asymmetries were observed in patients with AIS than controls[34,45,54,55], and higher activity was noted on the convex side of the curve, specifically in patients with progressive curves.[34,54,55] Prolonged latencies were observed in AIS groups especially on the concave side and prolonged durations of activation were noted during gait.[44,48,49,58] Correlations between muscle impairments and progression or curve severity were noted as well.[54,55] Those with scoliosis tended to demonstrate weakness in the paraspinal muscles when compared to controls[51,66], however no correlation was found between strength and curve severity.[46]
More quality research needs to be done in order to draw definitive conclusions about the findings reported above for which, at best, limited evidence exists. More broadly, research is required regarding which muscle impairments characterize scoliosis and are associated with curve progression. Such research is needed to provide a rationale to inform scoliosis-specific exercise prescription. Specific research gaps were identified with a need to explore functional characteristics based on curve types and examine additional muscle properties for their relationship to progression. Research into the fatigability/endurance of postural muscles that maintain posture over long durations in daily life is necessary. Finally, the coordination of postural trunk muscles needs be studied to provide an understanding of the patterns of muscle recruitment needed to maintain posture as well as those deficits affecting the ability of patients with scoliosis to maintain spinal alignment.

Table 2.1 Criteria used to appraise research quality

	Criteria	Score
Methodological quality		
1	Was a representative sample of participants used?	+/-/?/ ≠
2	Was a representative sample of examiners used?	+/-/?/ ≠
3	Is replication of the assessment procedure possible?	+/-/?/ ≠
4	Were participants' characteristics stable during research?	+/-/?/ ≠
5	Were examiners blinded to clinical information from participants?	+/-/?/ ≠
6	Can non-random loss to follow up be ruled out?	+/-/?/ ≠
Study design		
7	Was the study design adequate? (eg prospective, RCT, case control etc)	+/-/?/ ≠
Population selection		
8	Was the sample size justified?	+/-/?/ ≠
9	Were the inclusion and exclusion criteria of participants stated clearly?	+/-/?/ ≠
10	Was a consecutive of random sample of patients enrolled?	+/-/?/ ≠
11	Were the demographic characteristics of the sample reported?	+/-/?/ ≠
Hypotheses		
12	Were hypotheses regarding the associations between subjective and physical exams formulated a priori?	+/-/?/ ≠
13	Was the expected direction of the association or mean differences included in the hypothesis?	+/-/?/ ≠
14	Was the expected absolute or relative magnitude of associations included in the hypotheses?	+/-/?/ ≠
15	For convergent validity: was an adequate description provided of the comparator instrument(s) (including measurement properties)?	+/-/?/ ≠
16	For convergent validity: Were the measurement properties of the comparator instrument(s) adequately described (including measurement properties)?	+/-/?/ ≠
Raters & testing procedures		
17	Were the trainings and qualifications of the rater(s) reported?	+/-/?/ ≠
18	Was/were the rater(s) blinded to the results of the comparator test when assessing the muscle function test measurements?	+/-/?/ ≠
19	Was/were the rater(s) blinded to the results of previous measurements performed by the same or different rater(s)?	+/-/?/ ≠
20	Was the time interval between physical examinations and comparison measurement appropriate?	+/-/?/ ≠
21	Were standardized and valid test procedures adopted for both the subjective and physical examinations?	+/-/?/ ≠
22	If anything occurred in the interim period between repeated measurements (e.g. intervention, other relevant events), was it adequately described?	+/-/?/ ≠
Missing data		
23	Was the percentage of missing data given?	+/-/?/ ≠
24	Was there a description of how missing items were handled?	+/-/?/ ≠
25	Were the reasons for missing data given?	+/-/?/ ≠
Confounding factors		
26	Were the confounders defined clearly (e.g. comorbidity, work compensation, litigation, ceiling or floor effect…)?	+/-/?/ ≠
27	Were the confounders measured by reliable and valid tools?	+/-/?/ ≠
Statistical analyses		
28	Were design and statistical methods adequate for the hypotheses to be tested?	+/-/?/ ≠
29	Were correlations calculated?	+/-/?/ ≠

+ Yes, - No, ? Unclear, ≠ Not Applicable. Quality was assessed based on the sum of the yes (+) scores out of the total relevant scores.

Table 2.2 Summary & scoring of EMG quality criteria

	Criteria	Score
1	EMG methods stated?	+/-
Electrodes		
2	Electrode type?	+/-
3	Electrode size?	+/-
4	Skin preparation?	+/-
5	Inter electrode distance?	+/-
6	Electrode location?	+/-
Settings		
7	Low pass filter?	+/-
8	High pass filter?	+/-
Processing		
9	Type of processing used?	+/-
10	Sampling frequency?	+/-

(+) Yes, (-) No

Table 2.3 Criteria for drawing conclusions regarding levels of evidence

Levels of evidence (Adopted from Cornelius et al.)[43]	
Strong	Consistent results (≥80%) from at least 2 high-quality studies
Moderate	1 high quality study and consistent findings (≥75%) in 1 or more low-quality studies
Limited	Findings in 1 high-quality cohort or consistent results among low-quality studies
No	No study
Conflicting	Inconsistent results irrespective of study quality

Table 2.4 EMG methodology in the included studies

Study	Electrode type	Electrode size	Skin preparation	Inter-electrode distance	Electrode location	Low pass filter	High pass filter	Processing	Sampling frequency
Alexander et al. (1978)[53]	Teflon coated monopolar	Missing	Missing	Missing	Concave & convex sides of the spine	Not specified	Not specified	Not specified	Missing
Cheung et al. (2006)[55]	Bipolar	10mm	Missing	Missing	30mm from spinous process of primary curve at UEV, apex, and LEV	1000Hz	16Hz	Rectification	800Hz
Cheung et al. (2004)[54]	Bipolar	10mm	Missing	Missing	30mm from spinous process of primary curve at UEV, apex, and LEV	1000Hz	16Hz	Rectification	800Hz
Cheung et al. (2005)[34]	Missing	10mm	Missing	25mm	Superficial erector spinae (longissimus) 30mm from spinous process parallel to UEV, apex, LEV (six pairs of electrodes)	1000Hz	16Hz	Rectification	800Hz
Dobosiewicz et. al (1997)[44]	Bipolar	Missing	Missing	Missing	15-20mm from spinous process at T8, L1, & L3	Not specified	Not specified	Not specified	Missing
Feipel et al	Ag/AgCl	10mm	Mild	10mm	T6, T8, T10, L1, L3, L5. 3 and	1000Hz	1Hz	RMS	2000Hz

(2002)[45]			abrasion		6cm from the spinous process **Rectus abdominus**: 3cm from umbilicus **obliquii**: 2cm above iliac crest.				
Filipovic et al (2006)[46]	Missing	Missing	Missing	Missing	Gluteus maximus (left & Right) Erector spinae (left & right)	Missing	Missing	Missing	Missing
Gram et al. (1999)[56]	Missing	Missing	Missing	Missing	2cm on either side of T6 & L1 6cm either side of L1 2cm both sides of L3	Not specified	Not specified	Not specified	Not specified
Mahaudens et al (2005)[48]	Missing	Missing	Missing	Missing	Gluteus maximus, Gluteus medius, Quadratus lumborum, erector spinae (no levels listed)	25Hz	300Hz	Rectification	1000Hz
Mahaudens et al	Missing	Missing	Missing	Missing	On muscle bellies of	25Hz	300Hz	Rectification	1000Hz

(2009)[49]					quadratus lumborum, erector spinae, gluteus medius, rectus femoris, semitendinosus, tibialis anterior, and gastrocnemius				
Odermatt et al (2003)[62]	Paper-thin	Missing	Missing	Missing	22 Pairs of electrodes: Thoracic apex, curve change site, lumbar apex, L5, rectus abdominus, obliquis externis	3Hz	1000Hz	RMS	2000Hz
Shimode et al (2003)[58]	Plate	Missing	Missing	2cm	**AIS**: UEV, apex, LEV **Controls**: T5, T8, T12, L2, L5	Not specified	Not specified	Not specified	Not specified
de Oliveiria et al (2011)[50]	Ag/AgCl	10x2x1mm	Alcohol, shaving	10mm	2.5cm bilateral of spinous: T8, L2, L5.	Not specified	Not specified	RMS	Missing
Tsai et al (2010)[52]	Missing	11.4mm	Alcohol	2cm	**Medial paraspinals:** T7 & L2 bilaterally (2cm from spinous process	Not specified	Not specified	RMS	Not specified

					Lateral paraspinals: T7 & L2 (4cm lateral to spinous)				

Table 2.5 Study type, inclusion & exclusion criteria, and group characteristics of included studies (Gender, diagnostics, age, curve magnitude, and curve type)

Study	Study type	Inclusion & exclusion criteria	Population & group characteristics
Alexander et al. (1978)	Cross sectional case series	**Inclusions:** AIS referred for neuro exam but with normal neurological exam, absence of spinal anomalies **Exclusions:** Bladder or bowel symptoms	**Scoli:** n=31 subjects with AIS (3 males, 28 females) *Mean age:* males: 14.7 (13-17), females: 14.9 (12-19) yo *Cobb angles:* males: 51.5° (48-58°), females: 41.5° (10-82°).
Anwajler et al. 2006	Cross sectional	**Inclusions:** Girls with AIS in a treatment centre **Exclusions:** Not reported	**Scoli-lord**: 18 females with AIS. Age: 14.9 (2.4 yo) **Scoli-equi:** 10 females with AIS, age: 15.4 (1.7yo) **Scoli-kyph:** 7 females with AIS, age: 13 (2.1yo) **Overall**: 35 Girls with AIS, age 14.7 (2.3yo) Cobb: 0-30°: 18 subjects with primary thoracic, 9 with primary lumbar curves Cobb 31-60°: 7 primary thoracic, 1 lumbar
Cheung et al. (2006)	Prospective cohort	**Inclusions:** Posterior-anterior & lateral radiographs between 4 & 6 months. Diagnosis of scoliosis for left and right curves **Exclusions:** Corrective surgery before follow-up	**Scoli**: Overall scoliosis, n=105 subjects (19 males, 86 females), age: 14 (5.1-19.5 yo) **Scoli-Nprog:** n=18 subjects (54 intervals) 2 males, 16 females Cobb angles: 44.3° (34.5 – 54.3°) **Scoli-Prog**: (increase ≥10°/yr) 10 subjects (16 intervals) 2 males, 8 females. Cobb: 32.3° (27-34.9°)
Cheung et al (2004)	Prospective cohort	**Inclusions:** All with AIS attending visits at institution with right sided thoracic curves over 2 yo. **Exclusions:** Not reported	**Scoli:** Scoliosis overall: n=30 subjects 4 males, 26 females. Ages 10-16yo. Cobb angle range 10-60º **Scoli-Nprog:**; n=19 subjects(68 intervals). 2 males, 17 females. Age 14.6 (2.4yo), growth velocity: 3.8 (2.6-5.6mm/yr)

			Scoli-Prog: n=11 subjects (17 intervals). 2 males, 9 females. Age 13.2 (1.5yo), growth velocity 20.5 (14.6 – 28.6 mm/yr)
Cheung et al (2005)	Prospective cohort	**Inclusions:** AIS visit at dept with right sided curves **Exclusions:** No history of other physical disorders	**Scoli:** Overall scoliosis: n=23 subjects. Cobb angle 10-60°. 3 males 20 females. Risser sign 1-4 **Scoli-Nprog:**: n=15 subjects 2 males, 13 females. Ages 14.6 (11-16yo). Cobb 9.8 (11.1°). **Scoli-Prog:** n=8 subjects, 1 male 7 females. Age: 13.6 (12-16yo), Cobb: 39.2 (18.3°).
Dobosiewicz et al (2002)	Cross sectional case/control	**Inclusions:** Not reported **Exclusions:** Not reported	**Scoli:** Scoliosis overall: n=394 subjects, 83 males. 311 females. Age 12.5 (9-18yo). 9 cervico-thoracic (mean Cobb 30.9°) 111 with thoraco lumbar (mean Cobb 26.8°), 63 with lumbar scoliosis (mean Cobb 27.9°), 90 with double major (mean cobb: 29.2° and 28.5°) 231 right sided and 163 left sided curves. **Scolifastprog** n=112 subjects. Cobb 36.1 (8-77°). 76 right sided and 36 left sided curves **Scolislowprog:** n=182 subjects. Cobb 20.3 (3-48°), 113 right sided and 69 left sided curves **Pelvic tilt scoli:** n=100. Cobb 8.2 (2-25°). 42 right and 58 left sided curves **Ctrl:** n=70. 10 males, 60 females. Age: 12.8 (10-17yo)
Feipel et al (2002)	Cross sectional case/control	**Inclusions: Scoli:** Indications for surgical correction for AIS. **Ctrl:** matched (criteria for matching unclear) group of non-scoliotic teenagers **Exclusions:** Not reported	**Scoli:** n=10. 4 males, 6 females. Age 16 (2yo;14-19 yo). Cobb 56 (15°). 5 right thoracic, 2 right thoracic left lumbar, 2 left thoracolumbar, 1 right thoracolumbar curve types. **Ctrl:** n=10. 3 males, 7 females. Age 13 (2yo; 11-19 yo).
Filipovic et al (2006)	Cross sectional case/control	**Inclusions:** **Scoli (all)** AIS with not indication for surgery. **Ctrl.** Elementary school	**Scoli:** n=36. 4 males, 34 females. Age (9-14yo). Cobb (18-42°). **Scoli≤25:** n=21. Ages 9-14yo. **Scoli≥26:** n=17. Ages 9-14yo.

		students in Zagreb and surroundings. **Exclusions:** Not reported	**Ctrl:** n=38. 7 males 29 females. Age 9-14yo
Fuller et al (1991)	Cross sectional case/control	**Inclusions: Scoli.** Girls with AIS and structural curvatures of the spine. **Ctrl.** Girls with normal spines. **Exclusions:** No other known disabilities	**Scoli:** Overall scoliosis: n=48 females. Age 12.3 (1.2yo). 37 right, 11 left curves. **Scoli-11-12yo:** n=19 females **Scoli-13yo:** n=15 females **Scoli-14-15yo:** n=14 females **Ctrl** n=48 females. Age 12.8 (1.2yo) **Ctrl-11-12yo:** n=20 females **Ctrl-13yo:** n=12 females **Ctrl 14-15yo:** n=16 females.
Gram et al (1999)	Cross sectional	**Inclusions:** AIS from 2 clinics in Chicago metropolitan area **Exclusions:** <6 yo, >17 yo old, Cobb<10°	**Scoli:** Scoliosis: n=19. 2 males 17 females
Mahaudens et al (2005)	Cross sectional case/control	**Inclusions: Scoli.**: Progressive AIS with lumbar or thoraco-lumbar curve (>10°/yr) **Matched controls** (for age, height, weight) Normal x-ray of spine, 12-14 yo old **Exclusions: Both:** <6 yo old, >17 yo old Cobb<10°. central or peripheral disorders or other spinal disorder. **Scoli.** previous conservative or surgical treatment, **Ctrl.** spinal disorders, orthopedic surgery.	**Scoli:** n-=12. Age 13.2 (0.8yo). Risser 1 (0-2). Thoracic curve: 11.9° (7°), Lumbar curve 22.5° (4°) **Ctrl:** n=12. Age 12.9 (0.9yo). Risser 1 (0.25-1)

