Chapter

The Use of a Dynamic Elastomeric Fabric Orthotic Intervention in Adolescents and Adults with Scoliosis

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Abstract

The use of dynamic elastomeric fabric orthoses in the non-surgical management of scoliosis has been growing over the last 20 years in the paediatric populations and has now started to be used in adolescent and adult patients as well. The concepts of treatment concentrate on the use of movement and changes in the neurological pattern generation, to reduce scoliosis curve Cobb angles and pain that is sometimes experienced due to an altered positional sense. This chapter introduces research, including recent computer modeling, to demonstrate the effects of the combination of two different layered textiles which enable improved comfort, aesthetics as well as scoliosis clinical management. The textile combination enables a total body suit to use 3D scoliosis brace knowledge to assist in developing new orthotic interventions for adolescents and adults with both neurological and idiopathic onset scoliosis, for several different presentations.

Keywords: dynamic elastomeric fabric orthoses, spinal decompression, spinal translation, spinal tone management, pain relief, proprioception, exoskeleton

1. Introduction

There are different presentations of scoliosis, including genetic spinal deformities, neuropathic and idiopathic onset scoliosis, that develop in two to three percent of the population (depending on the research report) during skeletal development. Sometime this can cause complex management issues which can present at any age and continue well into adulthood and throughout the geriatric years. These presentations at times require differing orthopaedic, physical therapy and orthotic interventions to improve symmetry and pain management.

Rigid and semi-rigid bracing has been in existence for thousands of years. One of the earliest examples being an orthopaedic corset of a tree bark that was discovered painted in cliff dwellings of pre- Columbian Indians circa 900 AD (**Figure 1**) [1].

Furthermore, a number of interesting historical, almost medieval (by today's standards) devices have been designed to counter the deformities utilising complex metal designs to force the spine into a required position. A number of researchers have incorporated thigh fixation as described by German orthopaedists in the 19th and early 20th centuries (**Figure 2**) [1].

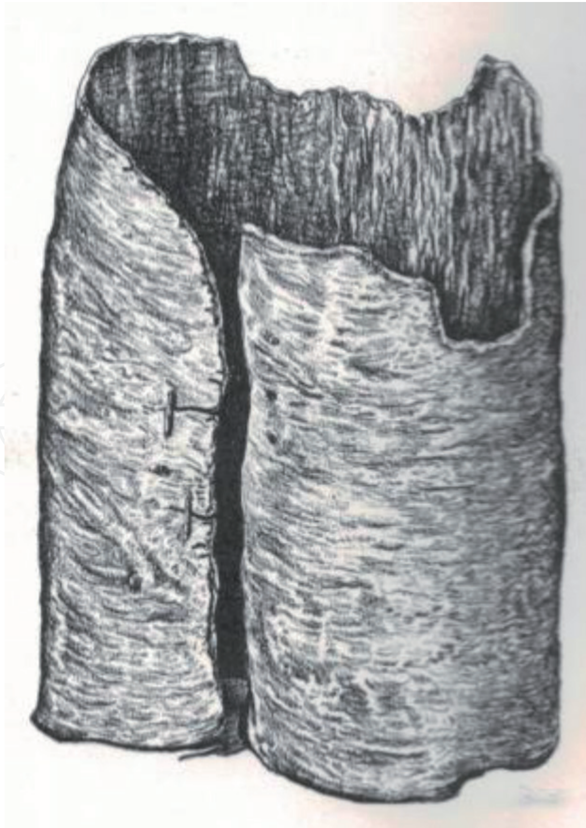

Figure 1.
Drawing of an orthopaedic corset of tree bark from the pre-Columbian Indians cliff dwellings Circa 900 AD. Colorado State Historical Museum (Denver).

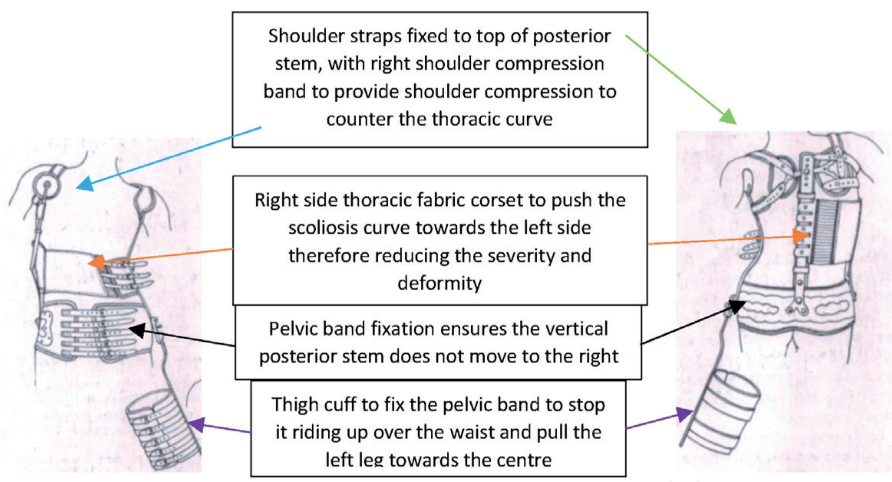

Figure 2.
Scoliosis brace with thigh attachment (Redrawn from an early print).

In 1971, the Boston modular rigid (**Figure 3**) and semi-rigid plastic spinal brace system was developed and has been used (and evolved) for over 40 years [2], becoming the stalwart of scoliosis management of both neurological onset and idiopathic scoliosis around the world.

Rigid bracing has been proven to be effective in preventing curves from progressing to the point of needing surgery and in some cases, have helped to reduce the curve magnitude [3]. The "Dose", the amount of time the patient wears the brace, has proven to be vital to bracing success. An international, partially randomized control trial (BRaist study) showed that if patients wore their full time brace an average of 12.9 hours per day or more, they had a 90–93% chance of not having

Figure 3.
Original Boston Brace made with 15 degrees of lumbar lordosis, fitted with compression pads and cut out to provide spinal asymmetry.

their curve progress to the point of requiring surgical intervention [4]. Wearing the brace for less than 6 hours per day, equated to a 42% chance of surgery requirement.

The opposite is true for neurological onset scoliosis, where a child with cerebral palsy (for instance), would wear similar corrective cast bracing. Spinal bracing would require "anniversary" casting (annual corrective brace casting) to ensure the brace was fit for purpose. The curve, however in neurological cases generally continues to worsen until the child reaches maturity in late adolescence and requires surgery to correct the spine. This happens even, with self-reported compliance. When compared to the natural history of neuromuscular scoliosis, bracing does not prevent the rate of curve progression [5], however there are reports that bracing improves seating [6], standing and walking postures as well as other benefits for people with neurological disorders.

Both idiopathic and neuropathic onset scoliosis presentations use the basic brace concept of marking up an x-ray to show the left/right lean and rotation of the vertebra at each level to inform the positioning of pads or pressure required to provide

Figure 4.
Bston Brace 3D-custom fabricated from scan, built in asymmetry.

the corrective force on the body, known as "blue printing". Blue printing also informs the position of the cutaway areas of the brace. **Figure 4** illustrates the result, using computer aided design and manufacturing (CADCAM) to carry out this role.

