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RESEARCH

Impact of growth on spinal biomechanics and tether force in VBT: a simulation study

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Abstract

Purpose Vertebral Body Tethering (VBT) allows correction of scoliosis while preserving the spinal mobility. Despite an increasing availability of data on clinical experience and surgical techniques, there is still a lack of knowledge on the underlying biomechanics, specifically when considered in combination with growth. Therefore, the purpose of this study is to develop a growing flexible spine model to investigate spinal biomechanics after VBT surgery.

Methods A multi-body simulation approach was chosen. A growing, flexible thoracolumbar VBT spine model was developed to analyze the spinal biomechanics during various physiological movements and growth. The model includes a flexible spine with a VBT device and a musculoskeletal system. Therefore, the resulting tether tension and intervertebral compression force can be calculated with respect to the human anatomy and material properties of the VBT device.

Results During growth, the tether and compression forces increase continuously with the highest forces between L1 and L2. The highest tether force is measured at 50° lateral bend at 200 N pre-tension. The compression forces in a tethered spine are during adolescence up to twice higher than in a healthy spine.

Conclusion The simulated biomechanical data provides insight into the forces exerted on the spine during various physiological movements and the remaining growth. They are consistent with previously published clinical data and underlie the finding that age at surgery or residual growth doesn't greatly affect tether forces. During growth, however, intervertebral compression forces increase.

Keywords Adolescent idiopathic scoliosis (AIS) · Multibody simulation · Growth · Vertebral body tethering (VBT) · Tether force · Compression force

Introduction

Adolescent idiopathic scoliosis (AIS), a 3D spinal deformity in children > 10 years, is a common disease in pediatric orthopedics with a prevalence of 0.47–5.2% [1]. Among various well-established treatment options, Vertebral Body Tethering (VBT) is a non-fusion surgical technique for scoliosis correction. It allows to reduce the curve magnitude in immature patients, while preserving spinal flexibility. The working mechanism of VBT is based on Hueter-Volkman's and Wolff's principles, which rely on growth modulation and tissue remodeling; specifically, it involves deceleration of growth by compression on the convex side and unloading of the concave side [2]. The scoliotic spine is corrected once by the intraoperative tether pre-tension and once by the guided and remodeled residual growth. There still is no consensus on the best indication but the FDA (Food and Drug Administration) has approved VBT for skeletally immature

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patients (Risser≤2 or Sanders≤5) with curves between 30° and 65° [3]. The timing of the surgery, the remaining growth and the durability of the implant seem to be important parameters for a successful outcome [4].

Growth can be defined as a succession of periods of acceleration and deceleration [5] and is one additional influence on the tether device. Girls' and boys' growth curves are almost identical up to the age of ten, after which they begin to differ. Studies have shown that the beginning of puberty is best characterized by the change from a phase of deceleration to a phase of acceleration in the rate of growth [6]. Statistically, girls enter puberty at an average age of 11 years, boys at 13. During puberty, standing height increases by about 1 cm per month. Dimeglio et al. reported that at the onset of puberty, boys have approximately 14% (±1%) of their remaining standing height left to grow (22.5±1 cm), while girls have about 12% (±1%) of their remaining height to grow at the same stage (20.5±1 cm). Consequently, the pubertal growth rate peaks at different ages. For boys, the peak growth rate is between 13 and 15 years of age, and for girls between 11 and 13 years of age. Therefore, spinal biomechanics differ between genders.

Clinical studies show good post-operative outcomes and adequate curve reduction for VBT. However, tether breakage remains a common post-operative negative event [3, 7]. The incidence for tether breakage after thoracic VBT has been reported up to 48%, an up to 90% after thoracolumbar VBT [8]. Studies have shown that tether breakages have a major impact on the clinical outcome, especially when they occur within the 12 months post-surgery, the period of greatest remaining growth potential. Nevertheless, little is known about the risk factors for tether breakage, particularly for biomechanical reasons. While available studies have focused on the clinical risk factors, the biomechanical background and causes – specifically in combination with growth - aren´t yet fully investigated [9].

