Clinical Biomechanics 54 (2018) 118–124

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Biomechanical analysis of the durability of a modified S1 vertebrae transpedicular screws insertion technique

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ARTICLE INFO

Keywords:
Sacral bone
Transpedicular screw
Pull-out strength
Biomechanical test
Lumbosacral fixation

ABSTRACT

Background: One of the most important elements of the transpedicular screw implantation technique, which enables a strong screw-bone interface, is the precise choice of the site of screw insertion and the screw's trajectory. Due to the complex biomechanics of the lumbosacral interface and different shape of the sacrum, fixation of this segment remains a challenge for surgeons. Because of this, Kubaszewski et al. proposed a modified technique in which the entry point for screw insertion in the S1 vertebra is changed.
Methods: Six human cadaver specimens of the S1 vertebrae were examined. Two transpedicular screws were inserted into the body of each examined vertebra using two implantation methods with different screw entry points and trajectories. The screws were subjected to cyclic preloading, followed by the pull-out test. The ultimate pull-out force, displacement, stiffness, and failure energy were measured.
Findings: The average pull-out force obtained for the standard method of implantation was 498 N (SD 201), whereas for the modified technique, it was 1308 N (SD 581). Displacement of the inserted screws in the new method was 36% higher than in the case of the standard method. This method is also characterized by the greater stiffness of the obtained interface and greater failure energy than the normally used technique.
Interpretation: The obtained results demonstrate that the use of the new technique of implantation significantly increases the strength of the obtained screw-bone interface. It should also increase the success rate of the performed fixations and increase the safety of such fixations in clinical practice.

1. Introduction

Pain in the lumbosacral spine is one of the most common health problems and reportedly affects up to 80% of the population (Cassidy et al., 2005). It is a lifestyle disease that hinders normal functions and disrupts the ability to perform work. Pain in this spinal segment is mostly caused by progressive degenerative changes, past injuries, or spinal tumours. One of the most serious consequences of this situation is the loss of stability of the spinal column (Rubin, 2007). Similar to the cases of advanced spondyloarthrosis or spondylolisthesis, performance of fixation with the use of transpedicular screws can restore stability and provide very good results (Lee and Langrana, 1984; Okutan et al., 2003).

The most common causes of failure of transpedicular fixation are: loosening of the screws and screw pull-out, breakage, or displacement (Pihlajamaki et al., 1997). Other factors that are equally important to the success of the performed fixation are the implantation technique itself and quality of the osseous tissue into which the bone screws are inserted. A key element of the implantation technique, which makes it possible to obtain a strong interface between the inserted screw and bone tissue, is the precise specification of the anatomical points identifying the site of insertion of the screw into the vertebra and its trajectory.

In clinical practice, there are two techniques for implantation of transpedicular screws in the area of the S1 vertebra, which are characterized by the anteromedial trajectory (the most popular technique)

Abbreviations: BMD, bone mineral density; F_{max}, ultimate pull-out force; d, screw displacement; k, stiffness; E_{fl}, failure energy

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https://doi.org/10.1016/j.clinbiomech.2018.03.015
Received 2 February 2017; Accepted 19 March 2018

and anterolateral trajectory of the inserted screw in the transverse plane (Carlson et al., 1992; McCall et al., 2010). Despite the use of different screw trajectories in each implantation technique, all of the methods are characterized by the same site of screw insertion in the first vertebra of the sacrum. Smith et al. (1993) and Carlson et al. (1992) defined the starting site as a point located 2 mm distant laterally and below the inferior surface of the S1 superior articular process. Due to the large discrepancy in the interpretation of the starting site in the implantation methods used and the variable thickness of compact bone tissue in this area, Kubaszewski et al. (2014) proposed a modified technique in which the starting site for the insertion of the screw in the S1 vertebra is changed. Compared to classical methods, this site is located more intracranially and medially. The implanted screw passes through the superior articular facet of the S1 vertebra in which the screw is inserted following an earlier execution of the osteotomy of the cortical layer of that process. The removal of the articular surface creates a natural saddle that is formed by a layer of cortical tissue of increased thickness and supports the inserted screw from the bottom (Kubaszewski et al., 2013). Additionally, and thanks to the modification of the implantation site, the screw trajectory passes through an area with the highest density of cancellous bone tissue in the S1 vertebra as determined by Richards et al. (2010). It is located on the extension of the axis of the upper facet process.