Mahaudens et al (2009)	Cross sectional case/control	**Inclusions**: **Scoli.** Untreated girls with AIS attending outpatient clinic. Left thoracolumbar or lumbar primary curves (Lenke 5,6) **Ctrl**. healthy girls **Exclusions:** **Scoli.** Leg length discrepancies > 1cm, locomotor disorders, low back pain, neurological abnormalities, previous tx for scoliosis. **Ctrl.** spinal deformation or disease affecting gait.	**Scoli<20:** n=12 females. Age 14 (13-14yo). All post-menarche. Risser Mdn 2 [1-2]. Cobb 15.3° (5°). All with left thoracolumbar or lumbar primary curve (Lenke 5 or 6) **Scoli20-40** n=13 females. Age 14 (12-15 yo). All post-menarche. Risser Mdn 2 [2-3]. All with left thoracolumbar or lumbar primary curve (Lenke 5 or 6) **Scoli>40:** n=16 females. Age 16 (14-17yo). Cobb: 44.3° (8.1°). All post-menarche. Risser Mdn 3 [3-4]) All with left thoracolumbar or lumbar primary curve (Lenke 5 or 6) **Ctrl:** n=13 females. Age 16 (15-16yo). All post-menarche. Risser Mdn 4 [3-4]. Cobb 0.8° (1.6°)
Mcintire et al (2008)	Prospective cohort	**Inclusions:** AIS Cobb 20-60°, Risser ≤3. Age 10-17yo. **Exclusions:** Any diagnosable cause of scoliosis. left thoracic curves, hyperkyphosis (prior MRI for chiari malformation, syringomerlia, structural neural abnormality)	**Scoli:** n=17, 12 females, 3 males. Age 13.9 (1.7yo). Cobb 33° (12°). Post-menarche in 5/12 girls. Risser 0 in 7/14, Risser 1 in 3, Risser 2 in 3 and Risser 3 in 1 (1 missing). 8 thoracic, 2 double thoracic, 5 thoracolumbar/lumbar curves.
Mooney et al (2000)	Prospective case series	**Inclusion:** Not reported **Exclusion:** Not reported	**Scoli:** n=12, 2 males, 10 females. Age 13.1 (1.6yo). Cobb 33.5° (12.8°; 20-60°). Risser 2.4 (1.4; 0-4). 3 left thoracic, 6 right thoracic, 2 right thoracic lumbar, 1 left thoracic lumbar curves.
Odermatt et	Cross-sectional case series	**Inclusion:** Diagnosis of AIS,	**Scoli:** n=11 females. Age 13.2 (1.2yo; 12-16yo). Thoracic

al (2003)		King I or II classification, treated with Boston brace, female **Exclusion:** Not reported	Cobb 31.8° (9.6°) Lumbar Cobb 26.5° (6.4°). Risser 0.9 (1.2; 0-4). All King 1 or 2 (right thoracic or left lumbar curves).
Shimode et al (2003)	Cross sectional case/control	**Inclusion: Scoli:** AIS, single right thoracic curve. **Ctrl:** Nonscoliotic teenage girls **Exclusion: Scoli:** Follow-up not possible at 1yr. **Ctrl:** spinal deformity on posterior-anterior or lateral x-ray.	**Scoli:** n=40, 3 males, 37 females. Age 13.0 (1.4yo; 0-16yo). Cobb 31.5° (12.6°; 15-66°). Risser: 1.6 (1.5;0-4). All with right thoracic curve. **Ctrl:** n=10 females. 5=11yo and 5, 19 yo.
De Oliveira et al (2011)	Cross sectional case/control	**Inclusion:** Not reported **Exclusion: Scoli** Prior surgery or brace. **Ctrl**: volunteers with spinal misalignment, trauma, painful trunk motion or any other orthopedic or systemic condition	**Scoli:** n=15, 3 males 12 females. Age 15 yo (10-20yo). Cobb thoracic 25 °(10-36°), Cobb left lumbar 21° (10-30°). 60% of curves were double curves with right thoracic. **Ctrl:** n=15, 3 males, 12 females. Age: 15 yo (11-20yo).
Skrzek et al (2003)	Cross sectional case/control	**Inclusion: Scoli.** AIS, treated as in-patient at centre. **Ctrl.** Junior high school girls **Exclusion:** Not reported	**Scoli:** n=35 females. Age 14.7 (2.3yo). 26 thoracic (24 of these right). 10 primary thoracolumbar scoliosis (9 of these left). **Ctrl:** n=26 females. Age 15.8 (0.7yo).
Tsai et al (2010)	Cross sectional case/control	**Inclusion: All.** Adolescents 10-17yo, **Scoli.** AIS, right hand dominant. **Ctrl**. Healthy. **Exclusion:** No backache, underlying neurological deficit, history of spine injury, brain injury, polio,	**Scoli:** n=33, 8 males, 25 females. Age 14.7 (2.6yo;11-17yo). Cobb: 16.3° (9.4°; 10-50°). All had double curves (with right thoracic apex T6-T8, lumbar apex L2-L3). **Scoli10-19:** n=23, 7 males, 16 females. Age 14.6 (3.2yo). Cobb 11.7° (2.7°; 10-20°). All had double curves (with right thoracic apex T6-T8, lumbar apex L2-L3). **Scoli20-50:** n= 10, 1 male, 9 females. Age 14.9 (1.7yo). Cobb 29.3° (9.6°; 20-50°). All had double curves (with

		CP or congenital or acquired bone deformities	right thoracic apex T6-T8, lumbar apex L2-L3). **Ctrl:** n=41, 12 males, 29 females. Ages 14.7 (2.8yo; 11-17yo).
Zoabli et al (2007)	Retrospective cohort	**Inclusion:** AIS where the entire span of the curve had been imaged using SE_T1 MRI images **Exclusion:** Not reported	**Scoli:** n=17patients (25 curves), 4 males, 13 females. Age 11.6 (3.2yo). 9 single, 7 double, 1 triple curve. 2 proximal thoracic, 14 main thoracic, 9 thoracolumbar/lumbar curves.

***Group characteristics not reported were not reported in the paper**
Abbreviations: Ctrl – control group; Lbs – pounds, Reps – repetitions, Scoli – overall Scoliosis group; Scoli-prog = progressive Scoliosis; Scoli-Nprog = non progressive Scoliosis; Scoli<x –Cobb angle descriptor; Scolipre-op- preoperative Scoliosis; Scolifastprog- fast progressive Scoliosis; Scolislowprog- slow progressive Scoliosis, yo = Years old,
Symbols: *p<0.05, ~ p<0.01, Ŧ p<0.001, § p<0.10, Symbols are reported when exact p value was not reported in the reviewed paper. ±X=SD ()= range []=median/interquartile range

Table 2.6 Description of the tasks and measurements used to test muscle function for each study included in the review describing differences in functional properties between AIS and controls.

Study	Measurement and task (dose)	Muscle groups & outcomes	Differences in functional properties in AIS vs. controls
Dobosiewicz et al (1997)[44]	EMG latency Standing on a box with a trapdoor allowing the box to tilt 8 ° to either side. (4 times on each side. 30 seconds between recordings)	Paraspinal muscles EMG Latency at T8 (time from stimulus to the unloading reflex response in ms) Number of rebound/silent reflex cycles	**Mean latency of unloading reflex** **Scoli FastProg** (73 to 94 ms) larger than **ScoliSlowProg** (51 to 60 ms)*, **Pelvic tilt Scoli** (41 to 50 ms,*) ŧ and* **CTRL**(47 to 49 ms, *$p<0.001$)ŧ* **The number of unloading reflex cycles at T8** **Scoli FastProg** (1.5 to 2.1) smaller than **ScoliSlowProg** (3.0 to 3.8) *ŧ*, **CTRL** (4.1 to 4.3*)ŧ and* **Pelvic tilt Scoli** (4.2 to 4.7*)ŧ*
Feipel et al (2002)[45]	EMG activity: 1) isometric contraction of heterolateral obliques, 25kg in opposite hand 3reps/side (1min rest between sides) 2) one way bending with arm swing 3) one way bending without arm swing 4) bending and return without arm swing 5) bending and return with 2kg in each hand Tasks 2-5**:** 5 reps/side (30sec rest)	Rectus abdominii, obliques, spine extensors RMS ratio calculation: Heterolateral RMS /Homolateral RMS	**Group by side interaction:** A significantly larger RMS ratio and asymmetry (larger during left tasks) in **Scoli** compared to **CTRL**. **Group by muscle interaction:** Differences between groups at recording sites at T10 and L1(both 3 and 6cm from midline), L3 (6 cm), and abdominal sites. **Group by Task interaction:** Not significant $p>0.05$ Pairwise comparisons missing for all interactions and main effects involving factors with more than 2 levels. Means provided for all group, muscles, sides and tasks even though 3 way interactions were not reported and the 4 way interaction was not significant.
Filipovic et al (2006)[46]	EMG activity Two different step tests, left	Erector spinae, gluteus maximus	**Mean during the left step test** Erector spinae **Scoli:** left: 0.141±0.047; right: 0.140±0.051

	& right. Subjects stepped up to a 16 inch tall bench and stepped down on a force plate. Subjects stepped alternating left and right at the sound of a signal for 15 seconds	Undefined parameter to quantify EMG activity	**CTRL:** Left: 0.220±0.238; Right: 0.245±0.249 Gluteus maximus **Scoli:** left 0.448±0.299; right: 0.096±0.049 **CTRL:** left: 0.414±0.251; right: 0.187±0.242 A significant discriminating function between the **Scoli** vs **CTRL** (Wilks lambda, 0.639*, canonical correlation coefficient = 0.60)*. Among 14 discriminating variables considered, there were somewhat more significant correlation (0.26 – 0.45) for the function of the variables of the right and left erector spinae muscles, right gluteus maximus, as well as the latero-lateral ground reaction force. The discriminative function successfully classified 78.7% of all subjects. The classification was more successful in Scoli (90.6% identified as Scoli) than Ctrl(53.3% identified as Ctrl). The right step test did not show any significant discriminative value.
Fuller et al (1991)[66]	Spring scale dynamometer, Leighton flexometer, Overhead pull, overhead push, press of arms and shoulders, knee extension. (3 reps bilaterally, then 3 reps unilaterally) ROM for trunk lateral flexion and rotation.	Dynamometer "tests for shoulders and arms require the action of transverse spinal muscles." Best score of 3 trials in lbs of weight lifted ROM (units not specified)	Significant **group** by age interaction in MANOVA of 4 strength variable using $\alpha<0.10$ ($p=0.0989$) Of 4 post-hoc ANOVA, 2 had significant **group** by age interactions (strength both arms p=.0252, strength dominant arm p=.0462). **Scoli-14-15yo** had significantly lower strength in unilateral and bilateral movements, regardless of dominance than **Ctrl 14-15yo** **Arm Shoulder Strength scores:** **Bilateral Scoli**- 2.10 vs **Ctrl** 2.43lbs§ **Dominant**: **Scoli**- 1.23 vs **Ctrl**- 1.45lbs§ **Non-dominant: Scoli**: 1.16 vs **Ctrl**: 1.41lbs § No significant differences in overall strength tests in **Scoli vs. Ctrl** for age 11-12 and age 13 subgroups.

			Scoli (268§) significantly less trunk flexibility towards the dominant side than **Ctrl (**280) (p=0.0677)
Mahaudens et al (2005)[48]	EMG activity, strength measurement Walking (5 strides averaged from one 10m walk) Kendall manual muscle strength tests	Quadratus lumborum, erector spinae, gluteus maximus, gluteus medius, abdominals Duration of EMG activity as a % of stride Kendall manual muscle testing (0-5 scale: 0= no contraction – 5=normal strength)	EMG: Prolonged duration of activation in erector spinae (**Scoli**: 141.4±27% vs **Ctrl:** 102.5±33% p=0.01)* and quadratus lumborum muscles (**Scoli**: 146.7±40% vs **CTRL:** 109±34% p=0.02) but not in other muscles. Manual muscle test: No differences in median scores for erector spinae, and both gluteus (5 both groups) but abdominal muscles weaker in **Scoli** (median 3/5) than **CTRL**. (4/51)
Mahaudens et al (2009)[49]	EMG activity Walking on a treadmill at 4km/hour (Variables recorded for 20secs and averaged for 10 successive strides)	Erector spinae, quadratus lumborum, gluteus medius, rectus femoris, semitendinosus, tibialis anterior, gastrocnemius Duration of EMG activity as a % of stride	EMG activity duration was higher bilaterally in **Erector spinae** **Scoli<20°, Scoli-20-40°, & Scoli>40°** (50.8±11%, 42.9±10%, and 40±8.8%, respectively)* compared to **Ctrl** (31.4±6.7%) ŧ **Quadratus lumborum** **Scoli<20°, Scoli-20-40°, & Scoli>40°**(50.5±8.2%, 43.8±9%, and 42.8±9% respectively)* vs. **Ctrl** (34.5±7.1%) ŧ **Gluteus medius** Prolonged duration in **Scoli<20°, Scoli-20-40°, & Scoli>40°** (49±4.3%, 48±4%, and 47.3±3.5% respectively)* vs. **Ctrl** (40.4±5.2%) ŧ Overall muscle activation duration higher for 46% of stride in **Scoli** vs 35% in **Ctrl** ŧ
de Oliveira et al (2011)[50]	EMG activity, torque measurement during trunk extension 3 isometric contractions (8	Erector spinae Normalized RMS (to MVIC) Mean torque (Nm)	There were no significant differences in erector spine muscles activity between **Scoli** and **CTRL** groups at T8, L2 and L5 at 40, 60, or 80% MVIC (P >0.05). No significant differences in mean MVIC torque between

	seconds for each of 3 MVIC percentages: 40%, 60%, and 80%)		**Scoli** 12.9 ± 4.2Nm and **Ctrl** 14.2 ± 5.7Nm p>0.05
Skrzek et al (2003)[75]	Strength measurement Maximal extension/flexion strength tests (from 20^{O} hyperextension to 50^{0} flexion in sitting) @ 90°/s and 120°/s in both groups Max strength (10 reps)	Trunk flexors and extensors Extension peak torque (Nm) Flexion peak torque (Nm) Extension peak torque/body mass (%), Flexion peak torque/body mass (%), Extension time to peak torque (ms) Flexion time to peak torque (ms) Extension total work (J) Flexion total work (J) Extension mean power (W) Flexion mean power (W)	Significant differences in most outcomes **90° Scoli:** 133.8±37.2Nm, **CTRL:** 157.8±27.9Nm, p=0.008 **120° Scoli**: 110.4±41.2Nm, **CTRL**: 146.2±31.4Nm p=0.000 **90⁰ Scoli**: 101.9±25.9Nm, **CTRL**116.0±19.1Nm, p=0.022 **120° Scoli**: 83.9±27.2 Nm, **CTRL**: 115.1±20.3Nm p=0.000 **90° Scoli**: 278.1±77.3%, **CTRL**: 294.5±57.2% p>0.05 **120° Scoli**: 230.1±91.2%, **CTRL**: 273.9±66.2% p=0.042 **90⁰ Scoli**: 211.8±53.8%, **CTRL**: 217.0±42.1% p>0.05 **120⁰ Scoli**: 174.6±55.9%, **CTRL**: 215.9±46.1% p=0.003 **90° Scoli**: 255.4± 131.8, **CTRL:** 428.5± 202.7ms p<0.001 **120° Scoli**: 195.1 ±62.8, **CTRL:** 120°: 365.8± 131.0 p<0.001 **90° Scoli:** 238.6± 61.5ms, **CTRL:** 324.6± 200.0ms p=0.0019 **120° Scoli:** 262.6±75.7ms, **CTRL:** 309.6± 150.8ms p>0.05 **90° Scoli:** 333.4± 112.6J, **CTRL:** 396.1± 88.8J p=0.022 **120° Scoli:** 240.7± 123.0J, **CTRL:** 316.9± 111.3J p=0.016 **90° Scoli:** 234.8± 59.8J, **CTRL:** 328.9± 72.3J p<0.001 **120° Scoli:** 193.4± 66.2J, **CTRL:** 291.9± 73.7Jp<0.001 **90° Scoli:** 127.0± 43.7W, **CTRL:** 129.7± 30.6W p>0.05 **120° Scoli:** 110.8± 59.0W, **CTRL:** 125.1± 43.9W p>0.05 **90° Scoli:** 88.6± 27.5W, **CTRL:** 117.8± 23.8W p<0.001

			120° Scoli: 89.1± 32.4W, **CTRL:** 127.8± 31.2W p<0.001
		Extension acceleration time (ms)	**90⁰ Scoli**: 53.7± 14.0ms, **CTRL**: 55.8± 21.9ms p>0.05 **120**° Scoli: 63.7± 17.5ms, **CTRL:** 65.0± 22.1ms p>0.05
		Flexion acceleration time (ms)	**90⁰ Scoli**: 119.7± 37.9ms, **CTRL**: 84.2± 26.3ms p<0.001 **120**° Scoli: 127.4± 30.0ms, **CTRL:** 94.2± 30.1ms p<0.001
		Extension deceleration time (ms)	**90⁰ Scoli**: 145.4±27.3ms, **CTRL**: 266.5± 36.3ms p<0.001 **120° Scoli**: 146.3±16.5ms, **CTRL**: 273.1± 36.0ms p<0.001
		Flexion deceleration time (ms)	**90⁰ Scoli**: 72.0±9.9ms, **CTRL**: 148.1± 38.9ms p<0.001 **120° Scoli**: 77.4±8.5ms, **CTRL**: 163.5± 30.6ms p<0.001

Abbreviations: Ctrl – control group; Lbs – pounds, Reps – repetitions, Scoli – overall Scoliosis group; Scoli-prog = progressive Scoliosis; Scoli-Nprog = non progressive Scoliosis; Scoli<x –Cobb angle descriptor; Scolipre-op- preoperative Scoliosis; Scolifastprog- fast progressive Scoliosis; Scolislowprog- slow progressive Scoliosis, yo = Years old,
Symbols: **p*<0.05, ~ *p*<0.01, Ŧ *p*<0.001, § *p*<0.10, Symbols are reported when exact *p* value was not reported in the reviewed paper. ±X=SD ()= range []=median/interquartile range

Table 2.7 Description of the tasks and measurements used to test muscle function for each study included in the review with results describing differences in functional properties between sides in patients with AIS compared to controls.