An attempt to quantify the required forces for an adequate correction, while preventing tether breakage has been done in previous work [10]. The authors have developed a flexible spine model in order to simulate the tether and intervertebral compression forces during various physiological movements. However, the evaluation of the forces during the remaining growth is unclear, especially when considering that tether breakage often occurs one or two years after surgery.

The timing of VBT surgery is important for several reasons: residual growth potential, preservation of flexible curves and Cobb angles between 30 and 65 degrees. However, the influence of residual growth at the time of surgery on spinal biomechanics, especially on tether and intervertebral compression forces, is not known. Therefore, the aim of this study was to analyze the biomechanical effects and consequences of growth in a tethered spine during various physiological movements.

Method and material

A multi-body simulation (MBS) approach was chosen to gain insight into spinal biomechanics during growth and different physiological movements. An existing validated flexible VBT spine model was extended with a growth function using the AnyBody Modelling System (AnyBody Technology) software. In contrast to finite element method, MBS allows analyzing the biomechanics in the spine and tether device during various physiological movements as well as during growth development while respecting the muscle and ligament properties.

The used and validated spine model has been originally developed based on representative patient data [11, 12], existing static scoliotic MBS spine models utilize e.g. EMG measurements as a means of validation [13, 14]. It depicts the thoracolumbar spine, including the main muscle groups, ligaments, and intervertebral discs, which are approximated as spring-damper systems with constant material properties. The vertebrae are connected by spherical joints. Various physiologically representative motion tasks (flexion-extension, lateral bending, axial rotation) can be simulated by using the multibody simulation software, AnyBody Modelling System (Fig. 1). For the simulations the used tether has a diameter of 4 mm, a tether stiffness of 9000 N/m and has been fixed between T7 and L3. The modulation of the tether is based on its biomechanical properties, which were described by Guldeniz et al. [15, 16]. The tether pre-tension, screw position, as well as the tethered levels can be customized (Table 1).

Implantation of a growth evolution

While respecting age and gender of the patient, the spine model reflects natural growth, and the biomechanics of the spine can be simulated at any point in time. Technically, the spine model is scaled using patient input data from the KiGGs study. Furthermore, the growing VBT spine model accurately represents the anatomical changes in height and weight that boys and girls experience during puberty. It simulates the synchronous growth of muscles, bones and ligaments, reflecting natural human growth.

During the simulated growth, the screw position in the vertebra remains unchanged; only the distance between the screws increases due to the vertebra and disc grow. As in the model, the tether is connected to the screws, the tether elongates after each increase in height, which results also in an increasing tether pre-tension. In other words, as the spine