Due to the complex biomechanics of the lumbosacral interface and different shape of the sacrum in comparison to the other vertebrae, fixation of this segment remains a challenge for surgeons (Kubaszewski et al., 2013). The load amount transferred by the sacrum (in particular the bending forces acting on the lower spine) and sizes of the vertebrae themselves (in particular the S1 vertebra) necessitate the use of longer transpedicular screws of larger diameter than in the case of the fixation of the thoracic and lumbar spine (Kast et al., 2006). Moreover, the lumbosacral segment is the region of the spine that is most often affected by degenerative changes, which results in, among others, reduced quality of the bone tissue (osteopenia and osteoporosis). This aspect, particularly in elderly patients, significantly impedes obtaining a durable and strong bone-screw interface and accelerates the occurrence of the inserted screw loosening phenomenon. Despite this and due to the dynamic development of spinal surgery and an increasingly ageing society, more and more elderly patients are subjected to surgical treatment of the spine with the use of transpedicular fixation (Lotz et al., 1997).

Because of the presented difficulties related to the issue of lumbosacral fixation, in particular, the insertion of transpedicular screws in the S1 vertebra, very few studies have investigated this topic. The vast majority of studies on the strength of the bone-screw interface are conducted on the vertebrae of the cervical and lumbar spine (Sagi et al., 2004; Wittenberg et al., 1991; Zhu et al., 2000). The conducted research mainly focuses on the impact of the quality of bone tissue and geometric, material, and strength parameters of the inserted screws on the strength of the obtained interface. A significant correlation was found between the force required to cause failure at the screw-bone interface and the bone mineral density (BMD) (Okuyama et al., 1993; Seller et al., 2007; Wittenberg et al., 1991). It was also proved that both the length of the implanted screws as well as the shape and diameter of the thread significantly affect the pull-out force (Filipiak et al., 2004; Seller et al., 2007). The commonly used static pull-out test ('pure' pull-out) is often insufficient to describe the process of failure of the screw-bone interface; therefore, cyclic preloading is becoming increasingly common before the final pull-out test (Pezowicz and Filipiak, 2009; Zhu et al., 2000).

The aim of this study was to determine the effect of the applied technique of transpedicular screw implantation in the sacral bone on the obtained strength of the screw-bone interface. We evaluated two ways of fixing screws: the commonly used classical technique and a modified technique in which the starting point for the insertion of screws in the S1 vertebra was changed.

Table 1
Donor demographics.

Specimen	Sex	Age [years]
1	Female	72
2	Male	71
3	Male	85
4	Male	78
5	Female	82
6	Male	72
	Average	77
	SD	6

SD - standard deviation.

2. Methods

2.1. Research material

Six human cadaveric sacral bone (S1-S5) specimens from random donors (71–85 years of age) were tested (Table 1). The soft tissues were removed and the specimens were stored in plastic bags at −20 °C until the day of testing. The study was approved by the Bioethics Committee of the Poznan University of Medical Sciences.

Transpedicular screws were inserted into each S1 vertebra using two implantation methods (Fig. 1). A screw was inserted on the left side of the vertebra using the classical technique described by Morse et al. (1994) and on the right side using the technique modified by Kubaszewski et al. (2013, 2014, 2016) (Fig. 2a). For the classical technique, we chose the method with the standard entry point using the anteromedial trajectory in the transverse plane and parallel to the endplate of the vertebra in the sagittal plane. A schematic representation of the applied screw trajectories is presented in Fig. 1. The study uses transpedicular monoaxial screws (SOCORE, Novaspine, Amiens, France) that have a diameter of 6 mm and are composed of Ti6Al4V titanium alloy. The length of the individual screws were chosen by a medical specialist during the implantation process and ranged from 45 to 55 mm (Fig. 2b). To assess the quality of the bone tissue of the tested specimens within the area of the inserted transpedicular screws, radiological examinations were performed with the use of a CT scanner (Somatom Emotion 16, Siemens, Erlangen, Germany).

2.2. Biomechanical testing

The tests were conducted on an MTS 858 MiniBionix strength tester (MTS Corporation, MN, USA). Due to the specific shape of the sacrum and need to obtain a surface appropriate for correct mounting on the test rig to conduct biomechanical testing, the specimens were embedded in a polyester resin. For test purposes, we designed a test rig that permitted us to perform the following analyses. During the first stage, each screw was subjected to cycle loading with the bending force

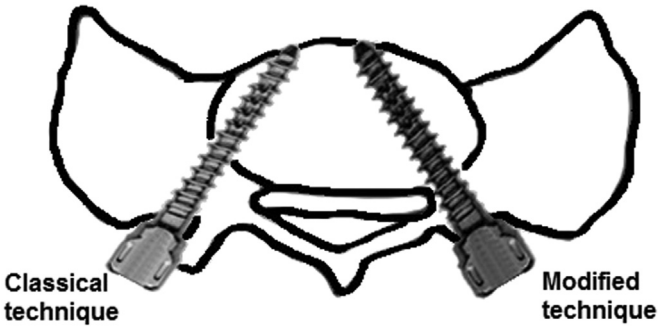

Fig. 1. Schematic comparison of the trajectory of transpedicular screws implanted with the use of the classical technique and modified technique presented in the transverse view.