2. Scoliosis presentations

Scoliosis presentations are due to numerous causes and include genetic changes and omissions to the bony structures; neurological dysfunction to the muscles that support and stabilize the spinal structure; hypo-mobility disorders (Ehler Danlos Syndrome); degenerative scoliosis and dysfunctional learnt patterns of movement. All learnt functions like sitting and walking is a learned pattern of movement, which rely on movement through error based learning to recalibrate a particular movement and altered position awareness [7]. In children, with cerebral palsy (CP) their image of self is different to reality due to the difference in their internal model of self [8]. This shows in sitting, where they feel they are sitting straight, however in reality they are sitting to one side. This loads one side of the spine and sets up a dysfunctional pattern, which they learn and understand as normal. This results in the complex scoliosis cases we see in adolescents and adults- particularly when requiring wheelchairs. Most of these issues are generally identified during childhood, however, they can affect adolescents and adults of all ages with scoliosis, whether idiopathic or neuropathic in origin. Bracing is therefore a major intervention in adolescents and adults who cannot or do not want to follow the surgical route. Although there are several different scoliosis causes, this section will concentrate on the two main causes of scoliosis in adolescents and adults, which require bracing: idiopathic onset scoliosis (IOS) and neuropathic onset scoliosis (NOS).

Idiopathic onset scoliosis is defined as a lateral curvature of the spine, that is greater than or equal to 10 degrees with no known cause. It is further defined by the age of initial presentation, infantile (zero to 3 years), juvenile (3–9 years of age) and, adolescent (10–17 years of age). Progression is related to growth, so patients are most vulnerable to curve progression during periods of rapid growth as occurs during the adolescent years. The Boston Brace, which introduced the concept of using a symmetrical form to fabricate the original modules which then, depending on the patient's x-ray analysis (blueprint) and physical presentation, is trimmed and had strategically placed pads added to make it asymmetrical. Numerous studies have shown this method to be effective [3, 9]. Recently, through the advent of scanning and CADCAM technologies, a custom fabricated asymmetric model of the patient is used to fabricate the brace rather than the symmetrical form. The Boston Brace 3D (**Figure 4**), the ARTbrace and Rigo Cheneau - type braces, are examples that utilise three point triangular sideways movement (known as translation) viewed from the posterior using x-rays of the back, re-aligning a small number of vertebra causing a localised positional change {segmental moulding [10]}. They included the combination of forces for regional and local de-rotation to achieve corrective balance and physiological alignment in the sagittal plane [11] **Figure 5**.

These coupled with physiotherapeutic scoliosis specific exercises (PSSE) like Schroth physiotherapy work to keep the spine mobile [12], but are also held physically by a brace, which encourage the re-alignment of the spine during wear.

Neuropathic onset scoliosis (NOS) typically appears in early childhood, particularly in children with cerebral palsy (CP), and continues into adulthood due to the dysfunctional loading on the spine which causes vertebral and rib remodeling. Twenty five percent of people with CP will develop scoliosis curves and range from 5% incidence for bilateral spastic to 74% in people with quadrilateral- spastic presentations due to the imbalance of muscle pull, and brain damage [13]. Most curves

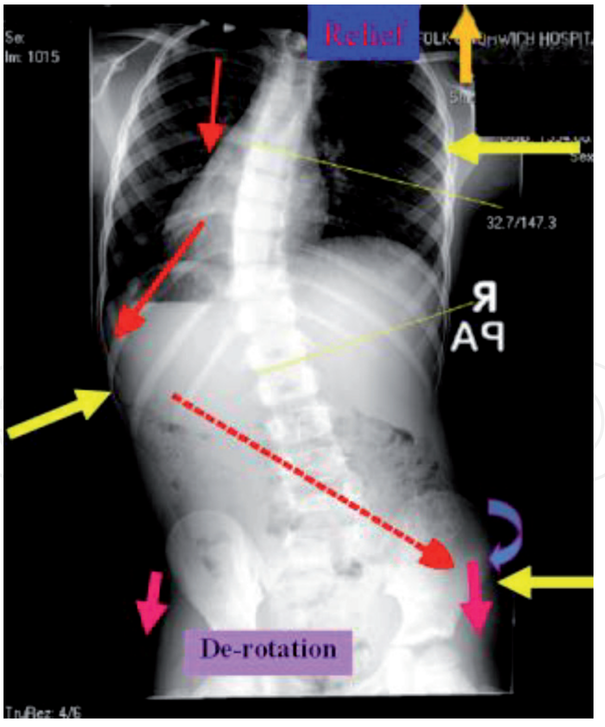

Figure 5.
Diagrammatic representation of X-ray blueprinting for dynamic elastomeric fabric scoliosis suit- identifying the three points of pressure (yellow arrows), distraction (orange arrow), downward compressive force (pink arrow) and de-rotational shoulder compression force (Red thin arrows).

present as a single thoracolumbar or lumbar "C" shaped curve associated with pelvic obliquity and hip dislocations, often seen in gross motor function classification scale (GMFCS) [14] Level 4/5 presentations.

The gross motor functional scale is a way of identifying what level of function a child with cerebral palsy can achieve and is divided into 5 levels.

Level 1 identifies children who can walk at home, school and in the community including outdoors with limited coordination, speed and balance when running and jumping.

Level 2 identifies children who can climb stairs holding on to a support rail, however they can experience difficulties in balancing and walking when on slopes and rough ground particularly when in crowded or confined areas.

Level 3 identifies children who need hand-held walking and mobility aids in doors and need supervision when climbing stairs. They will also tend to use self-propelled or powered wheelchairs for longer distances.

Level 4 identifies children with require physical assistance or powered mobility in most settings If physically assisted they can walk short distances around their homes and will often require powered wheelchairs and body weight support walkers. A self-propelled wheelchair or powered chair will be used whilst at school, outdoors and in the community.

Level 5 identifies children who are transported in manual wheelchairs in all areas. The children have a limited ability in maintaining head control and trunk posture [15]. They also have trouble with arm and leg control A classification at the age of 6 is unlikely to change level during adolescence into adulthood.

Therefore level 4 and 5 indicates that the child/young adults will be requiring wheel chair support, with basic or complex design dependent on severity [14]. A classification at the age of 6 is unlikely to change level during adolescence into adulthood. Twenty percent of scoliosis curves develop as a "S" shaped curve with balanced, symmetrical thoracic kyphotic and lumbar lordotic curves [13], normally associated with idiopathic scoliosis see **Figure 6a**, **b**.