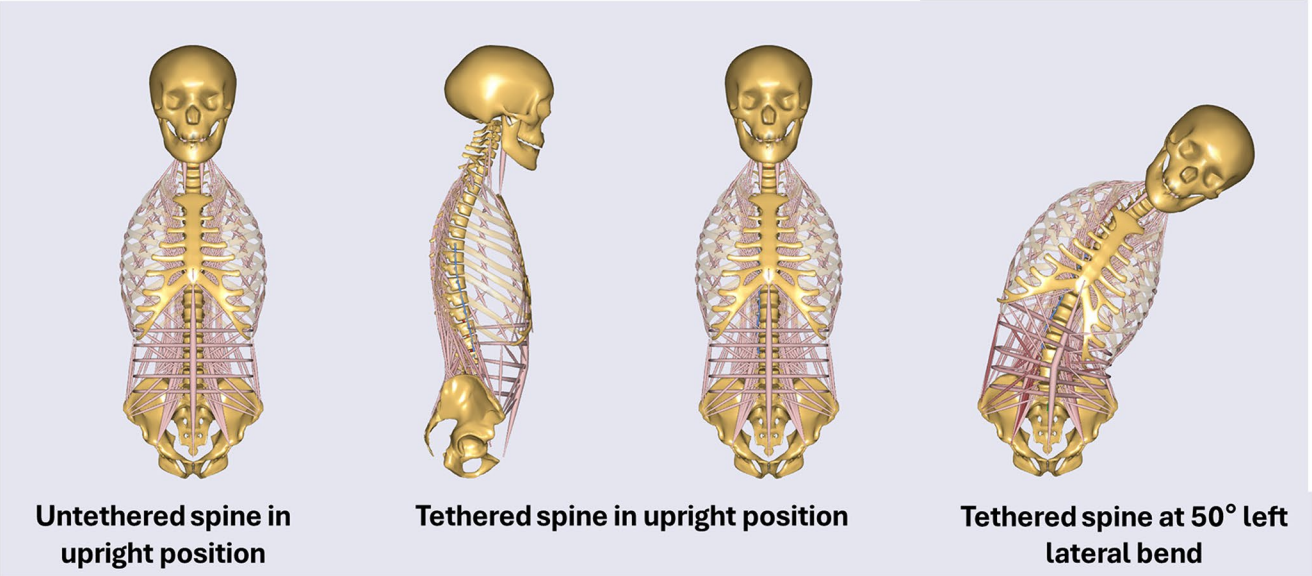


Fig. 1 Illustration of the spine model in the upright position and lateral bending to the untethered side. The selected ROM for physiological motion is based on clinical postoperative data [17]

Table 1 Boundary conditions and material properties for the simulations

	Executed motion tasks		Analyzed segment	Simulation period	Tethered vertebrae	Diameter tether cord (mm)	Tether stiffness (*N*/m)	Tether pre-tensions (*N*)
1. Analysis of the evaluation of the tether force (N)	50° left lateral bend		L1-L2	12.5–18 years	T7-L3	4	9000	200
2. Analysis of the evaluation of the compression force (N)	50° left lateral bend	Tethered spine	L1-L2	12.5–18 years	T7-L3	4	9000	200
		Healthy spine	L1-L2	12.5–18 years				
	Upright position	Tethered spine	L1-L2	12.5–18 years	T7-L3	4	9000	200
		Healthy spine	L1-L2	12.5–18 years				

Table 2 Anthropometric data from the KiGGs 2003–2006 study [18, 19]

Age (years)	Girls		Boys	
	Weight (kg)	Height (cm)	Weight (kg)	Height (cm)
11	39.37	147.65	38.88	146.68
11.5	42.05	151.04	41.00	149.35
12	44.87	154.31	43.25	152.22
12.5	47.59	157.22	45.82	155.43
13	50.02	159.53	48.81	159.13
13.5	52.16	161.33	52.14	163.1
14	54.01	162.74	55.51	166.93
14.5	55.55	163.81	58.75	170.35
15	56.80	164.58	61.69	173.12
15.5	57.79	165.09	64.26	175.2
16	58.53	165.39	66.3	176.66
16.5	59.07	165.50	67.87	177.62
17	59.47	165.54	69.15	178.24
17.5	59.78	165.65	70.30	178.68
18	60.08	165.77	71.39	179.04

grows, the position of the screws also changes, affecting the length of the ligament compared to its initial length at the time of surgery. The input data required for the simulations on height and weight have been taken from the KiGGs 2003 to 2006 study, a multicenter, Germany-wide study involving 17,641 children [18, 19] (Table 2). For the simulations performed, only the 50th percentile values for girls and boys between the ages of 12.5 and 18 years were considered. (Fig. 2) 12.5 years is before or just during the growth spurt and reflects realistic initial clinical characteristics. Therefore, this age was chosen to best illustrate the evaluation of tether and intervertebral compression forces.

Simulations

Prior simulations on tethered spines between T7 and L3 showed uneven force distribution along the spine with higher forces in the lumbar spine [10]. The highest tether forces have been described at 50° lateral bending to the untethered side. Based on these results and for comparison, the spine was also tethered between T7 and L3 in the growing spine model. Tethering and intervertebral compression forces are simulated and evaluated in 50° lateral bending and upright



Fig. 2 Illustration of physiologic idealized growth between the ages of 12.5 and 18

position semi-annually between ages 12.5 and 18. Due to the structure of the intervertebral disc and the minor effects of shear forces during the course of the simulations, only the compression forces were considered in this work.

The goal is to simulate and evaluate the biomechanics from a potential surgery age (12.5 years) to the end of growing (18 years) while considering gender differences. In particular, the simulations will provide an overview of the evolution of tether stress in relation to spinal growth.

Results

The results of the simulations are briefly described in the following section, detailed in Table 3, and presented in Figs. 3, 4 and 5.