Study	Measurement and task (dose)	Muscle groups & outcome	Differences in functional properties convex VS concave in AIS vs controls
Dobosiewicz et al (1997)[44]	EMG latency Standing on a box with a trapdoor allowing the box to tilt 8 ° to either side. (4 times on each side. 30 seconds between recordings)	Paraspinal muscles EMG Latency at T8 (time from stimulus to the unloading reflex response in ms)	In **ScoliFastProg, ScoliSlowProg, Pelvic Tilt Scoli and CTRL,** The reflex response was found to be symmetrical on both sides of the body when tilting to the right or left. In patients with progressive idiopathic Scoliosis, the latency was prolonged on the side opposite the curve during both left and right step tests.
Feipel et al (2002)[45]	EMG activity: 1) isometric contraction of heterolateral obliques, (25kg in opposite hand, 3reps/side, 1min rest between sides) 2) one way bending with arm swing 3) one way bending without arm swing 4) bending and return without arm swing 5) bending and return with 2kg in each hand (Tasks 2-5: 5 reps/side, 30sec rest)	Rectus abdominii, obliques, spine extensors RMS ratio calculation: Heterolateral RMS /Homolateral RMS	**Group by side interaction:** A significantly larger RMS ratio and asymmetry (larger during left tasks) in **Scoli** compared to **CTRL.** **Group by muscle interaction:** Differences between groups at recording sites at T10 and L1(both 3 and 6cm from midline), L3 (6 cm), and abdominal sites. **Group by Task interaction:** Not significant p>0.05 Pairwise comparisons missing for all interactions and main effects involving factors with more than 2 levels. Means provided for all group, muscles, sides and tasks even though 3 way interactions were not reported and the 4 way interaction was not significant.
de Oliveira et al (2011)[50]	EMG activity, 3 isometric extension contractions (8 seconds for each of 3 MVIC percentages: 40%, 60%, and 80%)	Erector spinae Normalized RMS (to MVIC)	There were no significant differences in normalized erector spine muscles activity between **Scoli** and **Ctrl** groups at T8, L2 and L5 at 40, 60, or 80% MVIC (*P* >0.05). Within each group, no significant differences between sides at T8, L2 and L5 at 40 and 60% MVIC and at T8 and L2 at 80% MVIC. **At 80% MVIC** **Scoli:** greater normalized RMS at L5 on the convex side 129±26.9 vs the concave side 76.53±6.7* **Ctrl:** greater normalized RMS at L5 on the left side 129±32.6 vs the right side 77.85±11.4*

Tsai et al (2010)[52]	EMG activity Concentric and eccentric contraction of trunk extensors at 30 and 90⁰/sec (3 reps of eccentric extension during flexion movement followed by concentric extension at 90 ⁰/sec then 30⁰/sec, over a range from 0° to 90⁰ where 90⁰ is standing, with 10 min rest between velocity levels)	Medial paraspinals (Day 1) Lateral paraspinals (Day 2) RMS	Did not test if the amount of convex/concave asymmetry differed between groups but reported within-group side comparisons. (RMS estimates reported graphically and therefore not extracted) **Thoracic region:** **Ctrl:** No significantly different RMS between sides in medial paraspinals **Scoli-10-20°:** No significantly different RMS between sides in medial paraspinals **Scoli >20-50°:** RMS of medial paraspinals on non-dominant side was significantly higher than on the dominant side eccentrically during flexion 90°/sec, and concentrically during extension 30° and 90⁰/sec No difference in thoracic lateral paraspinals between sides in any group **Lumbar region:** **Ctrl:** RMS in medial and lateral paraspinals was significantly higher on the dominant side eccentrically during flexion at 30 and 90°/sec and concentrically during extension at 30°/sec and only for lateral paraspinals at 90⁰/sec.Ŧ **Scoli-10-20°:** RMS in medial paraspinal was significantly higher on the dominant side eccentrically during flexion at 90⁰/sec and concentrically in extension at 30 and 90°/s. Ŧ Lateral paraspinals had higher activity on the dominant side only concentrically in extension at 30°/s. Ŧ **Scoli >20-50°:** No differences between sides in medial and lateral paraspinal muscles. P>0.05

Abbreviations: Ctrl – control group; Lbs – pounds, Reps – repetitions, Scoli – overall Scoliosis group; Scoli-prog = progressive Scoliosis; Scoli-Nprog = non progressive Scoliosis; Scoli<x –Cobb angle descriptor; Scolipre-op- preoperative Scoliosis; Scolifastprog- fast progressive Scoliosis; Scolislowprog- slow progressive Scoliosis, yo = Years old,
Symbols: *p<0.05, ~ p<0.01, Ŧ p<0.001, § p<0.10, Symbols are reported when exact *p* value was not reported in the reviewed paper. ±X=SD ()= range []=median/interquartile range

Table 2.8 Description of the tasks and measurements used to test muscle function for each study included in the review with results describing differences in functional properties between sides and levels in patients with AIS

Study	Measurement and task	Muscle groups & outcomes	Differences in functional properties within AIS patients between sides and levels
Alexander et al (1978)[53]	EMG Activity Lying prone and standing (unspecified duration)	Paraspinal muscles i) Insertional activity- muscle activity (raw signal) at rest. ii) Activity vs silence during tasks	No overall abnormal insertional activity. **In prone:** 30/31 patients had EMG silence on both sides of curve at the apex. 1 patient had activity at the apex **In standing:** In 20/31 subjects EMG activity was higher on the convex side and activity was minimal (or silence) on the concave side. In 6 patients there was silence on both sides of the curve, 2 of these were balanced curves. 2 subjects had balanced activity on both sides of the curve.
Cheung et al (2004) [63]	EMG activity Standing upright in a relaxed posture, with arms along the body and feet together (unspecified duration)	Erector spinae bilaterally at UEV, apex, and LEV Convex/concave EMG activity ratio	Ratios of convex:concave activity: **Scoli-Nprog:** UEV: 0.96 (0.81:1.15) *p*=N/A APEX: 1.30 (1.10:1.54) p=0.033 LEV1.09 (0.93:1.26) *p*=N/A Significant asymmetry only at apex **Scoli-Prog:** UEV: 1.47 (1.08:2.00) p=0.033 APEX: 1.94 (1.46:2.57) p=0.033 LEV: 2.23 (1.60:3.11)p=0.000 Significant asymmetry at all levels Significantly higher asymmetry in Prog vs Nprog curves at all levels.
Cheung et al (2005) [34]	EMG activity 1) lying supine head straight, feet together and arms alongside the body, 2) sitting relaxed with hands on lap feet on ground	Erector spinae bilaterally at UEV, Apex, and LEV Convex/concave activity ratio (of absolute summated EMG amplitude of the total recording time.)	**Scoli-Nprog** mean (95%CI) **UEV Supine**: 0.69 (0.47:1.02) **UEV Sitting:** 0.87 (0.56:1.36) **UEV Standing:** 0.74 (0.55:1.00) * **APEX Supine:** 1.83 (0.58:6.26)* **APEX Sitting:** 2.51 (0.34:14.4)*

	3) standing relaxed arms at side, feet together (unspecified duration)		**APEX Standing:** 2.10 (0.58:6.26)* **LEV Supine**: 0.91 (0.74:1.13) **LEV Sitting:** 1.09 (0.77:1.55) **LEV Standing:** 0.96 (0.80:1.15) **Scoli-Prog:** **UEV Supine**: 0.97 (0.64:1.47) **UEV Sitting:** 2.00 (0.98:4.06) **UEV Standing:** 1.88 (1.00:3.55) * **APEX Supine:** 0.90 (0.62;1.33) **APEX Sitting:** 2.13 (1.33;3.43)* **APEX Standing:** 1.65 (1.15:2.36)* **LEV Supine**: 1.74 (1.10:2.76) * **LEV Sitting**: 3.37 (1.84:6.15)* **LEV Standing** 2.55 (1.50:4.34)* NProg curves have higher ratios than Prog for Apex supine. Prog curves have higher ratios than NProg curves for LEV supine, as well as for UEV and LEV sitting and standing.
Cheung et al (2006) [55]	EMG activity Standing upright in a relaxed posture, with arms along the body and feet together (unspecified duration)	Erector spinae bilaterally at UEV, apex, and LEV Convex/concave EMG activity ratio (measured as the area under the curve)	Ratios of convex:concave activity **Scoli-Nprog** UEV=0.92 (0.90:1.38) APEX=1.15 (1.06:1.67)* LEV= 1.10 (0.94-1.25) Significant asymmetry only at apex **Scoli-Prog** UEV=1.34 (1.06:1.94)* APEX=1.73 (1.43-2.86)* LEV=2.13 (1.36:2.60)* Significant asymmetry at all levels Levels were not compared statistically. Significant higher asymmetry in Prog vs Nprog

			curves at UEV and LEV levels.
Dobosiewicz et al (1997)[44]	EMG latency Standing on a box with a trapdoor allowing the box to tilt 8 ° to either side. (4 times on each side. 30 seconds between recordings)	Paraspinal muscles EMG latency (time from stimulus to the unloading reflex response in ms)	In **ScoliFastProg, ScoliSlowProg, Pelvic Tilt Scoli** the reflex response was found to be symmetrical on both sides of the body when tilting to the right or left. In patients with progressive idiopathic Scoliosis, the latency was prolonged on the side opposite the curve when tilting to the right or left. Means and significance not reported.
Feipel et al (2002)[45]	EMG activity: 1) isometric contraction of heterolateral obliques, 25kg in opposite hand 3reps/side (1min rest between sides) 2) one way bending with arm swing 3) one way bending without arm swing 4) bending and return without arm swing 5) bending and return with 2kg in each hand Tasks 2-5**:** 5 reps/side (30sec rest)	Rectus abdominii, obliques, spine extensors RMS ratio calculation: Heterolateral RMS /Homolateral RMS	Main effects for side (greater RMS ratios on the left side during right-bending), muscle, and task all significant on RMS ratios ($p<0.01$). Post Hoc tests demonstrated significance in all tasks exept for task 5. Mean only reported for all muscles, all tasks and sides individually not specific to the significant main effects.
Gram et al (1999)[56]	EMG activity Relaxed standing, sitting, erect sitting, and writing while seated (3 trials of 2 seconds for each position. Rest between positions)	Multifidus, illiocostalis, longissimus Activity, in microvolts	**Standing:** T6 multifidus convex 26.0 µv, concave 34.2 µv L1 multifidus convex 34.1µv, concave 20.7 µv L3 multifidus convex 59.6µv > concavity 31.3µv* L1 illiocostalis convex 54.7µv > concave 25.8µv* **Relaxed sitting:** T6 multifidus convex 41.4 µv, concave 48.4 µv L1 multifidus convex 29.5µv > concave: 22.1µv* L3 multifidus convex: 44.6µv > concave 19.4µv* L1 iliocostalis convex: 28.8µv, concave 20.9 **Erect Sitting**:

			T6 multifidus convex 88.3µv, concave 62.6 µv L1 multifidus convex: 49.2µv > concave: 29.7µv* L3 multifidus convex 64.6µv > concave 29.4 µv* L1 iliocostalis convex 53.7µv, concave 27.5µv **Writing**: T6 multifidus convex 65.3 µv, concave 65.6 µv L1 multifidus convex: 33.6µv > concave: 23.7µv* L3 multifidus convex: 48µv > concave 35.4µv* L1 iliocostalis convex: 42.6µv, concave 23.6µv Muscle activity varied significantly with posture on the concave side of the curve for the multifidus at Ll, Ŧ and for the iliocostalis at Ll,(p=0.01) with larger activity during the erect sitting posture compared to relaxed standing and sitting postures.
Mahaudens et al (2005)[48]	EMG activity Walking (5 strides averaged from one 10m walk)	Erector spinae, quadratus lumborum, gluteus maximus, gluteus medius, abdominals Duration of EMG activity as a % of stride	No differences in duration of EMG activity between concave and convex in **Scoli**. Means and statistical estimates not reported.
Mahaudens et al (2009)[49]	EMG activity Walking on a treadmill at 4km/hour (20secs recordings and averaged for 10 successive strides)	Erector spinae, quadratus lumborum, gluteus medius, Duration of EMG activity as a % of stride	No significant between side difference for duration of EMG activity in each Scoliosis group. **Erector spinae convex; concave** **Scoli<20°,** 50.8±11.0%; 43.3±6.7% **Scoli-20-40°,** 42.9±10%; 42.6±9.5% **Scoli>40°,** 40±8.8%; 42.7±6.9% **Quadratus lumborum** **Scoli<20°,** 50.5±8.2%; 43.9±8.9% **Scoli-20-40°,** 43.8±9%; 42.8±7.4% **Scoli>40°,** 42.8±9%; 48.8±9.8% **Gluteus medius** **Scoli<20°,** 49±4.3%; 46.2±3.2% **Scoli-20-40°,** 48±4%; 49.2±4.9% **Scoli>40°,** 47.4±3.5%; 50.7±3.9%

			No significant difference between the three Scoliosis groups for the EMG variables.
Mcintire et al (2008)[59]	Isometric trunk rotation strength Isometric rotation both toward and away from midline at starting positions of 36 , 18, 0, -18, and -36 ° (negative numbers indicate starting positions in rotation to the convex side) using Biodex Multijoint System 3 Pro testing machine.	Trunk rotators Torque normalized to lean body weight (Newton.meters/ kg)	No difference in normalized strength between corresponding contractions on the convex and concave side at any prerotated trunk position from neutral position - contractions towards concave (0.81± 0.25) vs convex (0.93± 0.23Nm/kg) **contractions towards midline:** -from an 18^0 pre-rotated position to the convex side (0.94 ± 0.17) vs to concave (1.00 ± 0.27) - from a 36^0 pre-rotated position to the convex side (1.07 ± 0.23) vs to concave (1.08 ± 0.25) **contractions towards outside (lateral):** -from an 18^0 pre-rotated position to the convex side (0.67 ± 0.20) vs to concave (0.62 ± 0.22) - from a 36^0 pre-rotated position to the convex side (0.55 ± 0.17) vs to concave (0.53 ± 0.25)
Mooney et al (2000)[57]	EMG activity & isometric trunk rotation strength Isometric rotation both toward and away from midline at starting positions of 36 , 18, 0, -18, and -36 ° (negative numbers indicate starting positions in rotation to the convex side) using MedX Torso Rotation Unit.	Paraspinal muscles, obliques EMG activity (raw), Isometric rotation torque (N.m)	In patients with AIS, EMG activity was asymmetric (between lumbar paraspinal muscle sides with direction not specified, higher activity in oblique, diminished in paraspinal. Mean activity not quantified. All participants with AIS had strength differences between sides ranging from 12-47% with 10/12 subjects weaker on concave side. (means reported graphically only.)
Shimode et al (2003)[58]	EMG latency Neck extension in prone position following a sound cue provided with random delays. (30-50 repetitions)	Erector spinae Difference in side to side premotor time in ms (D-PMT = Left PMT- Right PMT)	**Mean values of D-PMT** **UEV** = 1.17 ± 3.81ms p>0.05 **APEX** = 2.60 ±5.59ms p=0.007 **LEV** = 3.34 ± 6.72ms p=0.004 All ratios of D-PMT were significantly different

			from 0ms
Zoabli et al (2007)[60]	MRI None (Position when MRI captured)	Erector spinae Muscle volume, Muscle difference index MDI %= 1 / N Sum (I,N)(1-(volumeconcave/volumeconvex)x100	**% of sample with MDI values larger than 5% on each side:** Upper third of curve concave side : 15.3% vs convex 9.9% Middle third of curve (apex) concave: 15.8% vs convex 12.1% Lower third of curve concave: 14.3% vs convex: 9% -Similar over each third on the concave side and more important at the apex than above or below on the convex side. Largest muscle difference index more prevalent on concave side. **Muscle volume overall:** Concave: 103.3±51.3cm^3 Convex: 102.8±52.8cm^3 (Not significant)