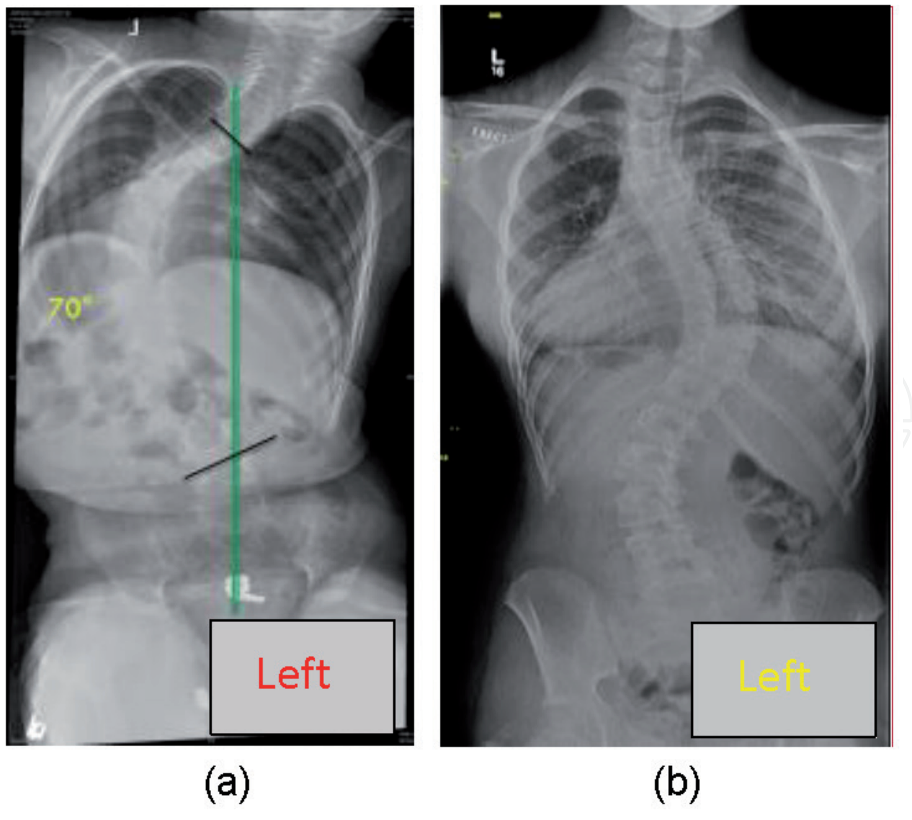

Figure 6.
(a) A typical "C" shaped curve to the left. (b) A typical "S" shaped curve with a left lumbar and right thoracic curve.

Adolescents with GMFCS Level 4/5 are dependent on wheelchairs for mobility, which due to a neuropathic or neuromuscular disease, have a 90% increased risk of progressive spinal deformities due to the impairments in postural balance and motor control [16]. There is also an increased risk of flexed sitting patterns due to hip flexion contractures, encouraging spinal deformity due to the loss of the protective lordosis and atypical loading patterns. These can lead to pain and discomfort leading to increased decline in the patients quality of life (QOL) [17].

Ehlers Danlos Syndrome is a group of disorders that affect the connective tissue that supports the tissues and human body organs, blood vessels, bones and skin [18]. The signs include extremely loose joints, which can sublux completely, coupled with extreme pain. In recent years, this connective tissue disease has been linked with young women presenting with scoliosis [19]. The women are often in their mid-thirties, following pregnancy and present with extreme pain, often due to nerve compression.

3. Elastic scoliosis bracing

Rigid and semi- rigid (foam based) spinal orthoses have been the common bracing option for adults, however the developments in dynamic elastomeric fabric orthoses (DEFO) using form fitting elasticated orthoses, have shown promise in the clinics based on the authors' clinical use. The use of "elastic" orthoses has become an additional bracing option, alongside rigid and semi-rigid scoliosis braces.

There are two variants of DEFOs that have evidence for use in scoliosis management, namely SpineCor® and Dynamic Movement Orthoses (DMO®). There are other Lycra suits, but they are mainly used in juvenile (less than 9 years of age) patients. As this chapter is concerned with adolescents (10–17 years of age) and adults (18 years of age and older) with scoliosis, they will not be discussed.

SpineCor® has a resemblance to an early somewhat simple, but controversial idea of using "Oblique and Spiral bandage" utilized by Richard Barwell of London in 1868 that purported to assist in scoliosis management (**Figure 7**).

An eminent surgeon of his time, Henry Bigg in 1877 [1], questioned the validity of this bandage. However, in recent years the use of diagonally activating compressive force correction now supports the early thinking behind the bandage type orthoses.

The SpineCor® brace has had some success in younger patients with idiopathic scoliosis, utilizing the compressive and de-rotative effects of strong elastic bands fixed to a bolero shaped vest and either a plastic anterior and posterior shell held in place by webbing straps, or shorts which enable fixation of the corrective straps. The original prospective observational study on the effectiveness of the SpineCor brace, used a standardised criteria proposed by the Scoliosis Research Society (SRS). The study included 170 patients (158 girls and 12 boys). Thirty-nine participants required spinal surgery, 12 withdrew and 14 participants were weaned out of the treatment as curve progression was deemed to be stable. Of the 105 remaining participants, 47 completed the 2-year brace follow up [20].

A more recent retrospective study evaluating the effects of the SpineCor brace that also followed the Scoliosis Research Society criteria for brace management of adolescent idiopathic scoliosis reported that the SpineCor® brace treatment could increase the risk of curve progression, when compared to the Boston Brace. Scoliosis curve progression occurs in the spine due to changes occurring naturally in the vertebra and intervertebral discs. If left without treatment the curve will increase exponentially [21]. The use of correctly fitted and function spinal brace will reduce the rate of curve progression and in most cases reducing the Cobb angle indicating curve regression. In the SpineCor brace study, a total of 243 patients were treated with either the Boston brace (146) or the SpineCor brace (97) with scoliosis

Figure 7.
Oblique and Spiral bandage utilised by Richard Barwell of London in 1868. (Page 182 Orthopaedic Appliances Atlas, Vol.1 1952).

curve progression recorded across the group. The average curve progression for the SpineCor cohort was 14.7° ±11.9°, compared to 9.6° ± 13.7°. The proportion of patients reaching 45° was 51% (SpineCor) and 37% (Boston Brace), however the proportion of patients referred for surgery was 39% (SpineCor) and 30% (Boston Brace). The paper concluded that the odds of reaching a ≥ 45 was 2.07 times greater when using a SpineCor brace [22].

Further comparison studies showed that the SPoRT (Symmetric, Patient oriented, Rigid, Three-dimensional, active braces) was more effective than SpineCor® [23, 24]. The SPoRT concept provides evidence of effect and is shared in three types of rigid braces. The Sforzesco brace joins two previous brace designs (Sibilla & Lapadula), to provide a new spinal concept which avoided the need for casting the worst scoliosis presentations. Brace compliance was a key driver for the new treatment journey and included mechanical efficacy, the active brace principle, versatility, and adaptability coupled with teamwork and patient compliance. Scoliosis correction is provided through the shape of the adjustable rigid body envelope, mechanical" pushes" encouraged the spine to move into a predetermined void, that adapted and remodeled body shape to unwind the scoliosis curve presentation (**Figure 8**).

A randomised controlled trial compared the SPoRT rigid concept with the SpineCor dynamic brace to identify the treatment effect over time. Using a retrospective controlled study, two groups were reviewed using clinical and X-ray evaluations. Data was recorded at the beginning and end of the study to record the scoliosis curve angles for SPoRT braces (20 patients) and SpineCor braces (41 patients). Both brace interventions proved to be effective in improving the aesthetics of the deformities, however the SPoRT brace was found to be more effective than SpineCor in avoiding scoliosis curve progression [23].