Analysis of the evaluation of the tether force

The semi-annually evaluation of the tether force at 50° (left) lateral bend to the untethered side between the ages of 12.5 and 18 is shown in Fig. 3. A continuous increase in the tether forces as well as gender differences can be observed. For girls, the tether force between L1 and L2 at 50° lateral bending to the untethered side at 12.5 years of age is estimated to be 924 N. At 18 years of age, the force is estimated to be 937 N. For boys, the tether force at 12.5 years of age is also estimated to be 924 N. However, at 18 years of age, the tether force is 962 N.

Analysis of the evaluation of the compression force

A constant increase in compression force can be observed during adolescence at 50° lateral bend and in the upright position (Figs 4 and 5).

The highest measured compression forces for both girls and boys are between L1 and L2 at 50° lateral bend (Fig. 4). At each time point, the compression forces in a tethered spine are more than twice those in a healthy spine. At 12.5 years of age, the compression force in a tethered spine is higher in girls (1932 N) than in boys (1827 N). Compare this to a healthy spine at the same age, which is 861 N for girls and 843 N for boys. The gender difference increases with age. At 18 years of age, the estimated compression force is 2070 N for girls and 2242 N for boys. The untethered compression forces are more than half as high as the tethered compression forces, namely 999 N for the girls and 1114 N for the boys.

As shown in Fig. 5, the highest percentage increase in compression force is observed in the upright position between L1 and L2. Between the ages of 12.5 and 18 years, the increase is up to 11% in girls and up to 25% in boys. In terms of absolute values, compression forces increase from 1046 N postoperatively to 1312 N at 18 years of age in boys and from 1055 N to 1166 N in girls.

Discussion

Motion preservation, growth modulation and the remaining growth potential are fundamental working mechanism of VBT [20]. In the current literature a common median surgery age is 12.5 years [3, 21, 22]. However, despite the fact, that VBT is a growth-based correction technique, the VBT device itself, especially the nominal tether length stays constant. Therefore, the knowledge about the occurring forces during various physiological motions and during the remaining growth are extremely important in order to reduce the number of post-operative negative events.

Analysis of the evaluation of the tether force during adolescence

The simulations have shown that the tether forces are slightly but continuously increasing over the simulated period of 7.5 years. Overall, higher tether forces are observed in boys

Table 3 Evaluation of the tether and compression forces in a tethered and healthy spine during adolescence

		Sex	Age (years)										
			12.5	13	13.5	14	14.5	15	15.5	16	16.5	17	17.5	18
Tethered spine	Tether force (N) between L1 and L2 at 50° left lateral bend	Girls	923.54	927.27	930.17	932.45	934.18	935.42	936.25	936.73	936.91	936.97	937.15	937.15
		Boys	923.54	929.51	935.92	942.11	947.63	952.11	955.47	957.83	959.38	960.38	961.09	961.67
	Compression force (N) between L1 and L2 at 50° left lateral bend	Girls	1931.95	1955.32	1980.68	2002.67	2022.22	2036.16	2047.01	2054.93	2060.11	2063.69	2066.92	2069.54
		Boys	1927.45	1957.50	2001.52	2047.63	2094.63	2133.22	2165.66	2189.69	2204.95	2220.15	2231.05	2241.60
	Compression force (N) between L1 and L2 in upright position	Girls	1054.67	1080.55	1101.81	1119.23	1133.10	1143.75	1151.56	1156.88	1160.09	1162.19	1164.31	1165.67
		Boys	1046.39	1083.52	1123.80	1163.55	1199.92	1230.75	1255.51	1273.91	1288.28	1296.80	1304.82	1312.05
Untethered spine	Compression force (N) between L1 and L2 at 50° left lateral bend	Girls	861.04	886.48	909.48	930.28	947.44	961.52	972.77	981.11	987.33	992.00	995.49	998.85
		Boys	842.84	872.58	906.86	942.76	976.87	1008.08	1035.47	1057.12	1073.81	1088.08	1101.36	1113.98
	Compression force (N) between L1 and L2 in upright position	Girls	306.62	320.12	331.75	342.70	351.80	359.15	364.96	369.29	372.44	374.77	376.58	378.33
		Boys	296.63	313.38	331.64	351.62	370.66	387.81	402.68	414.42	423.41	430.71	437.25	443.42

than in girls due to the higher increase in height due to a lower growth period. In fact, the KiGGs study has shown that boys grow by an average of 23.6 cm between the ages of 12.5 and 18 years, based on the 50th percentile. Over the same period, girls grow by an average of 8.6 cm [19]. This 15.5% increase in height for boys and 5.4% for girls results in a 4.13% increase in tether force for boys and a 1.47% increase in tether force for girls.

