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Intra-operative measurement of applied forces during anterior scoliosis correction

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ABSTRACT

Background: Spinal instrumentation and fusion for the treatment of scoliosis is primarily a mechanical intervention to correct the deformity and halt further progression. While implant-related complications remain a concern, little is known about the magnitudes of the forces applied to the spine during surgery, which may affect post-surgical outcomes. In this study, the compressive forces applied to each spinal segment during anterior instrumentation were measured in a series of patients with Adolescent Idiopathic Scoliosis.
Methods: A force transducer was designed and retrofit to a routinely used surgical tool, and compressive forces applied to each segment during surgery were measured for 15 scoliosis patients. Cobb angle correction achieved by each force was measured on intra-operative fluoroscope images. Relative changes in orientation of the screw within the vertebra were also measured to detect intra-operative screw plough.
Findings: Intra-operative forces were measured for a total of 95 spinal segments. The mean applied compressive force was 540 N (SD 230 N, range 88 N–1019 N). There was a clear trend for higher forces to be applied at segments toward the apex of the scoliosis. Fluoroscopic evidence of screw plough was detected at 10 segments (10.5%).
Interpretation: The magnitude of forces applied during anterior scoliosis correction vary over a broad range. These forces do reach magnitudes capable of causing intra-operative vertebral body screw plough. Surgeons should be aware there is a risk for tissue overload during correction, however the clinical implications of intra-operative screw plough remain unclear. The dataset presented here is valuable for providing realistic input parameters for *in silico* surgical simulations.

1. Introduction

Scoliosis is a complex, three-dimensional spinal deformity most commonly affecting adolescents in the form of Adolescent Idiopathic Scoliosis (AIS). The severity of the deformity is described clinically by measurement of the Cobb angle (Cobb, 1948), the angle of curvature in the coronal plane. Severe and progressive scoliosis is treated by surgical instrumentation and fusion of the spine. This is primarily a mechanical intervention to both reduce the size of the deformity and limit further deformity progression. Corrective forces are applied to the spine *via* structural implants which are then required to sustain these loads, maintaining spinal alignment until bone fusion is achieved.

Anterior instrumentation consists of a single rod anchored to the convex side of the deformed spinal column *via* vertebral body screws. Discectomies clear the intervertebral fusion sites and correction is achieved by compression forces applied sequentially between each adjacent pair of screws along the length of the construct, thus reducing the curve convexity. Picetti et al. (2001) first described a thoracoscopic technique, which for selected thoracic curves, provides several advantages over more commonly used posterior approaches, including the fusion of fewer levels, quicker recovery and less scarring. Post-operative implant-related complications remain a concern, the incidence reported to be as high as 20.8% (Reddi et al., 2008), although rates of 10% are more typical. These include screw pull-out, rod fracture, inadequate spinal fusion (*pseudarthrosis*) and subsequent loss of correction.

Intra-operative corrective forces are a key component of spinal deformity surgery, yet little has been reported concerning their magnitudes. Distraction forces have been measured during early Harrington rod procedures (Waugh, 1966; Hirsch and Waugh, 1968; McBride et al., 1979), as well as derotation forces applied to modern posterior instrumentation (Lou et al., 2002). More recently, distraction forces were measured in a series of patients fitted with growing rods to treat early onset scoliosis (Noordeen et al., 2011). A sensor-equipped distractor was also used to capture the lateral flexibilities of scoliotic motion segments during posterior corrective surgery (Reutlinger et al., 2012). There have also been a few reports where transducers were attached to pedicle hooks, screws

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and the rod to measure implant loads directly (Nachemson and Elfstrom, 1971; Daniels et al., 1984; Smith et al., 1996).

In the first anterior corrections using a flexible cable, Dwyer et al. (1969) measured the tension induced in the cable and found loads exceeding the calibration limit of ~450 N. Snyder et al. (1995) mentioned use of a compression clamp instrumented with a strain gauge during anterior correction of lumbar deformity while Klöckner et al. (2003) described the development of instrumented forceps to measure tensile forces in the rod. There is currently no data reporting routinely applied corrective forces and therefore little is known of their role in effecting surgical outcomes.

Using a custom designed force transducer retrofit to a routinely used surgical compression device, the current study provides *in vivo* measurements of the corrective forces applied to each spinal segment during anterior scoliosis surgery in a series of AIS patients. The biomechanical effect of these forces was investigated by quantifying the immediate Cobb angle corrections achieved at each spinal segment, as depicted by intra-operative fluoroscope images. This study provides data important to improving our understanding of the biomechanics of spinal deformity correction.

2. Methods

2.1. Thoracoscopic surgical technique

All surgeries were performed at the Mater Children's Hospital in Brisbane, Australia by surgeons Geoff Askin and Robert Labrom. The surgical procedure has been described previously (Lenke, 2003). The instrumentation system consisted of the CD Horizon Eclipse spinal system with bi-cortical vertebral body screws (with staple) and a 5.5 mm diameter rod (Medtronic Sofamor Danek, Memphis, USA). Compression was applied sequentially from the most superior to the most inferior segment, using a ratchet style cable compression device (848–959 MM071001, Medtronic Sofamor Danek, Memphis, USA). The coronal plane orientation of surgical tools, spine and implant during compression of a single spinal segment is illustrated in Fig. 1. For each segment, the rod is fixed to the superior screw, while the inferior screw is free to slide along the rod. Compression between the two screw heads is applied in discrete increments until the desired correction is achieved, at which time the inferior screw is also fixed to the rod.