There is evidence that the SpineCor® brace relieves pain by improving posture following the reduction of mechanical strain on the neuromuscular system in adults. The brace enables spinal joint off-loading by reducing the misalignment of the spinal segments. Pain perception data from Marcotte [25] which reviewed the effect of SpineCor spinal braces used for between 18–28 months from 30 adults (26 females/4 males), which showed 77% overall improvement in pain recorded. Half of the patients reported total pain relief, although there was no significant reduction in spinal curvature in adults. This outcome may have been similar to the reasoning in the original designs in the 18th century.

Figure 8.
The Sforzesco brace- the most recent addition to the SPoRT scoliosis management concept.

Dynamic Elastomeric fabric orthoses (DEFO) were first reported in 1960. The authors described the use of crepe bandages wrapped around a child with athetoid cerebral palsy. This caused reduction in the muscle tone in his arms and legs which then enabled more stability and less fatigue [26].

In 1995, an Australian paper describing the use of custom "UPsuit" Lycra® suits on children and young adolescents, with semi-rigid reinforcement to provide stability to the spine and to improve sitting balance [27]. Management of the scoliosis was provided by metal spiral boning stitched in fabric pockets to provide rigidity and apply resistance to stretch - providing areas of higher resistance to stretch [28]. However, there is limited scoliosis management using Second Skin suits (**Figure 9**).

In 2007, a study from the United States introduced a basic base Lycra® short and pants with shoulder straps called the "Stabilizing Pressure Input Orthosis" (SPIO) [29]. The study stated that significant functional improvements to balance, improved postural control and muscle readiness were found, however as an observational and discussion report, the only evidence provided was photographic pre and in-intervention images. It was postulated that there were deep sensory changes which could account for the reduction in athetoid movement and the improved stability of the spine in children presenting with low tone [30].

In 1999, Rennie et al., in a repeated measures study of 8 children (7 children had cerebral palsy and 1 with Duchennes muscular dystrophy), used laboratory gait analysis to report on the outcomes of a long arm, long legged suit made by Camp Ltd., in the United Kingdom (**Figure 10**). Five participants showed a reduced root mean square error (RMSE) scores indicating improved postural stability, confirming the findings of Blair [28] and Hylton [30]. However, the improved postural stability only positively affected the distal stability in three participants, which could have been due to the short 6-week duration of the trial.

Compression at the pelvis in DEFO shorts [31, 32] can reduce the pain experienced by adults with intellectual disabilities, who experience high rates of falls and have gait and balance issues. The reason for this may be because the DEFO suits and shorts reduce the amplitude and range of movement in the spine and pelvis,

Figure 9.
Back view of a postural suit. https://www.secondskin.com.au/Products/postural_splint

Figure 10.
The original basic Lycra® long legged and armed suit used in the Rennie study.

therefore providing pelvic stability [33] which consequently enhance the quality of life in both children and adults.

Scoliosis suits were first reported by Matthews and Crawford in 2004 [34] in a single case study using a DEFO to treat a child with a tumour on the spine. The tumour had previously been excised at the age of 7 yrs. The tumor extraction operation caused a 33-degree Cobb angle scoliosis to appear at the tumour site T9 (**Figure 10**). The child, did not want a rigid brace due to the rigid brace appearance [34]. The orthotist prescribed a non-invasive vest top suit to control the curve, based on experience, with children presenting with hypotonic cerebral palsy with scoliosis.

The suit applies a tight fit at the hips and thighs to prevents the suit from riding up and therefore a resistant force is applied to the shoulders. The suit uses the principle of pressure applied to the shoulders to facilitate an improved sitting posture, as seen when neurodevelopmental physiotherapists place their hands on the shoulders of children with low spinal muscle tone and retract the shoulders coupled with downward pressure to facilitate an extension of the spine in sitting. The compression of the suit also enables the patient to become more aware of their bodies position in space through heightened proprioception.

Elastomeric fabric sideways translation reinforcement panels, which were designed to reduce the scoliosis Cobb angle were added, using the patient pre-intervention x-rays and blue printing process (**Figure 11a** and **b**), as described in the Boston Brace clinical manual. The manual describes how to use the patient X-rays to identify the vertebra levels, position of the spinal curve and rotation [35] to guide prescription. The addition of, overlying a "V" shaped translation panel (see yellow arrows on **Figure 11b**) to the convex side of the curve ensured a lateral force was applied below the apical vertebra as close to midline as possible – this provided a long low pressure on the ribs which encourage the patient to move away from the pressure point into the comparative void of no reinforcement on the right side. A further shoulder compression panel (see red arrows on **Figure 11b**), extends upward posteriorly over the left superior border of the scapula and over the anterior shoulder, before continuing downwards until clear of the axilla and then continues diagonally anteriorly across the anterior ribs to finish at the right greater trochanter. The left shoulder compression, spinal derotation panels were so efficient, that the suit required the addition of touch and close fastening over the left shoulder to allow for the left shoulder to rise to accommodate the right compression, so assisting curve reduction.