However, compared to the initial applied pre-tension (200 N in the simulations), there is an increase in tether forces during physiological possible movements. For example, for girls aged 12.5 years, the L1-L2 tether force was estimated to be 200 N in the upright position and 924 N at 50° lateral bend to the untethered side. This represents an increase of almost 724 N, corresponding to a percentage increase of 362%.

Especially considering that the goal of VBT is motion preservation and that 50° lateral bending is a realistic postoperative outcome in terms of ROM, this finding of a 3.6-times higher tether force during bending underscores the importance of proper pre-tensioning [17]. In particular, with regard to the findings of Guldeniz et al., a force of 582.2 N can potentially compromise the structural integrity of the tether [15]. Simulations have estimated tether forces above this value, which may explain the commonly reported postoperative complication of tether breakage. In fact, tether breakage often occurs one to two years after surgery and may lead to revision surgery or worsen the postoperative outcome [23].

Regarding the timing of surgery, tether force doesn't increase significantly during the simulated growth period. In fact, the elongation of the tether during growth is not significant compared to the elongation that occurs during a lateral bending task. Therefore, the remaining growth or the skeletal maturity of patient don´t influence significantly the occurring tether forces. This finding is also consistent with clinical findings that age and skeletal maturity are not risk factors for the mechanical complication of tether breakage [9].

Analysis of the evaluation of the compression force during adolescence

A continuous increase in the spinal compression force is observed both in the upright position and during lateral bending. In fact, the compression forces in a tethered spine are up to twice as high as in a healthy spine and increase by up to 25% over the simulated period. This continuous increase can be explained by both the increase in height and weight of the adolescent and the increase in tether force.

Additionally, weight increases constantly during adolescence, and so do the loads and forces on the vertebrae and

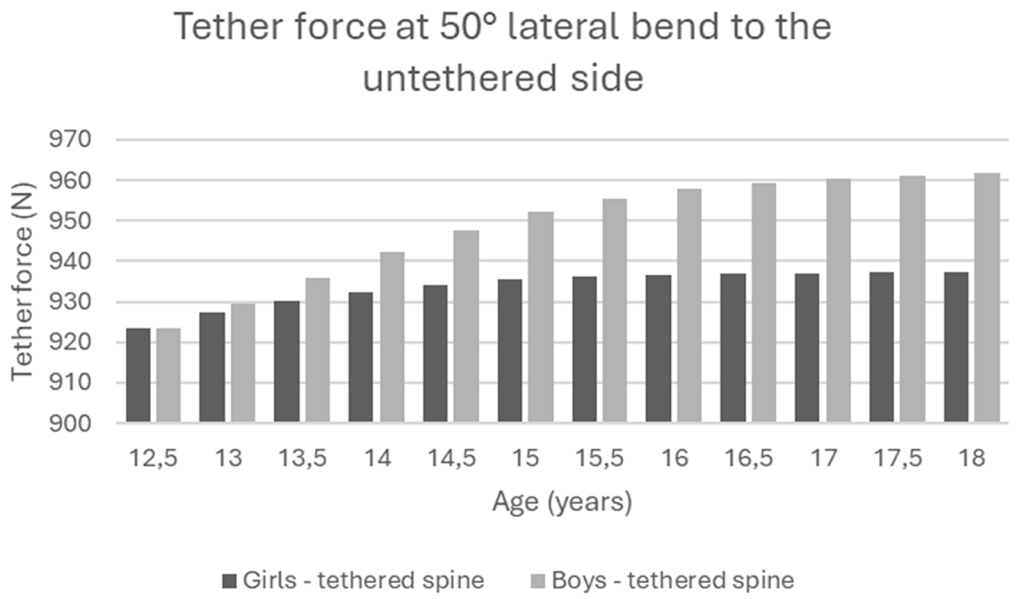


Fig. 3 The development of the tether force in girls and boys during adolescence during lateral bending to the untethered side. From 12.5 to 18 years of age, the force was evaluated semi-annually