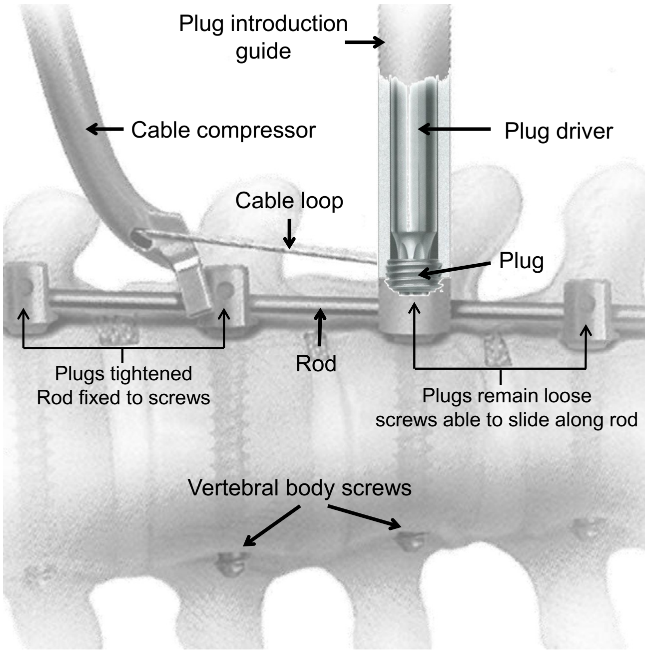

Fig. 1. Coronal plane illustration of spinal segment compression as applied by a cable compressor during thoracoscopic anterior scoliosis correction surgery (© Medtronic Sofamor Danek, adapted from the original image provided by Medtronic, Inc.)

As per normal surgical procedure, compression was performed under the visual guidance of coronal plane fluoroscope imaging. For each segment, an image was taken prior to, and then intermittently on the surgeon's demand throughout compression. Fluoroscope alignment remained static for the duration of compression for each particular segment.

2.2. Patient recruitment and clinical data

Fifteen patients scheduled to undergo thoracoscopic anterior instrumentation and fusion for treatment of thoracic AIS were consented for inclusion in this study. The clinical selection criteria for this treatment ensured patients with neuromuscular pathology were excluded. Pre-operative radiographic measures of deformity were obtained for each patient and included the spinal levels spanned, scoliosis apex and coronal plane Cobb angle. The post-operative Cobb angle was also obtained at patient follow-up one week after surgery. Approval from both the Mater Children's Hospital and Queensland University of Technology Human Research Ethics Committees was obtained before commencing this research.

2.3. Force transducer design and calibration

The force transducer consisted of two linear strain gauges (EA-06-015DJ 120/LE Vishay Precision Group Micro-Measurements, Raleigh, NC, USA) positioned symmetrically 180° apart on the top and bottom surfaces of the compressor actuator shaft (Fig. 2). The gauges were configured in a Wheatstone half bridge circuit and measured the bending strain on the shaft induced by the cable tension. The strain gauges and wiring were embedded within a medical grade silicone adhesive (MED3-4013, NuSil Technology, Carpinteria, USA) and enclosed by a stainless steel protective casing.

Data acquisition equipment included a signal conditioning unit (SCC-SG03/SCC-68, National Instruments, North Ryde, Australia), 16-bit resolution 1.25 MS/s data logger (USB-6259, National Instruments, North Ryde, Australia), laptop computer and LabView SignalExpress software (version 2.5, National Instruments).

Transducer output was calibrated to a measurement of applied cable tension by operating the cable compressor within a uniaxial testing machine. The external cable loop was applied to a vertically aligned load cell, while the compressor foot was positioned against a horizontally aligned screw fixed to the base of the machine. Calibration was performed regularly throughout the study.

Prior to each surgery the instrumented cable compressor underwent gas plasma sterilisation (Sterrad, ASP, Irvine, CA, USA) which provided

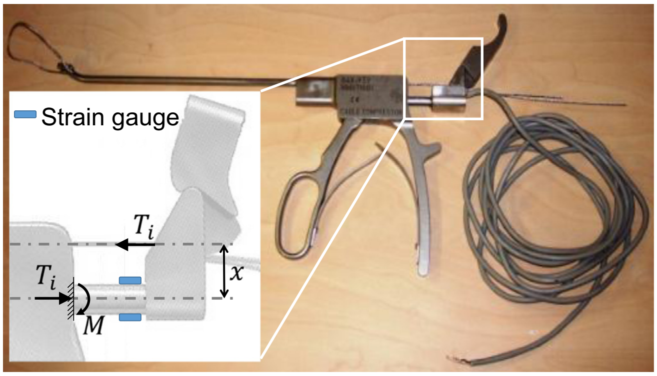

Fig. 2. Cable compression device retrofitted with force transducer. Insert shows strain gauge configuration on actuator shaft where T_i is the cable tension, M is the bending moment in the actuator shaft which is proportional to T_i ($M = T_i x$).