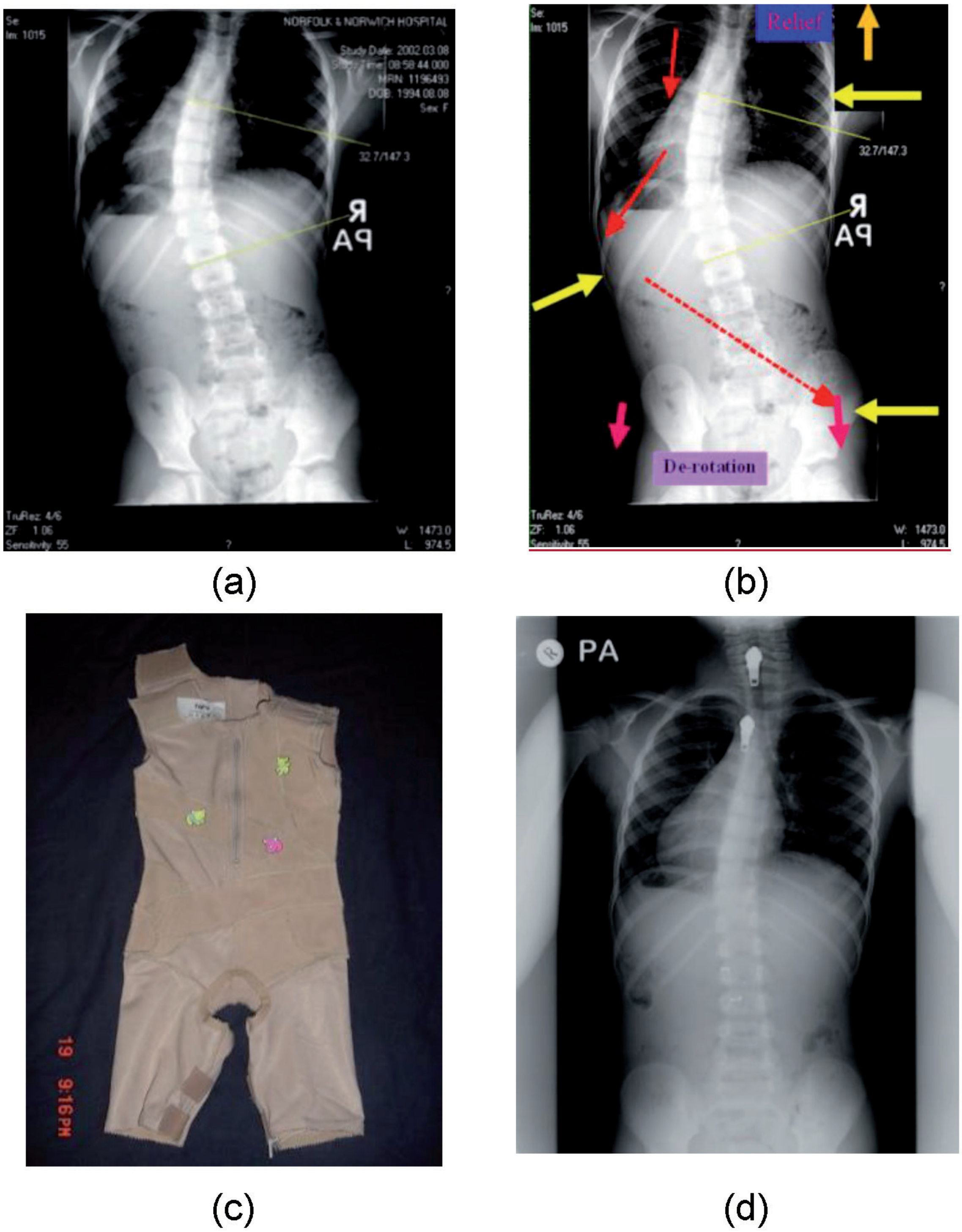

Figure 11.
(a) Before Suit X-ray shows 32.7° thoracic curve convex to the left. (b) The blueprinting which includes 3 point force (yellow) arrows, red full and dotted shoulder compression and de-rotation effect, and the upward shoulder movement (orange arrow) The two downward pink arrows indicate the counter force on the legs and hips that applies the pressure to the shoulders. (c) The scoliosis suit shows the lateral translation curve "V" shaped pane. The shoulder de-rotation and compression panel on the right of the photograph coupled with the touch and close over the shoulder pressure relief fastening. (d) In-suit X-ray shows 15° curve a reduction of 17.7 degrees, which was held for 2½ years. Note dual zips of suit.

The patient was provided with a 18 mm heel raise to accommodate the pelvic tilt, but this had no effect on the scoliosis. Throughout the next 2.5 years the patient was provided with three suits to accommodate natural growth. The suit was worn 23 hours a day. The in-suit x-rays (**Figure 11d**) showed that the curve was held at 15° Cobb angle, a reduction of 45%. The tumour re-occurred after 2 ½ year and was again removed, with additional surgery to staple the vertebrae above and below the tumor site to prevent a re-occurrence of the scoliosis.

Matthews & Bridges [36] reported a single case study of a 5-year-old child, presenting with myotonic dystrophy (a genetic disorder affecting muscle function), coupled with pectus carinatum (a chest wall deformity in which the breastbone pushes outward instead of being flat), and a left 70° Cobb angle thoracic curve, apex T8 with a vertebral rib angle difference greater than 20° and therefore very likely to worsen (**Figure 13a** and **b**). The x-ray provided the blueprint for a vest top scoliosis suit to be prescribed and supplied. One year later, routine x-rays showed that the curve had reduced to 35°, a 50% Cobb angle reduction in suit and the vertebral rib angle difference had reduced to under 20° and meaning that the curve was unlikely to get worse (**Figure 12**).

Although it is not normal to expect a 50% reduction in Cobb angle, this result proved that scoliosis suits could treat higher angle curves, than rigid braces successfully. This result also highlighted that the shoulder on the convex curve side should extend down over the upper arm to prevent the shoulder protraction (shoulder moving anteriorly) around the edge of the vest segment (**Figure 13c**).

In 2016, Matthews et al. [23] reported on an audit of 180 children and adolescents with, or at risk of developing scoliosis from five centres in the south of England, UK. The study reported on 121 subjects who had been supplied with DEFO suits and scoliosis suits within three centres. The centres used local protocols to use DEFOs to treat children identified as GMFCS Level 4/5, who were primarily wheelchair ambulators, starting to develop a small lateral body shift and were at risk of developing scoliosis prophylactically. Fifteen years of scoliosis suit management experience by the clinical team had indicated that patients with GMFCS level 4/5 had reduced surgical interventions due to early suit provision. The audit also reported the noncompliance in the use of rigid braces in this sample. It is understood that rigid brace use in neurological onset scoliosis is difficult to wear due to the rigidity and lack of movement within the orthosis. There is no convincing evidence in the recent literature to suggest that rigid spinal orthotic management in neurological onset scoliosis is effective [37], which was also confirmed in the audit data.

Over the years, the children who had DEFO scoliosis suits were followed through their peak growth rates as adolescents. As the scoliosis development was identified early, the clinical team were able to observe and develop an

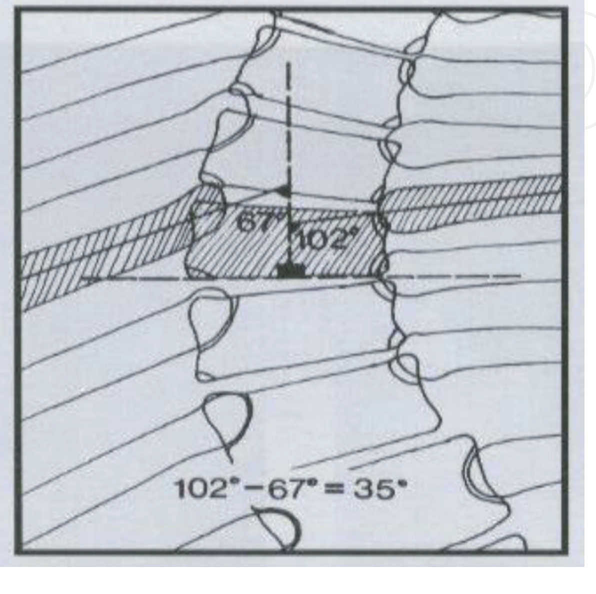

Figure 12.
This diagram shows the vertebral rib angle difference. If over 20° the curve is considered to get worse. https://boneandspine.com/rib-vertebral-angle-in-scoliosis/#how-to-measure-the-rib-vertebral-angle.