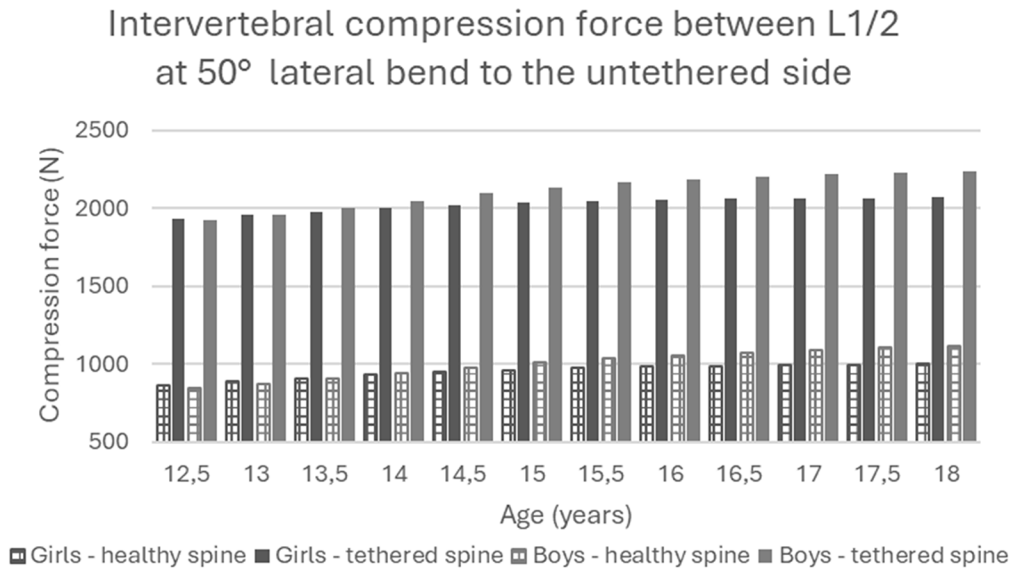


Fig. 4 Evaluation of the intervertebral compression force during at 50° lateral bend for tethered and untethered spines. The compression forces are evaluated half-yearly from age 12.5 to 18 years between vertebrae L1 and L2

intervertebral discs. For boys in the upright position, a 55% increase in weight results in an increase in intervertebral compression force of up to 250 N, or 25%. Girls gain only 12.49 kg (26%) in weight over the simulated period, resulting in an estimated 11% increase in forces [18]. In addition, as the height increases, the tether becomes more stretched. This consequently results in higher tether forces respectively higher tether pre-tension in the upright position. As shown in prior work, higher tether pre-tensions result in higher intervertebral compression forces [10].

Overall, intervertebral compression forces increase more than the prevailing tether forces during growth (idealized physiologic growth). While age and skeletal maturity aren't considered as risk factors for the mechanical complication of tether breakage, the intervertebral compression forces increase during the remaining growth [9]. The simulations suggest that age and skeletal maturity at the time of surgery influence the compression forces in adulthood. Due to the novelty of the surgical technique, no long-term studies are available. The long-term consequences on the IVDs are still unclear. 1- and 2-year clinical follow-up studies have shown