Abbreviations: Ctrl – control group; Lbs – pounds, Reps – repetitions, Scoli – overall Scoliosis group; Scoli-prog = progressive Scoliosis; Scoli-Nprog = non progressive Scoliosis; Scoli<x –Cobb angle descriptor; Scolipre-op- preoperative Scoliosis; Scolifastprog- fast progressive Scoliosis; Scolislowprog- slow progressive Scoliosis, yo = Years old,
Symbols: *p<0.05, ~ p<0.01, Ŧ p<0.001, § p<0.10, Symbols are reported when exact p value was not reported in the reviewed paper. ±X=SD ()= range []=median/interquartile range

Table 2.9 Description of the tasks and measurements used to test muscle function for each study included in the review with results describing differences in functional properties between patients with AIS with different curve types

Study	Measurement and task	Muscle groups & outcome	Differences in muscle properties in patients with AIS between different curve types
Anjwaler et al (2006)[61]	Isokinetic torque Flexion and extension in sitting and semi sitting. (**Strength** testing: 10 reps each, ROM from 20° hyperextension to 50° flexion or 70° overall, 1-3 min rest between tests at different speeds. Movement speeds for concentric strength testing at 60, 90 and 120°/s in both groups.)	Spinal flexors and extensors 1) Peak torque (N.m) & normalized peak torque (N.m/kg) 2) Time to peak torque (ms)	**Peak torque:** did not differ by posture type (kyph, lord, equi), scoliosis type (Th vs ThL) or by size for all velocities and test positions. Means only reported graphically for posture subgroups for sitting. **Normalized peak torque** for flexion at 120^0/s in sitting entered a discriminant function to identify posture types**. Scoli-lord** 273.2 ± 70.2; **Scoli-kyph** 252.9 ± 99.8**; Scoli-equi** 224.0 ± 56.0Nm/kg **Time to peak torque** entered discriminant functions to identify posture types, scoliosis location, and curve size. **Time to peak torque** discriminated between posture types: for flexion in sitting at 60^0/s **Scoli-lord** 273.3 ± 70.2ms; **Scoli-kyph** 252.9 ± 99.8 and **Scoli-equi** 224 ±56.0ms. For extension at 120^0/s in the semi-sitting position **Scoli-lord** 182.2 ± 60.0ms; **Scoli-kyph** 242.0 ± 60.2ms and **Scoli-equi** 214.0 ±35.7ms.
Mooney et al (2000)[57]	Isometric trunk rotation strength Isometric rotation both toward and away from midline at starting positions of 36 , 18, 0, -18, and -36 ° (negative numbers indicate starting positions in rotation to the convex	Paraspinal muscles, obliques Isometric rotation torque (N.m)	The only 2/12 subjects demonstrating weakness on the convex side had double curves. The other 10 subjects had weakness on the concavity.

	side) using MedX Torso Rotation Unit.		
Zoabli et al (2007)[60]	MRI None (Position when MRI captured)	Erector spinae Muscle volume (cm^3), Muscle difference index MDI %= 1 / N Sum (I,N)(1-(volumeconcave/volumeconvex)x100	For the 9 single curves, muscle volume was: Concave= 116 ± 64 cm^3 , Convex = 109 ± 64 cm^3. For the 7 double curves, muscle volume was: Concave = 103± 46 cm^3, convex= 105± 50 cm^3 For the triple curve, muscle volume was: concave = 67±9 cm^3, convex = 73±14 cm^3. None of the side to side difference were significant, differences between curve types were not tested. 6/9 with a single curve had their largest differences on the concave side, but only two at the apical level. In 7/7 double curves, the largest difference of both deviations was always on the same side of the spine (4 left and 3 right). In 9/14 thoracic curves, largest MDI was also on the concave side and 5 times in the apex region.

Abbreviations: Ctrl – control group; Lbs – pounds, Reps – repetitions, Scoli – overall Scoliosis group; Scoli-prog = progressive Scoliosis; Scoli-Nprog = non progressive Scoliosis; Scoli<x –Cobb angle descriptor; Scolipre-op- preoperative Scoliosis; Scolifastprog- fast progressive Scoliosis; Scolislowprog- slow progressive Scoliosis, yo = Years old,
Symbols: **p*<0.05, ~ *p*<0.01, Ŧ *p*<0.001, § *p*<0.10, Symbols are reported when exact *p* value was not reported in the reviewed paper. ±X=SD ()= range []=median/interquartile range

Table 2.10 Description of the tasks and measurements used to test muscle function for each study included in the review with results describing associations between functional muscle properties and different curve characteristics (location, severity)

Study	Measurement and task	Muscle groups & outcomes	Association between muscle properties of patients with AIS with different curve characteristics
Anjwaler et al (2006)[61]	Isokinetic torque Flexion and extension in sitting and semi sitting. (**Strength** testing: 10 reps each, ROM from 20° hyperextension to 50° flexion or 70° overall, 1-3 min rest between tests at different speeds. Movement speeds for concentric strength testing at 60, 90 and 120°/s in both groups).	Spinal flexors and extensors 1) Peak torque (N.m) & normalized peak torque (N.m/kg) 2) Time to peak torque (ms) 3) Deceleration time (ms)	**Peak Torque** in extension at 60⁰/s in semi-sitting entered a discriminating function to identify **Scoli-0-30º** 132.4 ± 32.2 and **Scoli-31-60⁰** 160.2 ±50.6 **Time to peak torque** differed only for extension in sitting at 90º/s between **Scoli-0-30º** 14.4 **±** 2.2 and **Scoli 31-60⁰** 15.7 **±** 2.2 p=0.041 (other means not reported.) **Time to peak torque** discriminated between Scoliosis curve size: for extension at 60⁰/s in semi-sitting **Scoli-0-30⁰** 478.1 ± 134.6 vs **Scoli-30-60⁰** 394.4 ± 159.8. For extension at 90⁰/s in sitting **Scoli-0-30⁰** 228.9 ± 102.7 vs **Scoli-30-60⁰** 332.2 ± 178.9. **Time to peak torque** discriminated between Scoliosis location: for flexion at 60⁰/s in sitting **Scoli-Th** 264.0 ± 77.6 vs **Scoli-ThL** 233.0 ± 63.3. For extension at 60⁰/s in sitting **Scoli-Th** 307.2 ± 121.7 vs **Scoli-ThL** 388.0 ± 176.7. **Time to peak torque** discriminated between Scoliosis curve location: for extension at 120⁰/s in sitting **Scoli-Th** 150.0 ± 15.0 vs **Scoli-ThL** 137.0 ± 17.0. **Deceleration time** differed only for extension in sitting at 120º/s between **Scoli-Th** 150.0 **±** 15.0 and **Scoli- ThL** 137.0 **±** 17.0 p=0.033; and flexion at 60º/s in sitting **Scoli-Th** 69.6 **±** 20.1 and **Scoli- ThL** 87.0 **±** 13.4 p=0.017 (other means not reported.)
Cheung et al (2006) [55]	EMG activity Standing upright in a relaxed posture, with arms along the body and feet together (unspecified duration)	Erector spinae bilaterally at UEV, apex, and LEV Convex/concave EMG activity ratio (measured	Axial rotation of the vertebrae at the UEV decreases with increasing EMG ratio at the LEV. Spearman rho=-0.268 p=0.03 Correlations between axial rotation and EMG ratio at the UEV (rho =-0.166 *p*=0.17) or apex (rho= -0.106 *p*=0.38) were not significant.

		as the area under the curve)	
Filipovic et al (2006)[46]	EMG activity Two different step tests, left & right. Subjects stepped up to a 16 inch tall bench and stepped down on a force plate. Subjects stepped alternating left and right at the sound of a signal for 15 seconds	Erector spinae, gluteus maximus Undefined outcome	The discriminative analysis including 4 candidate muscle variables to distinguish between the 2 groups of patients with AIS with a Cobb angle ≤25°, as well as >26°, is not statistically significant for either of the 2 methods of performing the step test (Wilks Lambda for the left test 0.787 with 7 discriminating functions, p=0.585; Wilks Lambda for the right test 0.771 with 7 discriminating functions, p=0.426).
Mooney et al (2000)[57]	Isometric trunk rotation strength Isometric rotation both toward and away from midline at starting positions of 36 , 18, 0, -18, and -36° (negative numbers indicate starting positions in rotation to the convex side) using MedX Torso Rotation Unit.	Paraspinal muscles, obliques Isometric rotation torque (N.m)	The severity of strength differences did not correlate with the severity of curves.
Odermatt et al (2003)[62]	EMG activity Resist a trunk flexion perturbation (tested out of brace, weighted at 12% bodyweight. each task lasts 5 sec repeated 5 times, rest between tasks)	Longissimus, illiocostalis, rectus abdominis, external oblique, gluteus maximus RMS ratio convex/concave side	Linear correlation between increase in lumbar EMG asymmetry during the unbraced resisted flexion and the lumbar cobb angle with a slope of 15.9 and regression coefficient of 0.73.*
Shimode et al (2003)[58]	EMG latency Neck extension in prone position. One round of 30-50 repetitions	Erector spinae Difference in side to side premotor time in ms (D-PMT = Left PMT- Right PMT)	Spearman correlation Cobb angle vs D-PMT. -at UEV = -0.312 ns -at apex = -0.028 ns -at LEV =0.001 ns **<u>Mean D-PMT Progressive vs non-progressive</u>** UEV Progressive= 2.88±6.43ns, Non-progressive = 0.511 ± 1.95 ns APEX Progressive= 6.90±7.51 ŧ, Non-Progressive = 1.06 ± 3.83 ŧ LEV Progressive= 9.58 ± 7.51 ŧ, Non-Progressive = 1.12 ± 4.63 ŧ

Tsai et al (2010)[52]	EMG activity Concentric and eccentric contraction of trunk extensors at 30 and 90⁰/sec (3 reps of eccentric extension during flexion movement followed by concentric extension at 90⁰/s then 30⁰/sec, over a range from 0° to 90⁰ where 90⁰ is standing, with 10 min rest between velocity levels)	Medial paraspinals (Day 1) Lateral paraspinals (Day 2) RMS	No association between severity of Scoliosis and RMS **Dominant side:** Thoracic flexion r=-0.09 Lumbar flexion r= -0.13 Thoracic extension r=-0.14 Lumbar extension r= -0.21 **Non-dominant side:** Thoracic flexion r=0.36 Lumbar flexion r=-0.15 Thoracic extension r=0.26 Thoracic flexion r=-0.05

Abbreviations: Ctrl – control group; Lbs – pounds, Reps – repetitions, Scoli – overall Scoliosis group; Scoli-prog = progressive Scoliosis; Scoli-Nprog = non progressive Scoliosis; Scoli<x –Cobb angle descriptor; Scolipre-op- preoperative Scoliosis; Scolifastprog- fast progressive Scoliosis; Scolislowprog- slow progressive Scoliosis, yo = Years old,
Symbols: *$p<0.05$, ~ $p<0.01$, Ŧ $p<0.001$, § $p<0.10$, Symbols are reported when exact *p* value was not reported in the reviewed paper. ±X=SD ()= range []=median/interquartile range

Table 2.11 Description of the tasks and measurements used to test muscle function for each study included in the review to determine the associations between muscle properties and curve progression

Study	Measurement and task	Muscle groups & outcome	The associations between muscle properties and curve progression
Cheung et al (2004) [54]	EMG activity Standing upright in a relaxed posture, with arms along the body and feet together (unspecified duration)	Erector spinae bilaterally at UEV, apex, and LEV Convex/concave EMG activity ratio	**Scoli-Nprog:** UEV: 0.96 (0.81:1.15) APEX: 1.30 (1.10:1.54)* LEV1.09 (0.93:1.26) Significant asymmetry only at apex **Scoli-Prog:** UEV: 1.47 (1.08:2.00)* APEX: 1.94 (1.46:2.57)* LEV: 2.23 (1.60:3.11)* Significant asymmetry at all levels Significant difference between Prog vs Nprog curves at all levels. The EMG ratio at the LEV at the start of the period was significantly associated with progression (*r* = 0.371ŧ). Multiple Regression with a standard error 4.4^{0} predicted change in Cobb angle ° = -0.882 + 1.177*ln (spinal growth velocity) + 2.403*ln (EMG ratio at LEV). Using ROC curve analysis, a cutoff point for the EMG ratio at the LEV of 1.25 yielded an equal sensitivity and specificity of 68.9%. A cutoff point for the EMG ratio of 0.79 showed a sensitivity of 95% but only 28.0% accuracy. A specificity of 95% could be achieved at a cutoff point for an EMG ratio of 2.91 with an accuracy of 82.1%. ROC data was used to create a nomogram to demonstrate the ability of spinal growth velocity (SGV) and EMG ratio to establish the probability of progression over the next 4-5 months. **EMG Ratio <0.8** SGV<8mm/yr=0% SGV 8-15mm/yr=0% SGV>15mm/yr=0% **EMG Ratio 0.8-2.0** SGV<8mm/yr=0% SGV 8-15mm/yr=20% SGV>15mm/yr=43% **EMG Ratio>2**

			SGV<8mm/yr=0% SGV 8-15mm/yr=60% SGV>15mm/yr=89% (sensitivity and specificity: 79.1%)
Cheung et al (2005) [34]	EMG activity 1) lying supine head straight, feet alongside the body, 2) sitting relaxed with hands on lap feet on ground 3) standing relaxed arms at side feet together	Erector spinae bilaterally at UEV, Apex, and LEV Convex/concave activity ratio (of absolute summated EMG amplitude of the total recording time.)	**NProg** curves have higher ratios than **Prog** at the apex supine. (p=0.021) **Prog** curves have higher ratios than **NProg** curves for LEV supine (p=*0.009*), sitting (p=0.003) and standing (p<0.001). **Prog** curves have higher ratios than **Nprog** curves at the UEV in standing (p= 0.007). (see means reported under objective 3 in table 3) Larger convex/ concave EMG ratios at the LEV in the sitting posture correlated with greater change in Cobb angle. (correlation estimates not reported)
Dobosiewicz et al (1997)[44]	EMG latency Standing on a box with a trapdoor allowing the box to tilt 8 ° to either side. (4 times on each side. 30 seconds between recordings)	Paraspinal muscles EMG latency (time from stimulus to the unloading reflex response in ms) Mean number of unloading reflex cycles	**Mean latency of the unloading reflex at T8** **Scoli-fastprog** (73-94ms)* **Scoli-slowprog** (51-60ms)* **Scoli-pelvtilt** (41-50ms)~ **Mean number of cycles** **Scoli-fastprog** (1.5- 2.1 cycles) ~ **Scoli-slowprog** (3.0- 3.8 cycles) ~ **Scolipelvtilt** (4.2-4.7 cycles) ~ For both variables all groups were significantly different from **Scoli-fastprog** Changes in latency correlated with disease progression and not age. (correlation estimates not reported)
Shimode et al (2003)[58]	EMG latency Neck extension in prone position. One round of 30-50 repetitions	Erector spinae Difference in side to side premotor time in ms (D-PMT = Left PMT- Right PMT)	Correlation between D-PMT at LEV and progression Spearman correlation: Change of Cobb angle vs D-PMT. -at UEV rho = 0.212 ns -at apex rho = 0.219 ns -at LEV rho =0.432 p= 0.009 **Mean D-PMT in Progressive vs non-progressive** **UEV :** Progressive= 2.88±6.43ns, Non-progressive = 0.511 ± 1.95 ns **APEX :** Progressive= 6.90±7.51 ŧ, Non-Progressive = 1.06 ± 3.83 ŧ **LEV :** Progressive= 9.58 ± 7.51 ŧ, Non-Progressive = 1.12 ± 4.63 ŧ

Abbreviations: Ctrl – control group; Lbs – pounds, Reps – repetitions, Scoli – overall Scoliosis group; Scoli-prog = progressive Scoliosis; Scoli-Nprog = non progressive Scoliosis; Scoli<x –Cobb angle descriptor; Scolipre-op- preoperative Scoliosis; Scolifastprog- fast progressive Scoliosis; Scolislowprog- slow progressive Scoliosis, yo = Years old,
Symbols: *$p<0.05$, ~ $p<0.01$, Ŧ $p<0.001$, § $p<0.10$, Symbols are reported when exact p value was not reported in the reviewed paper. ±X=SD ()= range []=median/interquartile range