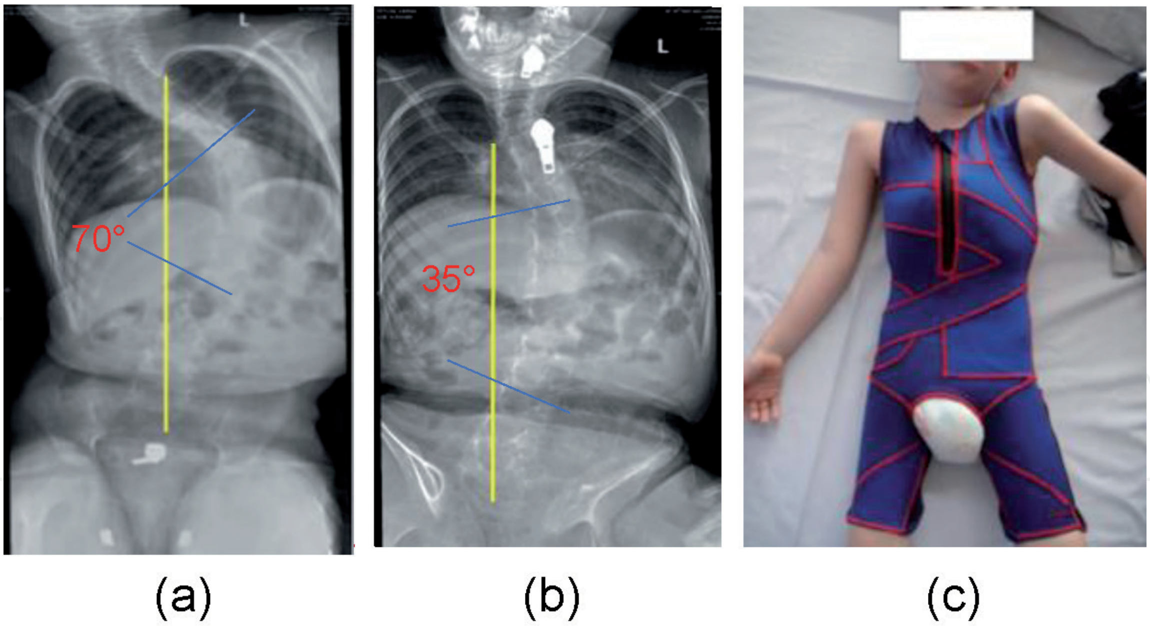

Figure 13.
(a) Pre suit X-ray. (b) X-ray in scoliosis suit. (c) The child in suit. "V" shaped translation panel is clearly seen originating from right hip to left waist and back to under right axilla. Note: shoulder protracting around the vest segment.

understanding of which scoliosis curves were at high risk of progressing. The clinical team understood that during growth, peak growth occurs during early adolescence and continued throughout adolescence. Scoliosis- specific DEFO suits were shown to maintain the corrections in Gross Motor Functional Classification Scale (GMFCS) level 4 and slow the curve progression for those patients in GMFCS level 5 throughout adolescence.

It is recognised that most of the research in this field is in paediatrics, however there are now papers in preparation on an adult male using the DEFO scoliosis suit management. The N = 1 single case study (currently in press) reports on the changes to an adult male with ataxia telangiectasia (a rare inherited disorder that affects the nervous and immune system resulting in difficulty with coordinating movement from early childhood) with poor head control and issues with poor control of posture and extrapyramidal movements. The design included baseline pre-intervention gait laboratory data collection of the patient sitting, carrying out a routine hand function, the quality-of-life task of taking a drink to his mouth and reach to touch function. This was repeated in a postural scoliosis design suit, which included bilateral enclosed shoulders and standard strength paneling, and then again in a stronger, higher specification paneled postural scoliosis suit with interesting outcomes [38].

Ehlers Danlos Syndrome (EDS), an inherited condition that affects connective tissue is characterised by hyper-elasticity of the joints and fragility of the skin [39]. There is anecdotal evidence of patients with scoliosis, where pain is a major problem due to the connective tissue lack of rigidity that allows joints to dislocate. Serious pain is often experienced in women with EDS caused scoliosis, often from the age of 30 years, preventing or making their activities of daily living difficult. They also have increased reliance on strong pain medication. The use of DEFO scoliosis suits for this client group has produced improved posture with similar results to the adult use of SpineCor brace. The effect on the scoliosis angle was minimal, but effective, because pain was reduced due to the improved positioning and stabilisation of joints [25]. Therefore, the improved quality of life often leads to reduced pain relief medication.

4. Concepts of treatment

The DEFO scoliosis suits use different mechanisms to correct scoliosis in comparison with rigid or semi-rigid braces and it is important to understand the fourteen concepts.

1. **Compression of the trunk** provides a bracing effect due to the circular support normally associated with a rigid brace. Circumferential pressure provides some compressive stabilisation to the spine [26] and can reduce pelvic pain due to pelvic force closure [40], resulting in an improved level of comfort and quality of life. The compression on the trunk is a maximum of 26.9 mmHg (2 layers of fabric) – well below the level required to risk skin damage caused by restriction of blood flow or ischemia. If additional elastomeric layer of material are added on top of two layers, the pressure applied is reduced due to the "bridging effect" seen were three layers of material do not expand and contract on a local basis, due to adhesion to the other overlaid layers [41].

2. **Upper body counter de-rotational reinforcement** panels applied to the base suit design to compress the thoracic curve [34]. This reinforcement panel enables containment of the shoulder complex (including the upper arm and distal clavicle) with downward pressure applied to the convex thoracic curve coupled with rotation to unwind the mobile scoliosis (See **Figure 11b** and **c**).

3. **Dampening effects on external dynamic forces** acting across joints may contain overshooting of specific movement and reduce unwanted movements due to restriction and compression of the orthosis. The use of compact compression orthoses show a reduction in uncontrolled movement-patterns [42]. This is often seen as extreme uncontrolled upper and lower limb movement in patient with spastic athetoid patients. Circumferential pressure applied to the trunk, arms and legs provide a heightened idea of body position in space via the sensory nerves which help the brain to understand where the body parts are. This can reduce the excessive movements seen in some cerebral palsy presentations.

4. **Enabling the brain to update the internal model of self** to formulate motor plans for movement is well recognised in patients with cerebral palsy, to predict the best muscle synergy to achieve the required motor goal [8]. Due to the brain damage in patients with cerebral palsy the brain's image of self is different to reality and is seen clearly in unilateral presentations (hemiplegia) or one affected side. Therefore, if a patient with unilateral upper arm involvement reaches out to reach an object, it is highly likely that they will miss the object by approximately 25 mm. If they carry out the same task but wearing a glove specifically designed to turn their hand upwards (to supinate), they will be more able to go reach out directly to the object without missing it. This is due to the change in sensory information going from the hand to the brain and the ability to alter the resultant movement **requirement to react to this sensation.**

5. **An Exoskeleton** provides reinforcement to weaker muscle and skeletal biomechanics as the support and dynamic panels enable clinicians to provide biomechanical assistance the weaker muscles, like supination to adult with cerebral palsy or strokes. For instance, patients who present with unilateral upper limb weakness due to the brain damage and cannot supinate their forearm (rotate their palm upwards). Diagonal panels are built into the arm section of the

glove which can put tension on the arm and resulting in derotation of the forearm to provide a functional position in supination rather than pronation (hand turning palm downwards). See **Figure 14** [43, 44].

A similar affect can be seen where DEFO suits will provide compression to stabilise the trunk and additional scoliosis specific panels can initiate lateral and/or rotational movement of the spine (See **Figure 15**).

6. **Improved motor control** treatments are valuable in improving long term outcomes such as seen in chronic low back pain [45].