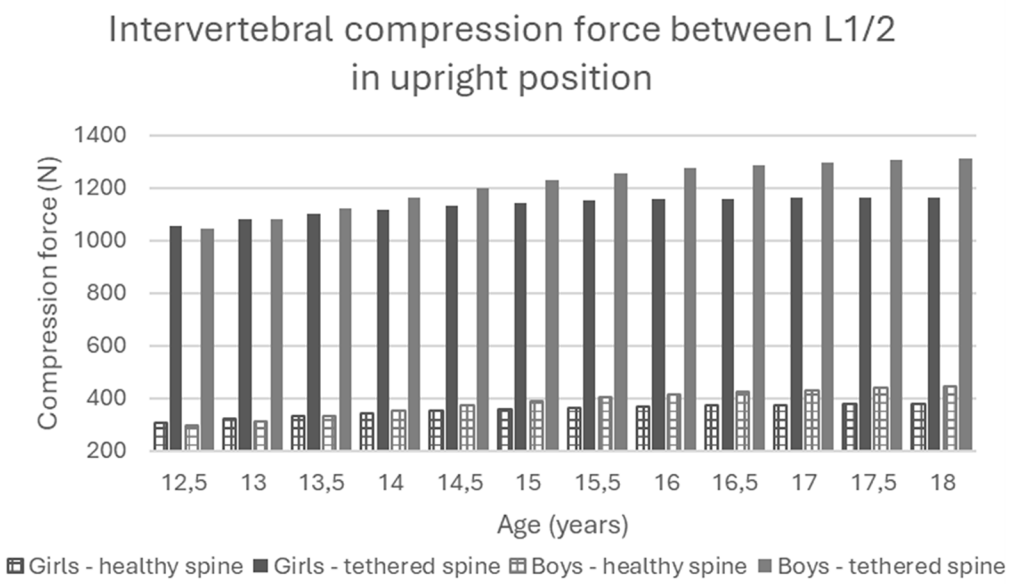


Fig. 5 The development of intervertebral compression force in the upright static position between L1 and L2. From 12.5 to 18 years of age, the force was evaluated semi-annually

controversial results regarding the health of the IVDs [24, 25]. A mild but not statistically significant IVD degeneration was observed in some patients [25]. Long-term studies are needed to evaluate the clinical consequences of intervertebral compression forces that are twice as high as in a healthy spine.

Limitations

As a first feasibility study, this paper uses an idealized, validated, non-scoliotic spine. Yet, the anatomical changes caused by scoliotic pathology, such as altered musculature and bone morphology, are neglected. However, there are several reasons for choosing a non-scoliotic spine. The first reason is validation and reproducibility of the model and results. Currently, there is no dynamic scoliotic spine model with intact musculature. The use of a scoliotic spine would require the assumption that the muscles and ligaments are shortened, which would make validation of the model difficult. On the other hand, a straight spine allows comparison of calculated values with experimental results. In addition, a straight spine most closely approximates the desired postoperative outcome. Since the biomechanical analysis ranges from 12.5 to 18 years, the aging process of the IVDs and the associated changes in their material properties are not considered in the model. A further limitation of our study is that the viscoelastic and volumetric properties of the intervertebral discs were not modeled, which could affect tether tension predictions under time-dependent loading conditions.

As no patient data was used, the study does not offer direct medical recommendations but serves as a biomechanical overview of the forces involved. The provided results should be interpreted as an insight into the spinal biomechanics to visualize the different influence and risk factors. However, the data provided should not be interpreted as absolute values. Although a strong correlation between increasing tether pre-tension, tether and intervertebral compression forces could be observed. Further refinement is needed to ensure the accuracy of absolute model predictions.

Conclusion and outlook

This MBS demonstrates a 4.13% maximum increase of tether force during growth. Comparing these data to maximum increases of tether forces that can be seen during thoracolumbar motion (i.e. lateral bending), the impact of growth on tether force can be considered negligible. The data of simulations underlie the clinical observation that age and skeletal maturity are not the most important risk factors for tether breakage [9] However, compared to a healthy spine, the compression forces in a tethered spine are up to twice as high. Further clinical studies are needed to better understand the long-term consequences. In addition, biomechanical and numerical studies are needed, especially in scoliotic spines, to analyze, for example, the influence of the initial internal stress due to the correction procedure on the breakage rate. In order to perform a comprehensive analysis of the biomechanical effects of asymmetric loading on the intervertebral disc, to elucidate its impact on disc material behavior and structural integrity.

Author contributions J.F. designed the study, developed the model, performed the computer simulations and the data analysis, drafted and critically reviewed the manuscript. M.P. critically reviewed the manuscript. P.T. critically reviewed the manuscript. F.H. supervised the study. Ma.P. developed the model and critically reviewed the manuscript.

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Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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