Table 2.12 Results of quality assessment based on COSMIN criteria

Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	Total
Alexander et al (1978)	?	-	-	?	?	≠	+	+	-	?	-	-	-	-	≠	≠	-	-	-	?	?	≠	+	-	+	-	-	-	-	4/25
Anwajler et al (2006)	+	-	+	+	?	+	+	-	-	?	+	-	?	?	≠	≠	-	?	?	?	+	-	-	-	-	-	-	+	-	8/27
Cheung et al (2004)	+	-	+	?	-	?	+	-	+	+	-	-	-	-	+	+	-	-	-	+	+	-	-	-	-	-	-	+	+	11/29
Cheung et al (2004)	+	-	-	-	-	≠	+	+	-	+	+	+	+	-	≠	≠	-	-	-	+	+	-	-	-	-	-	-	+	+	11/26
Cheung et al (2005)	-	-	-	+	-	≠	+	-	+	+	+	+	+	-	+	+	-	?	?	+	+	-	-	-	-	-	-	+	-	12/28
Dobosiewicz et al (22)	+	-	-	+	-	-	+	+	-	-	-	-	-	-	-	-	-	-	-	?	?	-	-	-	-	-	-	-	-	4/29
Feibel et al (2002)	-	-	+	≠	-	≠	+	-	-	-	+	-	-	-	≠	≠	-	-	-	+	+	≠	-	-	-	-	-	+	-	6/24
Filipovic et al (2006)	-	-	-	?	-	≠	+	-	?	-	-	+	-	-	-	-	-	-	-	?	?	?	-	-	-	-	-	+	+	4/28
Fuller et al (1991)	+	-	+	+	?	+	+	-	+	-	-	-	-	-	≠	≠	-	?	?	+	+	≠	-	-	-	-	≠	+	-	9/25
Gram et al (1999)	-	-	+	?	-	≠	+	-	+	-	-	-	-	-	≠	≠	-	-	-	+	+	-	-	-	-	-	-	+	-	6/26
Mahaudens et al (2005)	-	-	-	≠	-	≠	+	+	-	+	?	-	-	-	≠	≠	-	-	≠	+	+	≠	≠	≠	≠	-	-	+	-	6/20
Mahaudens et al (2009)	-	-	+	+	-	≠	+	-	+	?	+	+	+	-	≠	≠	-	-	≠	+	+	≠	-	-	-	+	+	+	-	12/24
Mcintire et al (2010)	-	?	+	+	-	-	+	+	-	?	+	+	+	-	-	-	-	?	?	?	?	-	+	+	+	+	+	+	+	14/29
Mooney et al (2000)	?	-	-	?	?	+	-	-	-	?	+	-	-	-	≠	≠	-	-	-	+	+	+	-	-	-	-	-	+	+	7/27
Odermatt et al (2003)	-	-	+	+	?	+	+	-	+	?	+	-	-	-	-	-	-	?	≠	?	+	≠	+	-	+	-	-	+	+	11/27
Shimode et al (2003)	+	+	+	+	-	?	+	-	+	?	+	+	?	+	≠	≠	-	-	-	+	+	-	+	-	-	-	-	+	+	14/27

de Oliveira et al (2011)	-	-	+	+	-	+	+	-	?	-	+	-	-	-	≠	≠	-	-	-	≠	+	≠	-	-	-	-	-	+	-	7/25
Skrzek et al (2003)	?	-	+	≠	-	≠	+	-	-	-	-	-	-	-	≠	≠	-	-	-	≠	+	≠	-	-	-	-	-	+	+	5/23
Tsai et al (2010)	?	-	+	+	-	≠	+	-	-	?	+	+	+	-	-	-	-	?	-	+	+	≠	-	-	-	-	-	+	+	10/27
Zoabli et al (2007)	-	-	?	+	?	+	-	-	-	+	+	+	-	-	?	?	-	?	?	≠	+	≠	-	-	-	-	-	+	+	8/27

+ yes; - no; ? Unclear; ≠ Not applicable. Refer to table 1 for a listing of numbered criteria

Table 2.13 level of quality of EMG reporting based on the proportion of the ISEK criteria met

Study	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total score**	**EMG quality 50%**	**EMG quality 60%**	**EMG quality 80%**
Alexander et al. (1978)	+	-	-	-	+	-	-	-	-	2/9	Low	Low	Low
Cheung et al. (2004)	+	+	-	-	+	+	+	+	+	7/9	High	High	Low
Cheung et al. (2004)	+	+	-	-	+	+	+	+	+	7/9	High	High	Low
Cheung et al. (2005)	-	+	-	+	+	+	+	+	+	7/9	High	High	Low
Dobosiewicz et. al (2002)	+	-	-	-	+	-	-	-	-	2/9	Low	Low	Low
Feipel et al (2002)	+	+	+	+	+	+	+	+	+	9/9	High	High	High
Gram et al. (1999)	-	-	-	-	+	-	-	-	-	1/9	Low	Low	Low
Mahaudens et al (2005)	-	-	-	-	+	+	+	+	+	5/9	High	Low	Low
Mahaudens et al (2009)	-	-	-	-	+	+	+	+	+	5/9	High	Low	Low
Odermatt et al (2003)	-	-	-	-	+	+	+	+	+	5/9	High	Low	Low
Shimode et al (2003)	+	-	-	+	+	-	-	-	-	3/9	Low	Low	Low
De Oliveira et al (2011)	+	+	+	+	+	-	-	+	-	6/9	High	High	Low
Tsai et al (2010)	-	+	+	+	+	-	-	+	-	5/9	High	Low	Low

Refer to table 3 for list of ISEK Criteria corresponding to numbering
+ yes; - no

<u>Figures</u>

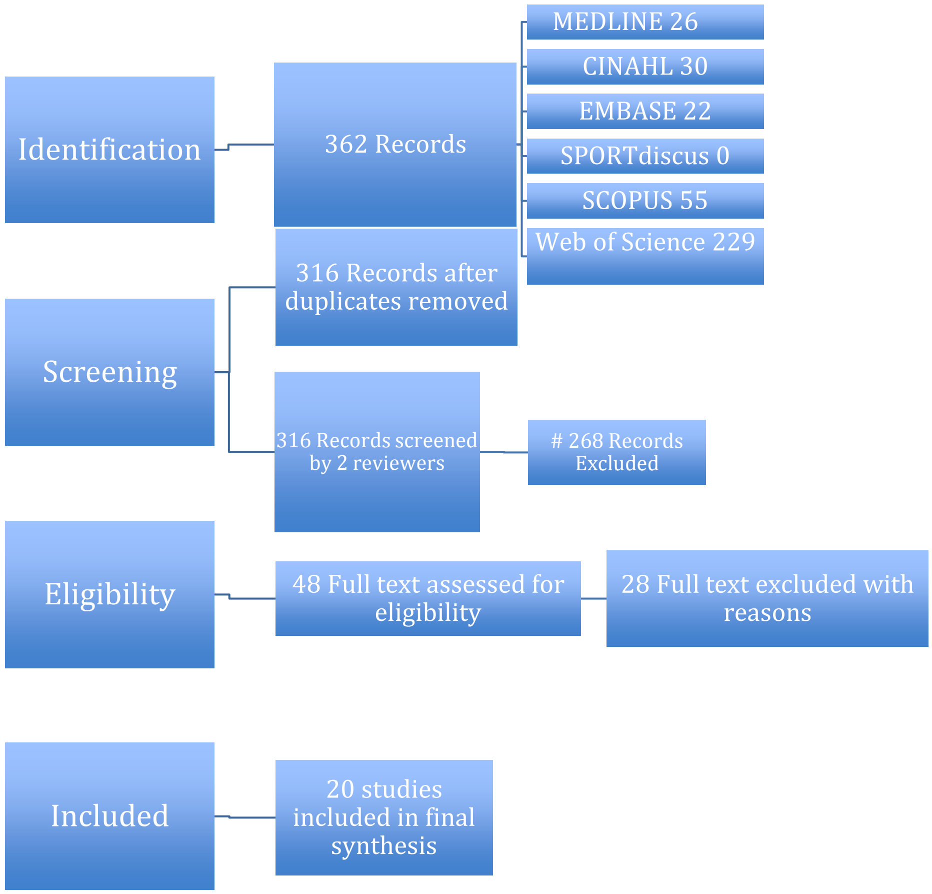

Figure. 2.1 PRISMA flow chart of the search process and inclusion/ exclusion numbers from the initial database search until final synthesis

Chapter 3:
EMG Measurement of the fatigability of paraspinal muscles of patients with adolescent idiopathic scoliosis: A case-control study

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Abstract

Introduction: Current exercise-based approaches to scoliosis management employ approaches to improve the endurance characteristics of paraspinal muscles. Our systematic literature review found no studies of paraspinal muscle endurance, however, a histochemical difference implying decreased endurance specific fibre types was previously reported on the curve concavity. This study aimed to determine differences in paraspinal muscle fatigability between patients with scoliosis and controls, between sides and between vertebral levels.

Methods: Adolescents with AIS treated non-operatively were recruited from a specialized scoliosis clinic and matched for age, gender and recording levels with healthy volunteers from the community. Subjects performed 3 'modified side planks' on both left and right sides as well as a Sorensen test. Bipolar sEMG electrodes were placed on either side of the spine at the upper end vertebrae(UEV), apex, and lower end vertebrae(LEV). The slope of the median frequency of the EMG power spectrum was extracted. A group by task by side by level repeated measures ANOVA was performed to detect differences in the average of the closest 2 out 3 fatigue trials. A group by task ANOVA was performed to determine if there were differences in trial duration between left and right planks and a t-test was performed to determine if there were differences between Sorensen durations.

Results: Twenty-one participants with scoliosis (age: 13.8±1.6 years, 18 females Cobb 24.2±9.9, BMI 19.7±3.5kg/m^2) were matched to control subjects (age 13.9±2.2 years, BMI:20.7±3.3kg/m^2). Fourteen subjects and controls also performed the Sorensen test. No interactions involving groups were found significant; the main effect of task on trial length was significant (longer on convex side in scoliosis and the corresponding right side in controls p=0.02). For side plank median frequencies, controls demonstrated more fatigue overall during planks compared to controls (p=0.046) and both groups demonstrated more fatigue on convex (right) sided planks p=0.045 and more fatigue at the UEV (p=0.007). In

contrast, both groups demonstrated more fatigue at the LEV during the Sorensen test compared to the UEV (p=0.015). Other effects did not reach significance.

Conclusions: While the hypothesized differences between patients and controls and between sides of the curves were not found, this study provides pilot information for future research by illustrating the variability resulting from heterogeneous curve types (13 double major, 5 triple major, 3 single curves) and severity (12-44°). Our sample size may have been too small to detect differences given the heterogeneity in curve types and recording levels in our sample. The tasks selected did not ensure as stable contraction and did not provide feedback to the examiner or patient on strength of contraction output or stability. As such it is unclear whether tasks elicited sufficient fatigue to detect differences. Future work should aim to use a stable task and measure activity in possible compensatory muscles in patients with scoliosis to understand their lower fatigability during side-planks.

Introduction:

Adolescent Idiopathic Scoliosis (AIS) is a 3-dimensional deformity of the spine diagnosed between the age of 10 and the completion of growth.[13] The cause of AIS is unknown but possibilities range from genetic influences, hormonal imbalances, and muscular imbalances.[2] However, it is unknown whether these factors are causes or effects of scoliosis.

Treatments for scoliosis within North America fall into one of three areas depending on the curve severity (measured by the Cobb angle) and progression (degrees of change in Cobb angle within a 6 month period). Adolescents with idiopathic scoliosis are simply observed periodically until their curve reaches 25° at which point a brace is prescribed. If progression continues and the curve reaches 45-50°, surgery is recommended.[2,13] Exercise approaches to scoliosis management exist, however, due to a lack of scientific quality of this literature[22,27] exercises have not made their way into North American guidelines for scoliosis management.[23]

One of the struggles facing advocates of exercise-based approaches for scoliosis is a lack of knowledge regarding the functional properties of paraspinal muscles and how imbalances in these properties affect patients with idiopathic scoliosis. Regardless of whether these imbalances are a cause or effect of the curvature, exercises should be justified by a rationale such as targeting the correction of known imbalances. The lack of knowledge on muscle functional properties makes it difficult to provide justification for exercises prescription parameters.

Our systematic review summarized in the previous chapter identified 20 studies o impairments related to the functional properties of paraspinal muscles. However, study quality was poor. The literature review highlighted a gap in documenting endurance as a functional property of paraspinal muscles in AIS. With such a gap there is poor background literature guiding investigation of endurance as a functional property of paraspinal muscles. Nevertheless, studying endurance is still important to understanding AIS especially in light of multiple scoliosis-specific exercise interventions using prescription parameters consistent with promoting endurance gains. The endurance abilities of paraspinal muscles have only been investigated with EMG methods in one study with less than 6 subjects. Endurance is relevant also because paraspinal muscles require endurance in order to maintain spinal alignment throughout the day and as such studying these muscles and their ability to perform their task is an important outcome to consider. Further contributing to the priority of studying endurance properties, prior research has identified imbalances in fiber type across the spine (decreased type 1 fibres), suggesting a deficiency in endurance properties of paraspinal muscles and their ability to maintain spinal alignment over a long period of time. In addition, McGill et al report that paraspinal muscle endurance is a better marker of spinal stability than strength, a more extensively studied outcome in the literature.[33,76] To our knowledge scoliosis-specific approaches do not state a rationale for their exercise parameters selection based on muscle impairments.[26] Nevertheless, an analysis of the prescription parameters used in different scoliosis-specific approaches shows that in the pursuit of better spinal alignment, postural muscles are challenged with high number of sets and repetitions are submaximal intensities consistent with targeting endurance capabilities. Thus research on scoliosis must explore whether a deficiency in muscular endurance exists in patients with scoliosis, and, if so, verify if it is an important target for exercise interventions. We postulate it is important due to the role of paraspinal musculature in maintaining alignment, and prior research findings into fibre type imbalances. Recommending exercise interventions before deficiencies have been confirmed and their manifestations understood might be suboptimal as the selected exercise parameters cannot be guided by documented muscle impairments.

Objectives

The aim of our study is to determine the differences in paraspinal muscle fatigability between patients with adolescent idiopathic scoliosis and matched healthy controls as measured by surface electromyography (sEMG) during side planks & the Sorensen test at the vertebral levels corresponding to the apex, upper and lower endpoint of the scoliosis curve on each side of the spine.

Based on fiber type research results on the paraspinals[8], we hypothesized that paraspinal muscles in patients will be generally more fatigable than controls and that the concave side will be more fatigable than the convex side at all levels.

Methods

Study design: A cross-sectional matched case-control study

Sample Size

Twenty-one adolescents with idiopathic scoliosis and 21 healthy controls were recruited for this project. This sample size was estimated to allow sufficient power (0.8) to detect an effect size of 0.6 for differences in fatigability (as measured by the slope of the median frequency in the EMG signal) between concave and convex sides of the curve within the patients with scoliosis using a bilateral hypothesis test and alpha level of 0.05. For comparisons between matched groups (related), with 21 subjects per group, with power of 0.80, an effect size of 0.60 could also be detected between patients and their matched controls.

Subject characteristics

Consecutive patients meeting the following selection criteria who attended the Edmonton Scoliosis Clinic were invited to participate. Participants with idiopathic scoliosis between the ages of 10 and 18 years old, with any scoliosis curve pattern and Cobb angles between 10^{O} and 50^{o} were included. Subjects having completed a scoliosis-specific exercise program, for whom surgery had been recommended, or those who had prior surgery were excluded. These selection criteria are consistent with patients eligible for scoliosis-specific exercises.[77]

Consecutive healthy teenage volunteers were matched to patients for age (±2 years), gender, and body mass index (BMI ± $5kg/m^2$). Healthy subjects were excluded if they presented with back pain (>2 pts on NPRS), leg length discrepancies (>2.5 cm), prior torso or lower extremity surgeries, contractures (>15^{o}), or a positive Adam's forward bending test (scoliometer>7^{o}). Any subject with low back pain due to a spinal fracture, tumor, infection, or signs of cauda equina compression; or pregnancy was excluded as these factors would affect the generalizability of the results.

Subject recruitment

Volunteers with AIS were recruited consecutively from the Edmonton Scoliosis Clinic by a research coordinator explaining the study to all eligible participants. Control volunteers were recruited consecutively from mailings to large local companies, local schools, as well as from posters and e-mailings on and nearby the University of Alberta campus. Patients with scoliosis participating in the trial were asked to invite friends without scoliosis to participate. The local health research ethics board approved the study. Informed consent was obtained from participants over 14 years old. Subjects under 14 signed an assent form while their parents signed a parental consent form.

Protocol

Volunteers attended one testing session. Both controls and volunteers with scoliosis were tested using the same protocol. Subjects first filled out questionnaires and underwent a physical examination to confirm eligibility. EMG electrode placement sites, identified by locating the vertebral level of the apex, upper and lower endpoints on recent radiographs from patients with AIS, were then located using ultrasound for both the patient and their matched control. EMG electrodes were placed on both sides of the spine at the identified levels corresponding to the curve apex, lower, and upper end vertebrae. Patients were instructed on proper execution while performing a 10 second modified beginner's side plank to warm up. After the warm-up, patients performed a modified beginner's side plank[38] (Fig. 1) on the left side.