7. **Low level continual pressure guides rather than forces positional changes** by encouraging movement or gradual muscular localized stretch of muscle sarcomeres [46]. Physiotherapists use a long low pressure stretch to gain movement in stiff limbs as this allows different muscle fibres to give and lengthen with the gentle pull. A hard pull would cause the body's damage limitations mechanisms to activate and resist the pull strongly as muscle damage might occur, which makes the outcome worse.

8. **Proprioception**, often referred to as (kinesthesia) and often thought of as the "six sense" [47] is the knowing of where your body is in space [48], when your eyes are shut. This is built up over a time of learning specific motor function patterns, utilising feedback from sensory receptors within the muscle, skin and joints (feedback) and central signals from the brain to the muscles (feedforward), which is related to motor output. This enables the individual to combine other sensory information to judge limb position and movements by learnt patterning and continues whatever the age [44].

9. **Reduction of pain** as seen in children with cerebral palsy [17], and chronic low back pain where pain impacts the quality of daily life [45].

10. **Reduction in time for sequential movement planning due to feedback/feed forward system** enables the improved ability to develop an effective motor plan for desired action [8], If you think about lifting your arm upwards with a weight, you will find your brain has to set several actions in progress prior to the movement. Firstly, the spinal muscles will be put under tension to stabilise the thorax before you can even extend your arm out to pick up the weight. Once you reach the weight you must further activate your spinal and now upper limb muscles to enable the weight to be lifted. If you failed to do this, you would find that the weight was not moving at all and there is a likelihood that you would already have fallen forwards due to the weight of your arm only. The process of preparation is a sequential movement. People with cerebral palsy therefore would find this task extremely difficult. Wearing compression orthoses again enables them to plan the task quicker.

Figure 14.
Shows the diagonal reinforcement built into the DMO long sleeved glove to provide a supinatory in-built rotation causing the wrist to be held in supination.

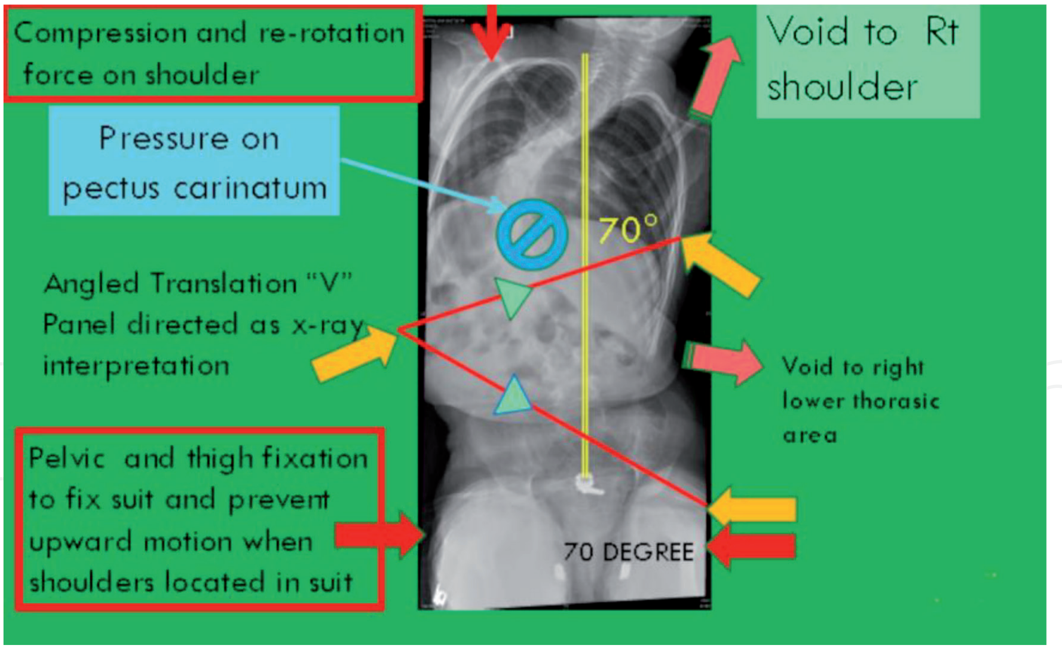

Figure 15.
The scoliosis blueprint for a scoliosis suit showing the translation panel with angulated yellow arrows on the left, representing the resultant force expected from the positioning of the two (upper and lower yellow arrows) on the right side of the image.

11. **Retraining of the motor control patterns** by repetition of sensation and movement have been used in rehabilitation of sports injuries particularly in patellofemoral pain and shoulder stabilisers, often after strength training has been unsuccessful in pain reduction [49, 50].

12. **Translatory reinforcement** to create a lateral shift to counter a lumbar or thoracolumbar curve [34].

13. **Truncal postural control is an important determinant of motor function** with a precise relationship between the control of the individual trunk segments and resultant effects on gross motor function and mobility [51]. In some very young children with cerebral palsy, they are unable to eat solid food as they are unable to move the food across their mouths due to the amount of energy, they have to use to hold their head ups as they are so floppy due to the cerebral palsy. However, if you stabilise them in a neonate suit or full height standing frame that allows the child to just concentrate on holding their head up and not the whole spine. They can often find that they are can start to eat solid foods after 6 weeks as they can learn to hold their heads up enough to move the food across their mouths so they can chew.

14. **Understanding the 3D nature of both idiopathic and neurological onset scoliosis** [11] is key to outcome expectation. The blueprinting principles (See **Figure 5**) used for the manufacture of the traditional Boston modular Brace and Boston 3D custom Brace apply to identify the correct vertebral level to treat and understand the vector forces required to reduce the curve and improve sagittal balance. The blue-printing process described in the clinical training manuals ensures the clinicians are totally focused on each vertebral level and fully understand the angle of inclination and the rotation of each vertebra.

5. Discussion

The criteria for using suits designed specifically for a person with scoliosis is like the use of rigid bracing, in that best outcomes are achieved in early intervention when children have good spinal mobility. When used in older adolescents and adults, it is sensible to encourage the patient to complete a course of physiotherapeutic scoliosis specific exercises (PSSE), which includes auto-correction in 3D, training in activities of daily living (ADL), stabilising the corrected posture and patient education. These exercise protocols have level II evidence, both for independent use and in conjunction with spinal bracing in patients with curves less than 45° Cobb angles and are also suggested prior to surgery to help improve outcomes [9].

In a testimonial, one patient reported improved balance, upright standing and patient confidence. The use of PSSE, combined with an enhanced power scoliosis DEFO suit provided a mechanism to ensure maximum vertebral movement, combined with the unique proprioceptive and long term low level force, known to be the most effective for muscle stretching [46]. When the suit was first applied the patient reported loss of balance, which indicated that the suit was having the desired effect and her mother reported a reduction in the pain she was experiencing [52]. After 3 years, the suit reduced the scoliosis progression and scoliosis surgery at the end of DEFO treatment was no longer required (**Figure 16**).

Figure 16.
Sixteen-year-old lady in structural scoliosis suit.