Patients rested for 1 minute between trials. After three trials were performed on the left side, patients rested for 5 minutes before performing another three side planks on the right side. Continuous EMG recordings were taken as the plank position was maintained as long as the participants tolerated or until the patient had been instructed to correct their body positioning on two occasions. If a participant was able to maintain the plank position for 3 minutes, fatigue was assumed to be present and the test was ended. After completing the 3 side planks on each side, subjects rested for 5 minutes to allow muscles to recover from the side plank protocol. After 5 minutes, muscle recovery was assumed. Subjects were instructed on the Sorensen test (Fig. 2) and body position. Their legs were secured to the bed in two locations, on the thigh below the buttocks and on the calf muscles. Subjects were instructed to perform a 5 second practice hold to familiarize themselves with the movement. Subjects then held the Sorensen position for as long as they could. Subjects were reminded to maintain body positioning if their body dropped below parallel. If they were instructed to correct their positioning twice or they exceeded 4 minutes, fatigue was assumed to be present and the test was terminated. Subjects only performed the Sorensen test once.

Questionnaires

Physical Activity

Subjects reported their physical activity levels by filling out the 3-day physical activity recall (3DPAR) questionnaire. This questionnaire consists of listing which physical activities out of 55 possible activities participants engaged in primarily for each period of 30 minutes over the course of the last 3 days along with a specification of whether each of the listed activity was deemed light, moderate, or vigorous. The 3DPAR score is based on Metabolic Equivalent (MET) scores.[78] MET scores were determined based off of previous research exploring quantifying the kcal/kg expended during the listed physical activity in the 3DPAR.[79] Results were analyzed by averaging the number of 30 min blocks of activities rated at 3 METs or more (moderate to vigorous) over the 3 reported days, as well as, the total METs per day averaged over the 3 days. The 3DPAR results were used to explore any differences in physical activity levels between groups.

Quality of life

The Scoliosis Research Society questionnaire (SRS-22r), containing 22 questions relating to scoliosis related quality of life, was also filled out by each participant. Questions focus on 5 domains: pain, self-image, mental health, function with 5 questions each and satisfaction with treatment (2 questions). The SRS-22r has good test-retest reliability (ICC 0.95-0.85), internal consistency (Cronbachs $\alpha = 0.92$ to 0.75) and concurrent validity with the SF-36 (≥ 0.70 $P < 0.0001$).[80] The total score and the function domain score were used to describe our sample.

Pain

A numeric pain rating scale (NPRS) from 0-10 was used together with a *pain diagram* for subjects to report pain intensity and location.[81] This helped confirm eligibility and describing the participants' pain.

Physical Assessment

A physical examination was performed to describe the participants, determine eligibility and the safety of participation. Measurements included scoliometer measurements[82], Schroth curve type assessment[83], pain-free range of motion assessments of the shoulders (ensuring minimum abduction to 90°), elbows, (flexion to 90°), lower extremities (full squat), spine (full flexion and extension) as well as an assessment of pain-free side-bending. Scoliometer measurements were obtained by asking patients to bend forward with their arms stretched forward with palms pressed together while keeping the legs straight. The scoliometer (an angle measurement tool) is placed across the back to determine the extremes of rotations to each side at the most prominent points on either side of the spine during the test.[82] Patients also demonstrated the ability to maintain the side plank position without shoulder or arm pain (no exclusions). The Schroth scoliosis curve type[83] was determined to explore whether results may be curve type specific to provide pilot information for a follow-up study.

EMG Assessment

EMG Set-Up

Ag/AgCl surface electrodes (Vermed A10040-60) with an active diameter of 10mm were placed at the upper and lower endpoints of the curve, as well as, at the apex of the curve on both sides of the spine. Skin was prepared by rubbing the site with an alcohol swab and electrodes were placed after alcohol had vaporized from the skin as per SENIAM guidelines.[84] Hair was shaved if present on the placement site. Electrodes were placed on the erector spinae muscles as well as on the medial deltoid muscle with an inter-electrode distance of 20mm. Electrode placement was determined as per SENIAM guidelines.[84] Placement on the medial deltoid muscle was in line with the acromion and lateral epicondyle of the elbow on the bulge of the deltoid muscle.

The levels of the apex, upper, and lower end vertebrae measured from the latest out of brace radiograph were extracted from the scoliosis clinic database and used to determine electrode placement levels for the volunteer with scoliosis and their matched control. The electrodes were placed 2cm lateral from the spinous process of these vertebrae. These levels were located using ultrasound imaging before placing electrodes. A Sonosite M-Turbo ultrasound imager was used in B-mode to locate vertebra levels. A 2-5MHz curvilinear probe was oriented parasagittally over the lumbar spine with the sacrum in view. The probe was then moved superiorly while counting vertebrae until each of the three target levels (LEV, Apex, UEV) were reached. These transitional levels of the curve were marked on patients and their respective matched controls. A reference electrode was placed on the middle third of the left clavicle. Girls were tested wearing a bikini top. Boys were tested with their shirt off for the duration of the study.

Fatiguing task

Participants were positioned in a side lying position. Each participant first performed three modified beginners side plank (Fig. 1) on their left side with their legs bent and body weight resting on their knees with a 1 minute rest in between each plank.[38] Patient's thighs and torso were elevated until torso and thighs formed a straight line while resting on their elbow flexed to 90^{O}. The non-weight-bearing arm was placed across the subject's chest with the hand resting on the weight-bearing shoulder. Subjects were instructed to perform the side plank for as long as possible or until up to the 180 seconds limit stated earlier. Normative values for left and right side planks are 83.4-104.1 seconds for men and 55.2-75.1 seconds for women, respectively.[33] Proper body position was determined using an adjustable tennis ball suspended from the ceiling. Proper positioning was indicated when the patient's hip was in contact with the tennis ball. The first time patients deviated from the target position patients were reminded to keep their body aligned. The test was terminated after the second 'deviation.' Subjects rested for 5 minutes after which they were asked to perform another three side planks on the opposite side following the same protocol for termination as above. A 60 seconds rest was taken between each trial. Patients with scoliosis and their matched controls completed the side plank tests in the same order.

After completing the side planks, patients rested for 5 minutes and performed the Sorensen test. The Sorensen test was added after we noted a lack of fatigue in a preliminary analysis of our side plank data in the initial group of subjects with scoliosis. We then added the Sorensen as a stable task directly challenging the paraspinal muscles.[85] Only one Sorensen test was performed. Subjects were asked to stop the Sorensen testing once they deviated from the correct body alignment on two occasions or they maintained the position for 4 minutes.

Data Processing

The EMG signals for all 8 sites were amplified 5000×, low pass filtered at 1kHz and high pass filtered at 10Hz (Grass Model P511) before being digitized at 4000 Hz and stored to computer using an analog–digital converter (BNC 2090, National Instruments) using Labview 8.2 software. Raw sEMG signal were monitored in real time to ensure an appropriate signal quality during acquisition. The EMG data was analyzed within the Matlab programming environment using custom written software. The first 5 seconds of the recording were discarded to control for movement artefact while subjects adopted the test position and immediately before the spike of activity corresponding to when they let go of the side plank (fig 3).

The power spectrum was calculated using the fast Fourier transform. Temporal changes to the power spectrum were characterized using a 1.5 second sliding window (6000 points) which provided 83% overlap (5000 points) between consecutive windows. The median frequency was calculated from each window. These median frequency estimates were plotted against time and the slope of the median frequency was estimated using linear regression.

Once the median frequency slope data was extracted for each trial, the slopes of the best 2 out of 3 fatiguing trials were averaged. The best two trials were identified by finding the closest 2 slopes out of the 3 trials. Data from left and right planks as well as the Sorensen test were recoded as concave or convex to ensure that fatigue measurement was associated with side relative to the curve characteristics in all subjects regardless of curve direction. A side plank was deemed performed on the convex side when during the performance the convex side was closest to the table. For healthy subjects, the right side was always considered to be the convex side. No averaging was done for the Sorensen as subjects only performed one trial.

Statistical Analysis

Descriptive statistics were used to report the characteristics of both groups of subjects.

A group (control vs patients) by task (convex vs concave plank) by recording side (convex vs concave) by site (apex, upper and lower curve endpoints) mixed model ANOVA was performed to quantify differences in EMG indicators of fatigue. Bonferoni post hoc tests were planned as needed. All factors were considered dependent including groups because subjects were matched in this study.

Further, a group by side by task mixed-model ANOVA was used to quantify differences in indicators of deltoid muscle fatigue and another analysis was used to compare holding times between the two side planks.

A group (control vs patients) by recording side (convex vs concave) by site (apex, upper and lower curve endpoints) mixed model ANOVA was performed to quantify differences in EMG indicators of fatigue during the Sorensen test. Bonferoni post hoc tests were planned as needed. A paired T-test was used to compare the Sorensen holding times between the groups.

Spearman Rank Correlation tests were performed to determine the association between SRS-22 function scores and time to fatigue.

Results

Forty-two subjects were recruited for this study. The groups consisted of 21 patients and 21 controls. Both groups consisted of 3 males and 18 females. The control group's age (13.9 ± 2.2 yo) was closely matched to that of the scoliosis group (age 13.8 ± 1.6 yo). In the scoliosis group, the mean Cobb angle was 24.2±9.9° and ranged from 12^o to 44°. In controls, the mean Body Mass Index (BMI = weight(kg)/(height(m))^2) was 19.7 ± 3.5kg/m^2 which is similar to 20.7 ± 3.3kg/m^2 in the scoliosis group. The demographic information is presented in table 1.

Curve Type
Only two out of the 21 participants with scoliosis had left thoracic convex curves. Thirteen subjects had double major curves, three had triple major curves, and five had single right thoracic curves. The most common spinal upper end vertebral level tested was T6, T8 for the apex, and T12 for the lower end vertebrae. Schroth curve classifications yielded 15 subjects who were classified as 3c, 2 as 3cp, and 3 as 4cp.

Questionnaires
SRS-22 function domains scores were high in both groups (control=4.89±0.20 Scoliosis= 4.66±0.38 out of 5). Total SRS-22 Scores were high as well (Control = 4.66 ± 0.03 Scoliosis = 4.30 ± 0.51). Pain levels were low in both groups (Scoliosis= 0.84 ± 1.06, Control = 0.27 ± 0.43). The 3DPAR physical activity questionnaires demonstrated consistent results between groups. The control group had a mean MET score of 1.85 ±0.21 METS per day with an average of 3.72 ± 1.65 30min blocks of activities per day at over 3 METS. The scoliosis group had a mean MET score of 1.89 ± 0.31 METS per day with 3.61 ± 1.98 30min blocks of activities per day at over 3 METS (Table 1).

Task length

Side Plank
The group by task interaction was not statistically significant (p=0.58). The difference between groups in holding time was also not statistically significant (main effect of group p=0.114). However, a significant difference was found between plank holding time in both groups with a greater holding time on the convex side (58.9 ± 4.3sec) than on the concave side (50.5 ± 4.3 sec) (*p*=0.02).

Sorensen
Only 14 participants with scoliosis performed the Sorensen test, and their 14 matched controls were included in the analysis. The difference in holding times between groups did not reach significance (*p*=0.52). The control group trial length was 108.79 ± 50.79 sec and the Scoliosis group trial length was 91.36 ± 66.8 sec.

Fatigue analysis

Side Plank

The mean median frequency slopes indicating paraspinal fatigue estimated for each group, each side plank task at all the levels on each side of the spine are reported in Table 3. Results of the group by task by side by levels mixed model ANOVA for the side plank fatigue analysis are presented in Table 4. There were no significant interactions. All the main effects were significant (group p=0.046 task p=0.045, level p=0.007) with the exception of side (p=0.816). The control group expressed more fatigue overall (MDF slope -0.114) than the scoliosis group (-0.019), the concave plank elicited significantly more fatigue than the convex plank in all groups at all levels (concave: -0.110 vs convex: -0.023), and the upper end vertebrae presented significantly more fatigue than the lower end vertebrae (UEV= -0.166 APEX=-0.048 LEV= .015). Other pairwise differences between levels were not significant.

Shoulder fatigue

A significant effect for the shoulder fatigue measurement was only observed for the interaction between task and side p=0.036 and not for the other main effects (p>0.365) or interactions(p>0.293). Significantly more fatigue was observed for the shoulder on the concave side when performing the thoracic concave plank compared to the thoracic convex shoulder. Means and standard deviation of the median frequency slopes at the shoulder in both groups during both tasks can be found in table 3.

Sorensen test

The mean median frequency slopes for each group, side and levels tested during the Sorensen test are reported in Table 5. No significant interactions were present for the fatigue mixed model ANOVA for the Sorensen test (p>0.112).(Table 4) The main effects for group and side were also not significant (p>0.350). However, the main effect of level was significant, demonstrating significantly larger fatigue at the lower end (-0.368 CI= -

0.497 to -0.239)) compared to upper end vertebrae (-0.109 CI = -0.227 to 0.060) $p<0.05$.(Table 4)

Correlation
In patients with AIS, the Spearman's rank correlation coefficients between SRS-22 function scores and each task length for Sorensen or the Plank tasks were not statistically significant (Table 6).

Discussion

Summary of whether hypotheses are supported.

Holding times:
Contrary to our hypothesis about task duration, no significant differences were observed between groups for the Sorensen test or the side planks. However, a significant difference in holding time was observed between side planks with prolonged holding times on the convex side plank in both groups. Since all but two curves were right thoracic curves and subjects were able to hold for longer when their right side (controls) or convex side (scoliosis) faced down during the plank. The longer hold times may be attributable to side dominance rather than curve characteristics. It may be important to account for side dominance in future comparisons of fatigability between sides.

In this small pilot sample, controls had over 8 sec or 14% longer average side planks holding times, however this difference did not reach statistical significance possibly because of the relatively high variability observed among our control subjects. The Sorensen holding times noted in our groups were shorter than the means in other studies employing the Sorensen test.[33,86] Dejanovic et al found a range of 163 to 185 second for mean Sorensen holding times for male adolescents and 147 to 227 seconds in female adolescents. For left side bridges (concave side in right sided thoracic curves) mean values ranged from 80.7 to 102.4 seconds for males and 55.7 to 73.5 seconds for females. For right side bridges (convex side in right sided thoracic curves) mean values ranged from 83.4 to 104.1 seconds for males and 55.2 to 75.1 seconds for females.[33] The side planks we used were beginner side planks that we felt were more stable than the regular side bridge. Therefore, while similar mean holding times were obtained, in fact, the subjects in our study performed poorly compared to the mean time for the more difficult task. The subjects in our study performed poorly in both the Sorensen and side plank task when compared to normative values.

Paraspinal Fatigability

We hypothesized that there would be significant fatigue differences between groups based on earlier fiber type research suggesting that patients with scoliosis would demonstrate more fatigue overall and more pronounced fatigue on the side of the curve concavity.[8] The link between median frequency measurement of fatigue and fibre type can be understood through the underlying causes of neuromuscular fatigue. A number of potential reasons for fatigue exist, ranging from increased lactate concentration within the muscle fibres decreasing the overall pH as well as decreased blood flow and thus decreased oxygen delivery to the muscle.[87] Both these factors affect the efficiency of energy systems and channels within the muscle fibre leading to a decreased conduction velocity.[87] This affects the shape of the waveforms measured by EMG, lowering the median frequency of the signal measured by EMG.[87] Other explanations for the decreases seen in median frequency are the remaining activity of slow motor units as the fast twitch units are shut off as well as a potential change in the time synchronization in the activity of motor units.[87] Some muscle fibre types are specialized to withstand the effects of muscle fatigue (with more efficient energy systems) and thus different fiber types can tolerate increased lactate concentration and decreased oxygen delivery before conduction velocity is affected. These fibre types are commonly found in muscles that maintain prolonged contractions, such as the paraspinal muscles. Thus the documented decrease in type I fibres should be associated with a marked decrease in endurance measured by EMG.

Main effects for group, task and level factors but not side were significant for the side plank tasks. However, contrary to expectations, the scoliosis group demonstrated less fatigue in the paraspinals than the control group. This may suggest that the scoliosis group uses a different recruitment strategy involving compensatory muscle activations involving muscles such as the obliques, trasverse abdominis, or intercostal muscles to maintain alignment during the side plank. The need to monitor this potentially compensatory muscles in the future is highlighted in Mooney et al's findings of elevated EMG activity in the oblique muscles in patients with scoliosis when compared to controls.[57]

Another hypothesis was not supported, as we did not observe more fatigue in muscles on the concave sites in the group with scoliosis than in controls. However, as expected, more fatigability was observed during the plank performed with the concave side (left side in controls) facing down. We did not expect to record a difference in fatigability between tasks in controls but they also exhibited more fatigue when doing the side plank on their left side (corresponding to the concave side in scoliosis). As suggested, to explain holding time differences, we may need to consider upper limb dominance or control for participation in asymmetric physical activities in future studies.

In addition, overall (for both groups, planks and sides) significant differences between levels were observed during the side planks with the strongest expression of fatigue at the upper end vertebrae compared to the lower end vertebrae. This may be due to the activity in the multiple layers of muscles at the upper end vertebrae (trapezius and rhomboids) working to maintain scapular stability during these tasks.

Contrary to our expectations, we did not observe any significant interactions, main effect of group or a main effect of recording side during the Sorensen test. We expected a difference between levels but with difference between groups. The lack of significant interactions noted in our study may be due to the pilot nature of this analysis which included only 14 matched pairs of subjects and a heterogeneous group of scoliosis curves. For muscles on the convex side (right side for controls) of the spine the differences in point estimates at all levels were not statistically significant and also clinically insignificant between patients and controls (effect size <0.12). However, on the concave side, although differences did not reach statistical significance, patients with scoliosis compared to controls exhibited more fatigability at the apex level (effect size = 0.57) and less fatigability at the UEV (effect size = 0.48). These differences may not have reached statistical significance due to the high variability seen among curve types and severity in the scoliosis group and among controls when using only one repetition of the Sorensen test to estimate fatigue.

Additional comparisons may reach statistical significance if our sample size was increased. Smaller effect sizes than this study was powered to detect may be considered clinically important. The 21 subjects per group powers this study to detect moderate Cohen's d effects sizes of 0.66 for paired subject comparisons. Only effect sizes exceeding 0.81 could be detected as statistically significant with 14 paired subjects. The observed effect size may become significant with a larger sample size and with efforts to reduce the sample variability. Variability can be reduced by selecting more stable tasks, averaging multiple trials, and forming subgroups more homogenous for curve types and recording sites. While groups were matched for age, BMI, and measurement location, there may also be differences between groups based on their sport specific training, limb dominance and activity levels. A subject who regularly engages in a sport activating paraspinal muscles may exhibit performance differences when compared to another active subject whose sports participation does not activate the paraspinal muscles to the same extent. This distinction is not possible when using the 3D PAR to document physical activity levels.[88]

The literature sparsely reports fatigue characteristics of paraspinal muscles. In our review of the literature, two studies measuring endurance properties were reviewed. One was excluded as the sample size was too small (n=6), the other measured endurance through the use of isokinetic measurement rather than EMG. Gaudreault et al found no fatigue differences in the slopes of the median frequency between scoliosis and controls.[72] However, with such a small sample size it is difficult to draw conclusions from this paper. The other paper examined the endurance of paraspinal muscles during isokinetic tasks, however no comparison was done with controls. Patients with scoliosis performed similarly on strength tests (10 reps at 120°/sec) and the endurance test (20 reps at 120°/s). These differences were not tested statistically.[51]

Population

Both patients with AIS and controls scored highly on function scores in the SRS-22 measurement and on their physical activity levels. The literature on the 3DPAR recommends interpreting a daily METS output of more than 2 as meeting physical activity standards. Both groups expended a mean of more than 3 METS per day. Thus both groups exceeded minimal requirements for physical activity by more than 1 MET and can be considered physically active samples.[89,90] It is not possible to say exactly, however, how being more physically active affects muscular fatigue outcomes as the activity type may make a difference in muscular recruitment and activation. Other studies using the SRS-22 in patients with scoliosis treated non-surgically have also found high level of function.[22,91,92] In the future, it would be relevant to separately document the level of physical activity participation for activities providing endurance challenges to the spinal muscles and activities that don't. Stratifying the sampling to ensure adequate representation of patients within different physical activity level strata may be of interest.

Task selection

We had initially chosen the side plank as our measurement task, as we wanted a task hat would unilaterally challenge the paraspinal muscles. We postulated that a unilateral challenge would demonstrate deficits in the paraspinal musculature based on the finding of Mooney et al who found asymmetries between left and right rotation efforts.[57] This postulate was also based on the fact that scoliosis-specific exercise programs aiming to limit curvature progression, such as the Schroth approach, teach asymmetric corrections in the frontal and transverse planes.[26] After analyzing a sample of the first 10 scoliosis patients in the present study, we determined that the side plank task did not elicit the anticipated levels of paraspinal fatigue measurements. Subjects needed to constantly reposition themselves to maintain the side plank and had to be reminded to maintain adequate body position regularly. Fatigue was apparent in shoulder muscles as measured by median frequency slopes but not in paraspinal muscles. This suggests deltoid muscle fatigue may limit our ability to detect paraspinal muscle fatigue in patients using the side plank task. In future research on paraspinal muscle fatigability to understand whether patients with scoliosis rely on compensatory muscles to perform side bending tasks we recommend recording EMG from possible compensatory muscles such as gluteus muscles, quadratus lumborum, abdominal obliques, intercostals, and transverse and rectus abdominal muscles. Unfortunately, the depth of some of these muscles requires invasive needle EMG recordings. The need for position correction introduced variability in the EMG measurements of the paraspinals. In addition, possibly due to the lack of familiarity with the side plank, some subjects took longer to reach a stable position at the onset of the task and would return to a side lying position without warning when they felt they could not continue. Thus, the examiners had to determine task initiation and termination cutoff times when performing EMG analysis based on detecting and excluding the initial and final activity spikes in the raw EMG signal corresponding to the repositioning efforts. In our systematic review of the literature we were unable to find other studies measuring EMG fatigue employing the side plank. Gaudreault et al used a static contraction in extension at 75% MVIC[72] while Anwajler et al and Skrzek et al used a biodex dynamometer with 120°/s angular velocity performing flexion and extension in sitting and semi-sitting.[51,61] We attempted to limit the variability in our results by averaging the 2 most similar out of every 3 side plank trials completed in the present study.

The Sorensen test was therefore introduced partway through the study because it is a more stable task focused more specifically on the paraspinal muscles, is not limited by the fatigue observed in the shoulder, and it generated more fatigue in both groups. However, our results showed that the test poses more of a challenge to the lower levels of the spine rather than the higher levels where the thoracic curve of interest is located. Indeed, the lower paraspinal muscles resist larger loads because of the distance of the LEV from the centre of mass and proximity to the center of rotation during the Sorensen task. However, the Sorensen test is also prone to similar variability in muscle activations as the side planks as subjects are able to reposition themselves freely throughout testing. A more suitable methodology to apply resistance would be an extension, rotation, or side-bending task utilizing a dynamometer or load cell device in which the subject would be secured and asked to maintain a constant isometric force against a stable resistance. Thus, the ability of patients to reposition themselves during both tasks may have led to variability in the EMG recordings and hindered the detection of clinically important findings between groups.

Curve type

By recoding trials based on convexity, our analysis took curve direction into account and the curve direction was fairly homogenous in the sample (19/21 curves were right thoracic). We also only measured the thoracic curves and standardized the vertebral levels evaluated relative to their position in the thoracic curve. We matched the vertebral levels tested in patients and their matched controls. However, we did not consider the number of curves present for each patient in our final analysis. Paraspinal muscles were classified as concave and convex relative to the thoracic curve but this distinction may be problematic when at level of transition between two curves. The musculature on the convexity of the lower end vertebrae of a thoracic curve may be considered the musculature on the concavity of the upper end vertebrae on the lumbar curve. It is unclear whether the fatigue properties of the musculature at the transitional vertebrae between curves differ from those in single curves. Thirteen subjects had double curves, three had triple curves, and five had single curves. Future research should investigate fatigability within different curve type subgroups. While the apices of the thoracic curves in our study are similar to those used in Mannion's study of fiber type (T9-T11), it is unclear whether their subjects had single or multiple curves. In our systematic review, 3 studies created subgroups based on curve type[57,60,61] and some studies recruited only one curve type. Due to the differences in the biomechanics of different curve severities, number, and location, it is important to take these curve differences into account when investigating muscle properties in adolescent idiopathic scoliosis. The data from this study will provide preliminary estimates of the effect of curve type to justify the planning of a larger study considering differences between curve type subgroups.

Cobb angle and progression

Mannion's work on fiber type imbalance, which influenced the formulation of our hypotheses, was performed in surgical candidates with a Cobb angle range of 40-75°. Our range of Cobb angles were quite broad but included much smaller curves (15-44°) in order to determine whether fatigability could be an impairment logically targeted by scoliosis specific exercise programs indicated in smaller curves. Indeed, the exercise prescription parameters of many scoliosis-specific exercise approaches suggest that reducing fatigability in paraspinal muscles may be a goal pursued with the exercises. This observation is based on the dose of the exercises prescribed (high repetitions at submaximal intensities). These exercise programs for Schroth vary from 30min 2x/week to 6-7 hours daily over a long period of time). The exercise schools do not specify the muscle impairments targeted by the exercises beyond targeting the straightening of the alignment of the spine.[26] In contrast to Mannion's work, being a surgical candidate was an exclusion criteria for our study. It is unknown, therefore, how these fiber type imbalances express themselves in smaller curves.

Further, we did not take curve progression into account. While Cheung et al did not investigate the paraspinal muscle fatigability they demonstrated that patients with progressive curves exhibited the following characteristics compared to patients without progression: higher activity at the lower end vertebrae was correlated with increased cobb angle and progression.[34,55] Future longitudinal fatigability testing may be able identify whether fatigability measurements at different levels and in different curve types may help predict which curves progress over time. Treatment studies addressing these deficits could then be planned to examine the effect of correcting the fatigability impairments on curve progression in order to finally provide a physiological rationale for the mechanism of action of scoliosis-specific exercises.

As part of our systematic review on paraspinal muscle function characteristics, we found papers providing limited evidence that there are correlations between increase in muscle activity asymmetry and Cobb angle[61,62], as well as between increased muscle activity at the lower end vertebrae and curve progression.[34,54,55] Similar analyses are needed involving fatigue measurements.

Strengths & Limitations

To our knowledge this is the first study examining paraspinal muscle fatigue differences between those with scoliosis and healthy controls and with a sample size of more than 10 participants. The study enrolled a sample with broad inclusion criteria representative of patients likely to meet indications for scoliosis-specific exercises.[23] To maximize study quality, EMG methods were planned and clearly stated following ISEK criteria.[41] The standardized study protocol included repeated measurements of the side plank tasks, localization of vertebra levels using ultrasound and matched control recording sites to account for variability in curve location between subjects. Subjects were matched for BMI, age, and measurement location allowing for a rigorous comparison between patients with scoliosis and controls. Nevertheless the variability detected for each measurement in both groups suggest there is a need to create subgroups sufficiently large and homogeneous to understand the differences due to curve type, curve location and possibly history of progression.[55] The present study provides data to justify planning such studies and suggests that tasks ensuring stable contractions may be worth considering to minimize variability in fatigue estimates.

Unfortunately, due to the short timeline and difficulty in recruiting subjects, our study was limited by similar pitfalls observed in our systematic review. We were unable to create large subgroups based on curve type, severity, or risk of progression. It would be possible to perform an analysis based on subgroups for curve type and severity however, these results would be underpowered due to the low sample size of each subgroup. Nevertheless, the present study provides the largest sample of data on paraspinal muscle endurance in patients with scoliosis. Data from the present study will be used as pilot data to plan a larger study investigating differences between curve types and provided information on the ability of the investigated tasks to elicit fatigue in our target sample.

Conclusion

This study provides pilot information and informs future research into the fatigue characteristics of paraspinal muscles. No significant interactions between task performance were noted between groups with AIS or controls. Both groups demonstrated longer holding times on the convex sided planks but no differences in Sorensen hold times. Controls demonstrated more fatigue overall during side planks than the scoliosis group and more fatigue was expressed at the UEV compared to the LEV. The opposite differences were noted in the Sorensen test where significantly more fatigue was noted at the LEV compared to the UEV. The lack of significance in the interactions for some of the hypothesized differences may have been due to an insufficient sample size, the variability in the muscle activation during the task selected as the subjects struggled to maintain positions, and the variability in the curve types and vertebral levels corresponding to the UEV, apex and LEV. Observations from the present study suggest it would be useful to measure fatigue in paraspinal muscles through the use of median frequency slope as an outcome employing a more stable task, a larger sample size, and subgroups homogenous for curve types and sites of the UEV, apex and LEV recorded.

Table 3.1 Demographic characteristics and questionnaire outcomes in both groups

	Scoliosis	**Control**
Age	13.8 ± 1.6 years	13.9 ± 2.2 years
Gender	Males: N=3 Females: N=18	Males: N=3 Females: N=18
Cobb Angle	24.2 ± 9.9°	Not Applicable
Scoliometer	Max-=7.9 ± 3.17° Min= -6.15 ± 3.52° Sum= 14.05 ±4.01°	Not applicable
BMI	19.7 ± 3.5kg/m^2	20.7 ± 3.3kg/m^2
Pain Ratings /10	0.84 ± 1.06	0.27 ± 0.43
3DPAR Mean METS /day	1.89 ± 0.31 METS	1.85 ±0.21 METS
3DPAR Mean # of 30min blocks of activities at >3 METS/day	3.61 ± 1.98 activities >3 METS	3.72 ± 1.65 activities >3 METS

Table 3.2 Location and frequency of transitional vertebrae in the AIS group

UEV		APEX		LEV	
T3	2	**T7**	2	**T9**	2
T5	2	**T8**	6	**T10**	3
T6	12	**T9**	5	**T11**	3
T7	1	**T10**	3	**T12**	5
T9	1	**T12**	4	**L1**	3
T10	2	**L1**	1	**L3**	3
T11	1			**L4**	2

Table 3.3 Average holding time for the most similar 2 out of 3 trials on the planks performed on the convex and concave side and for the Sorensen test.

	N	Control*	Scoliosis
Convex Plank (sec)	21	65.5 ± 36.2‡	52.3 ± 17.7‡
Concave Plank (sec)	21	54.3 ±33.6‡	46.6 ± 20.7‡
Sorensen test (sec)	14	108.42 ± 50.79	91.36 ± 66.8

*the right side was recoded as convex in CTRL.

‡ In group by task ANOVA, no significant difference between groups (p=0.114) or for the group by task interaction (p=0.518). Significant difference between planks (p=0.02).

Table 3.4 Means and Standard deviations of Slope of the Median frequency for side planks on convex & concave sides at each EMG recording location

			Scoliosis		Control	
Plank Direction	**Side**	**Level**	**Mean**	**Std. Dev**	**Mean**	**Std. Dev**
Plank with thoracic convex side facing down	**Thoracic Convex**	**UEV**	-.030	.258	-.026	.517
		Apex	.057	.556	-.097	.356
		LEV	.015	.486	-.040	.334
	Thoracic Concave	**UEV**	-.013	.362	-.252	.478
		Apex	.104	.466	-.103	.415
		LEV	.087	.341	.023	.380
Plank with thoracic concave side facing down	**Thoracic convex**	**UEV**	-.283	.516	-.278	.573
		Apex	-.067	.289	-.128	.552
		LEV	.107	.434	.023	.635
	Thoracic Concave	**UEV**	-.229	.451	-.220	.372
		Apex	.035	.385	-.184	.443
		LEV	-.007	.320	-.092	.355
[redacted]						
Plank with Thoracic convex side facing down	**Convex shoulder**		-0.091	0.532	-0.075	0.3284
Plank with Thoracic concave shoulder facing down	**Concave shoulder**		-0.286	0.256	-0.198	0.299

Table 3.5 Statistical significance of the main effects, interactions for the comparison of fatigue measurements using the groupXtaskXsideXlevel mixed model ANOVA for side planks and a groupXsideXlevel mixed model ANOVA for the Sorensen test.

Effect	**Side plank tasks** ***p*** **value***	**Sorensen** ***p value****
Group	**.046**	.929
Task	**.045**	
Side	.816	.350
Level	**.007**	**.015**
Group * Task	.658	
Group * Side	.257	.988
Task * Side	.950	
Group * Task * Side	.704	
Group * Level	.380	.112
Task * Level	.172	
Group * Task * Level	.688	
Side * Level	.798	.214
Group * Side * Level	.707	.391
Task * Side * Level	.102	
Group * Task * Side * Level	.394	

**p value corresponding to Pillai's trace test of the effect*

Table 3.6 Mean slope (Hz/sec) of the Median frequency for paraspinals at each tested level on each side of the spine in both groups during the Sorensen Task.