Improvements in walking have shown that improved proprioception and provision of a flexible supportive exoskeleton can improve image of self, reduced hip sway, hip force closure and to reduce the known mechanisms of increased lordosis to lock the spine, enabling smother movement [33, 40, 53]. People with scoliosis can learn a new sitting position by the mechanism of continual motor learning carried on throughout life. This can be initiated by external forces including poor sitting position, spinal injuries, strokes as well as left or right-handed wheelchair controls. The use of dynamic orthoses, therefore, have an important role to play in centralising the spine without the use of rigid force.

The mechanisms utilised in DEFOs dynamic orthotics became more objective than subjective, with more research and reports of use. It is important to understand the mechanism for the changes observed in the patients and their reaction to the intervention. For a number of years, the outcomes detected were put down to improved patient stability from the compressive forces on the hip and shoulder, coupled with the distraction of the shoulders as seen in proprioceptive neuromuscular facilitation (PNF) [54]. There is evidence that PNF on the trunk can reduce chronic low back pain in adult women, if applied in the sitting position [55]. There are two commonly used exercises. Rhythmic stabilisation training (RST) which uses isotonic (muscle working within normal contraction range) contraction of the agonistic (opposing) muscle patterns which results in co-contraction of the antagonists. The isometric contraction of the muscles is provoked into working by pushing or pulling an immovable object. This prevents muscles shortening in length and improves fitness and builds up strength. It is used where weakness is a primary factor. The combination of isotonic exercises (COI) is used to evaluate and develop the ability to carry out purposeful and controlled movements, involving alternating concentric (circular), eccentric (non-circular) and isometric movement to treat strength deficiency and range of motion. Four weeks of RST and COI proprioceptive neuromuscular facilitation have shown increased muscle endurance, decrease in back pain intensity, as well as improved functional ability.

There are several different mechanisms that appear to be working together to provide the DEFO's positive reported outcomes and therefore it is important to understand the different concepts of treatment. The orthoses initiate change where the effect is likely to be constrained by the linear range of elasticity of the fabric or "dynamic" [56]. The fabrics are designed to grip the skin while allowing air and moisture through without slippage. A DEFO uses these properties by griping onto the skin and therefore transfers the torsional resistance from the different reinforced fabric layers, which are designed to have different linear orientations. These forces are conveyed through the skin and soft tissue directly to the muscles and skeleton beneath with set movements expectations. For instance, if there is a long spinal curve to the right, set pattern options are applied to the left side of the trunk to resist stretch, therefore providing a stiffer area in the suit resulting with less of a lean to the right.

It is understood that slight compression of the trunk rather than distraction (as used in rigid and semi rigid spinal orthoses) can provide a stabilising effect on low core stability in children presenting with cerebral palsy. The same effect can be initiated in adults.

New innovations are signaling that the use of textile fabric materials can have positive spinal correction. Computer modeling has been developed to geometrically model scoliosis through finite element modeling (FEM). It is a numerical technique used to perform finite element analysis (FEA) of any given phenomenon (https://www.simscale.com/blog/2016/10/what-is-finite-element-method/). The use of 2D x-ray clinical data on appropriate textile materials, measuring physical and mechanical properties were used to determine the performance of the textile brace in terms of Cobb angle through FEM simulation. The results showed that textile materials with banded parallel fabric layers provide good softness and air permeability (key for compliance in hot climates). There was high capacity to provide a 14.4% Cobb angle improvement, when used on a teenage patient with adolescent idiopathic scoliosis presenting with a 62° typical double curve [57]. This provides some medical and biological engineering evidence of the orthotic effect.

This study also highlighted the need for cosmetic appearance and the effects on patient compliance. Rigid braces have been proven to be effective in reducing scoliosis progression [4], however there have been issues with compliance particularly from discomfort caused by the brace and psychological stress from the visual impact. Patient involvement in brace design and aesthetics have shown improved compliance [58], so the use of elastomeric fabrics will further enhance this patient based involvement and provide scoliosis suits which are more comfortable in both adolescents and adults alike thereby improving activities of daily life.

There is evidence for the use of DEFO scoliosis management in neuropathic onset scoliosis and early indicators that the same orthoses can be effective in adolescent idiopathic scoliosis. The key thing to remember is the need for flexibility of the spine to be able to use dynamic movement to facilitate a spinal scoliosis angle reduction, vertebral rotational control and improved cosmetic outcome. The most effective treatment plan would be to combine PSSE with the use of scoliosis specific DEFO suits to start the treatment early in the onset rather than wait for the 25° Cobb angle starting point, that has historically been suggested. This highlights the need for early intervention and further research on this specific scoliosis presentation.

6. Conclusion

The use of scoliosis DEFO suits have shown that specifically designed paneling can provide scoliosis curve reduction based on tried and tested clinical evaluation and design to provide cosmetic orthoses which are discrete and robust. The onset of dynamic elastomeric fabrics has provided both proprioceptive and mechanical means to change body movement and function for all age groups. The continuing research provides an insight into the future of orthotics and provision of patient involvement are assisting in improved outcomes offering new areas of use. The case study discussed earlier within this chapter, also shows the possibility of using DEFO structural scoliosis suits for adolescent idiopathic scoliosis, which provides a further orthotic option for treatment and research, particularly in the early stages of the disorder.

Compliance with the DEFO suits is presumed to be improved due to the less rigid orthotic structure and improved cosmesis, coupled with the use of low-level continual pressure to gradually encourage the patient to relearn motor pathways. These orthoses achieve improved sitting and standing posture, which results in the reduction of the scoliosis curve Cobb angles and pain for adolescents and adults. Dynamic elastomeric fabric orthoses have shown that orthotics do not need to be rigid to provide a lasting neurophysiological effect combined with the enhancement of continual motor learning and reprogramming of the brain and movement patterns.

Conflict of interest

Martin Matthews is employed as Chairman and United Kingdom state registered clinical specialist orthotist by DM Orthotics Ltd., UK in clinical roles, within the National Health Service hospitals. He is also an Honorary Associate Professor at the University of Plymouth.

James H. Wynne, CPO is employed as Vice President – Director of Education by Boston O&P, Boston, Massachusetts, USA. JIm Wynne and I worked as co authors and therefore although I fully acknowledge Jims involvement we worked closely together as dual authors.

Authors contributions

Both authors have contributed equally to the design and writing of this chapter and have over thirty years of personal experience in managing scoliosis in all age groups and presentations.

Acronyms and abbreviations

ARTbrace	asymmetrical rigid torsion brace
ADL	activities of daily living
Boston 3D	Boston three dimensional scoliosis brace
CADCAM	computer aided design and manufacturing
COI	combination isotonic exercises
CP	cerebral palsy
DEFO	dynamic elastomeric fabric orthosis
DMO	Dynamic movement orthosis
EDS	Ehlers Danlos syndrome
FEA	finite element anaylsis
FEM	finite element modeling
GMFCS	gross motor function classification scale
IOS	idiopathic onset scoliosis
NOS	neuropathic onset scoliosis
PNF	proprioceptive neuromuscular facilitation
PSSE	physiotherapeutic scoliosis specific exercises
QOL	quality of life
RMSE	root mean square error
RST	rhythmic stabilisation training
SPIO	stabilising pressure input orthosis
SPoRT	symmetric, patient oriented rigid three-dimensional

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