		Scoliosis		Controls	
Recording Side	**Level**	**Mean**	**Standard. Deviation**	**Mean**	**Standard. Deviation**
Thoracic convex	**UEV**	-.150	.564	-.156	.359
	Apex	-.201	.306	-.119	.428
	LEV	-.279	.293	-.325	.457
Thoracic concave	**UEV**	.051	.556	-.179	.407
	Apex	-.408	.337	-.167	.505
	LEV	-.441	.326	-.426	.462

Table 3.7 Correlations between SRS-22r function scores and task lengths for each side plank and for the Sorensen test.

Holding time variables	**Spearman correlation coeffficients vs SRS-22r Function**	**p values (exact)**
Convex side plank	0.088	p=0.517
Concave side plank	0.085	p=0.737
Sorensen	-0.219	p=0.728

Fig. 3.1: Modified beginner side plank

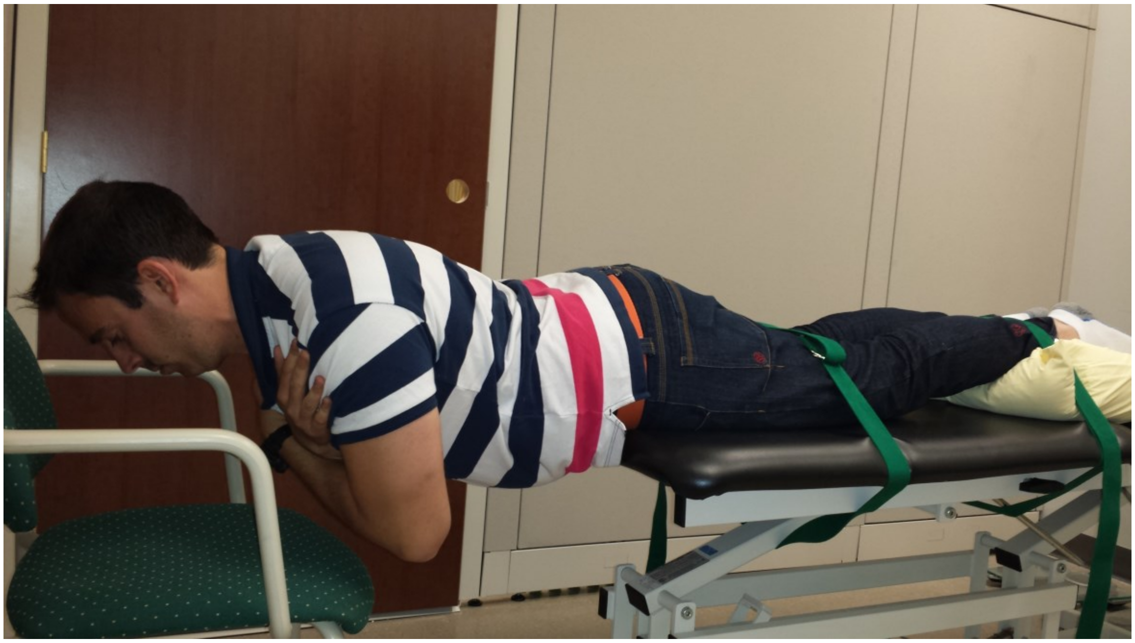

Fig. 3.2 Sorensen Test

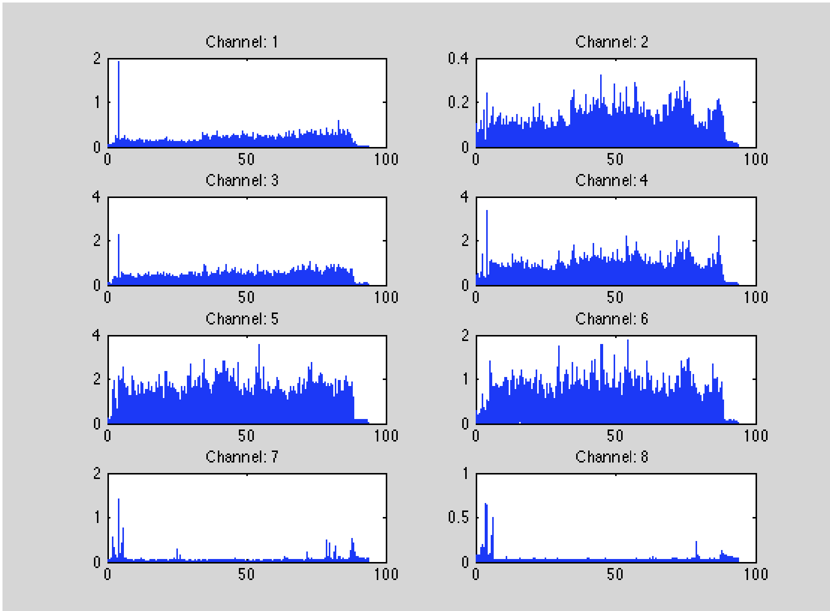

Fig 3. Raw signal of Sorensen test. A visible drop in signal can be seen when subject terminated the test. Channel 1,3,5= UEV, APEX, LEV on the left side. Channel 2,4,6=UEV, APEX, LEV on the right side. Channel 7,8= left and right shoulder respectively

Chapter 4: Discussion

This thesis sought to investigate the functional properties of paraspinal muscles in patients with adolescent idiopathic scoliosis. The thesis introduction and the chapter 2 and 3 discussions emphasized that endurance characteristics of paraspinal musculature in maintaining spinal alignment appear important to help prevent scoliosis progression. Histological analysis of paraspinal muscles has demonstrated that patients with scoliosis have type I muscle fibre deficiencies on the concavity of their curve, and a reduced proportion of type I fibres overall.[8] This deficiency may indicate a deficit in the endurance properties of paraspinal muscles in AIS. Due to the role of paraspinal muscles in maintaining spinal alignment, deficiencies in endurance may prevent them from maintaining alignment in response to postural demands over a long period of time. Current approaches to exercise appear to target endurance deficiencies[26,77], however, based on our systematic review in chapter 2, no specific impairments have been clearly documented to provide rationale for interventions targeting endurance. In summary, researchers and therapists need to be aware of the lack of research into the rationale behind current exercise interventions before recommending these approaches.

Our systematic review of the literature determined that exercise-based approaches were not yet based on a strong documentation of paraspinal muscle impairments within the literature. The scoliosis literature offers limited evidence to understand muscle properties, deficits, and imbalances.

Indeed for each of the 6 systematic review objectives at best limited evidence supported conclusions to understand differences between patients and controls, sides, curve location and severity, as well as the influence of muscle properties on progression risk within patients with AIS. The quality of research was poor. The reporting of EMG studies was relatively better in comparisons but still generally did not meet all ISEK criteria.[41] The level of evidence for each objective is only limited not only because of the study quality but also because of the heterogeneous methodology, subject characteristics, and outcomes studied to date. Interestingly, only one study was found that examined

EMG endurance properties[72] but unfortunately this study did not meet our inclusion criteria of a minimum of 10 subjects. Also for the only included study focused on testing endurance using isokinetic dynamometry unfortunately the analyses reported did not address the review objectives.[51] We therefore concluded that current exercise-based approaches to scoliosis management are not yet based on quality scientific inquiry. Specifically, the prescription of endurance-focused movements (high repetitions, long duration holds) often employed by popular exercise interventions are not yet based on scientific literature.

Overall, from our systematic review, we found that limited evidence existed to support the findings that:

- A prolonged bilateral EMG activation exists during gait between scoliosis & controls
- Elevated homolateral:heterolateral activity ratios exist during side-bending tests.
- Overall weakness in trunk extensor muscles between scoliosis and controls
- No asymmetry in normalized muscle activity during submaximal isometric contractions
- Prolonged latencies are present on the side of the spine opposite the curve and bilaterally in response to an unloading reflex
- Strength & muscle volume differences are present based on curve type with weakness and lower muscle volume present on the convexity in double curves.
- Axial rotation at the UEV is correlated with a high convex:concave ratio at the LEV
- No correlation exists between latency and curve severity, but prolonged latency can predict curve progression
- Larger convex:concave ratios can predict curve progression with correlations more pronounced during sitting postures

Conflicting evidence exists to support the findings that:

- Higher activity on the convexity of the curve exists during postural tasks in patients with AIS
- More pronounced activity on the convex side of the curve at the UEV, LEV, & APEX of the curve within patients
- More pronounced activity on the convex side of the curve at the LEV in progressive curves, and consistently pronounced activity at the APEX in non-progressive curves in patients.
- Strength differences exist between convex and concave sides of the curve in rotational strength.
- Muscle volume differences exist between concave and convex sides of the curve
- Correlations exist between RMS findings and curve severity and strength differences and curve severity

There are a number of outcomes that did not appear in the literature. As mentioned above endurance is an important marker of muscle function and as such should be studied further. In addition, muscle co-activations were studied by very few papers[57] and need to be studied further as they may shed light into compensatory patterns of muscle recruitment used by those with AIS.

To our knowledge this is the first review of paraspinal muscle functional properties in AIS. This review specifically aimed to document muscular deficits but did not aim to address the specific efficacy of treatment approaches at modifying these deficits. Future study of exercise interventions should aim to document muscle deficits at baseline and track changes in muscular properties throughout the treatment. This would allow for an understanding of the intermediate effect of exercises on physiological properties of muscle targeted by exercise interventions aiming to prevent curve progression.

With the documented lack of research into endurance outcomes related to the paraspinal musculature, a case-control study was designed to address this deficiency in the literature. Fatigability of paraspinal muscles was investigated through the use of the median frequency of the EMG signal over time to determine if differences exist between subjects with scoliosis and controls, overall, between sides, and levels of the spine. Subjects performed 3 side planks on each side as well as a Sorensen test. These were performed for as long as the subjects could hold the tasks. We expected to find differences between subjects and controls with greater fatigue expressed in subjects and more pronounced on the concave side of the curve. This was based on the findings of Mannion et al in which a lower proportion of type I (endurance specific) fibres were noted on the concavity. [8] However our hypothesis was not supported as we did not find any interaction between group, side, or level. Contrary to our expectations we noted that those without scoliosis demonstrated more EMG recorded fatigue than those with scoliosis during the side planks. We hypothesize that this result may be due to a different recruitment patterns of co-activations used by patients with scoliosis compared to controls. To confirm this hypothesis, in the future, it would be relevant to record activity in the abdominal, intercostal and possibly hips muscles which may have been compensatory muscles used by patients with scoliosis. Alternatively, this may also be due to our selection of an unstable task during which subjects could reposition themselves introducing variability in the EMG recordings, or to our small sample size combined with the heterogeneity in curve types and levels examined. For a follow up experiment, it may be more effective to use a task where subjects are stable and secured, such as a dynamometer in which the force exerted can be controlled and kept consistent between subjects. Our results suggest that to reduce variability in EMG estimates of fatigue, in the future, subjects could be recruited with only one curve type, preferable single main thoracic curves as a first attempt, in order to maintain a level of homogeneity between subjects and avoid the complexity in defining whether a muscles is on the convex or concave side of the curve due to the presence of other curves. In addition the time series measured as a part of the EMG signal analysis may play a role in the results of the median frequency. Certain factors such as de-recruitment of type II fibres,[93] or additional recruitment of type I fibres[94] may affect the consistency of the signal over time. Nevertheless, there is a possibility that no difference in muscular endurance exists between those with scoliosis and controls, however, more vigorous inquiry with higher methodological standards must be performed before that conclusion may be drawn as point estimates for some of our fatigue analyses appear clinically important although not yet statistically significant.

Fatigue is not present as an outcome in the systematic review, however measurement of EMG activity is common. Few studies measure this through a resisted task. Many studies employ short duration submaximal postural tasks[34,53-56] but these may not be effective at measuring fatigue to reflect the demand of daily tasks over long periods of time. Studies employing isometric holds often reported elevated EMG activity.[45,50,59] Despite conflicting results as to finding differences between patients and controls as well as sides, this elevated activity indicates that paraspinal muscles are firing and it would be useful to mimic these tasks in a prolonged activity in an attempt to induce and measure fatigue corresponding to daily challenges. Most commonly used tasks were isometric side-bending, rotation, and extension in a dynamometer.[45,50,57,62] Other studies used isokinetic movements, however, these are inadvisable when using sEMG as a measurement tool as EMG electrodes move relative to the muscles of interest throughout the dynamic ROM.[95]

EMG measurement of fatigue is used extensively in back pain research and it may be useful to employ methods of fatigue measurement used by back pain researchers.[96,97] Back pain studies have found consistent associations with back muscle extensor fatigue and trunk extension movements measured in a dynamometer at 25%, 50%, and 75% of MVC with an optimal MVC of 50%. Van Dieen et al also recommend fitting the slope of the median frequency to half of the total holding time in order to effectively assess the endurance capacity of trunk extensors.[96] It would be advisable for future research into paraspinal muscle fatigue in patients with scoliosis to examine the effect of adopting the methodologies used in the study of low back pain.

If no fatigue differences exist between patients and controls, as our pilot study results suggest, then another rationale must be given for justifying the use of exercise-based interventions to successfully limit curve progression. While not explicitly stated, the current application of exercise principles while analysis the dosage of exercises prescribed suggests that these interventions are aiming to improve endurance outcomes. If there is no endurance impairment, then exercise must achieve their effect on spinal alignment by targeting another outcome such as the latency, co-activation imbalances, the side-to-side strength differences or the strength differences documented related to controls.[47,51,57,58,61] However, as seen in the literature review, the research is still too limited to clearly identify a muscle impairment that would be applicable to prescribing targeted exercise interventions. At this point only the following impairments have demonstrated limited evidence of an association with risk of progression: Prolonged latencies and elevated convex:concave activity ratios particularly in sitting postures. These impairments may be primary targets to investigate to provide a rational to justify exercise interventions. While the current exercise-based approaches largely target endurance properties of paraspinal muscles, a number also address motor-control deficiencies. Prolonged latency is an indicator of poor motor control and therefore exercise interventions such as SEAS which aim to improve motor control[26] are consistent with this finding in our review.

Thus, this thesis has aimed to present a muscle impairment-based rationale for current providers of exercise-based therapy for scoliosis by systematically reviewing the literature and documenting paraspinal endurance impairments. Unfortunately, our review showed that currently the muscle impairment-based rationale is supported only by limited and conflicting evidence of generally poor quality. Our review also found no studies on endurance deficits. Nevertheless, this review's important findings of a lack of research on many muscle impairments and the limited quality of the available evidence, provides important guidance for future research on this topic. Gaps in the literature were clearly detailed in Chapter 2 and will help inform the planning of future research. Our investigation into the endurance properties of paraspinal muscles while aiming to match cases and controls, as well as control for physical activity levels, did not find the hypothesized lower endurance in patients with scoliosis compared to controls, possibly due to small sample size, unstable task selection, and not controlling for curve type. However, this pilot inquiry does open the door to study the endurance properties of paraspinal scoliosis by providing variability estimates for the planning of future studies of deficits of the paraspinal musculature in adolescent idiopathic scoliosis. Improving this body of evidence should guide the development of exercise protocols that are logically targeted to impairments related to curve progression.

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Appendix A:
Search strategy for Systematic Review

MEDLINE April 24, 2013

1. Scoliosis/
2. scoliosis.mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept, rare disease supplementary concept, unique identifier]
3. 1 or 2
4. spinal deformit*.mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept, rare disease supplementary concept, unique identifier]
5. 3 or 4
6. spinal muscl*.mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept, rare disease supplementary concept, unique identifier]
7. spinal musculature.mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept, rare disease supplementary concept, unique identifier]
8. erector.mp.
9. exp Spine/
10. exp Muscles/
11. 9 and 10
12. rotatores.mp.
13. longissimus.mp.
14. spinalis.mp.
15. iliocostalis.mp.
16. 6 or 7 or 8 or 11 or 12 or 13 or 14 or 15
17. force.mp.
18. strength.mp. or exp Muscle Strength/
19. exp Muscle Fatigue/
20. endurance.mp.
21. fatigability.mp.
22. muscle activity.mp.
23. exp Electromyography/
24. electromyogra*.mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept, rare disease supplementary concept, unique identifier]
25. muscle latency.mp.
26. latenc*.mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept, rare disease supplementary concept, unique identifier]
27. co-contraction.mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept, rare disease supplementary concept, unique identifier]
28. muscle timing.mp.
29. or/17-28
30. 5 and 16 and 29
31. limit 30 to humans
32. limit 31 to (("child (6 to 12 years)" or "adolescent (13 to 18 years)") and (english or french) and journal article)