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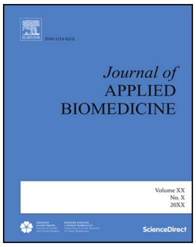

Original Research Article

Estimation of the spinal twisting angle using inertial measurement units during a rod derotation surgery in idiopathic scoliosis patients

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ABSTRACT

This study proposes a method to measure the twisting angle of a rod during a spinal correction surgery in real-time without performing an alignment procedure by using the six-axis data (tri-axis acceleration, tri-axis rate gyro) of the IMU and a Tait-Bryan Euler angle algorithm. To determine whether the twisting angle calculation algorithm offered an improvement, typical procedures described in existing studies were implemented using the same experimental data and were then validated using a three-dimensional motion analysis system (Vicon 460 motion analysis system). The correlation coefficients and the RMSE of the proposed method were 0.904 and 0.680° in the servo-motor experiment, and 0.988 and 0.691° in the mock surgery experiment, respectively, and these values were not significantly different from those calculated through other methods in previous studies. Therefore, if the proposed method is used during surgery, an alignment procedure and the assumptions following the morphology of body, which are limitations of prior research, are not necessary. Also the twisting angle of the rod can be observed without using magnetic data of IMU in real time during surgery. It is expected that the correction loss, which is a serious problem that can occur in patients after spinal correction, could be prevented.

Introduction

Idiopathic scoliosis is a disease characterized by an abnormal curvature of the spine caused by a three-dimensional deformity (Schlösser et al., 2014). Patients with mild scoliosis with a Cobb's angle of under 25° are usually treated with exercise, braces, etc. (Lam et al., 2011). In the case of severe scoliosis with a worse or worsening deformity, not only do patients suffer from an esthetic problem, but cardiopulmonary

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failure is also possible because the organs are pushed by the deformed spine (Johnston et al., 2011; Lam et al., 2011). Since those cardiopulmonary failures evoke disorders directly related to one's life, surgical treatment is commonly required to correct a spinal deformity (Asher and Burton, 2006).

Although there are several surgical treatment maneuvers that can correct a deformed spine, the about 96% of the correction techniques involve rod derotation, in which the surgeon can directly observe the surgical region when the patient is in the prone position during surgery (Qiu et al., 2011; de Kleuver et al., 2014). Rod derotation technique postero-medializes the deformed spine by rotating the rod coupled with the spine, transforming the coronal deformity into a kyphosis or lordosis in the sagittal plane, and then the spine is fixed trough osteosynthesis. This technique can achieve enough correction in the coronal or the sagittal plane (Cheng et al., 2008). However, since the preoperative transversal twisting angle between the upper and the bottom of the vertebral bodies reaches 29.3° on average (Cui et al., 2012), the rod is inevitably twisted during the correction procedure (Adam et al., 2008). In addition, since the rod used for the surgery is made of a material that exerts a force in order to restore itself, such as 316L stainless steel, titanium (Ti)-alloy, cobalt–chromium (CoCr) alloy, ultrahigh strength stainless steel etc., the vertebral body torsion resulting from the correction loss caused by a force exerted from the material during its restitution can be a problem after completing the surgery while the rod remains twisted (Cidambi et al., 2012; Serhan et al., 2013). According to Serhan et al. (2013), when titanium or ultrahigh strength stainless steel is used as the material for the rod, the shape maintenance of the material toward its original state generally reaches 77–90%. Salmingo et al. (2013) reported that the degree to which a rod is twisted can be high, and the restoration force increases as such. Also, Hwang et al. (2013) reported that patients with an upper body twisted to 18.9° improved to a state of 4.8°, and a correction loss occurred at 7.4° over time due to the restoration force. Therefore, in order to prevent secondary side effects, such as torsion of the upper body caused by the restoring force of the material of the rod and a subsequent loss of the correction angle, it is important to know the twisting angle of the cross section of the rod in real time with respect to the vertebral body during surgery.

Rod deformation in the coronal/sagittal plane is observable directly in the site or through a radiography (Cheng et al., 2008; Cidambi et al., 2012). However, since the rod coupled with the vertebral body is a thin isometric cylinder with a diameter of 5–7 mm, it is difficult to identify the cross-sectional deformation of the rod (rotation) through an identical approach of the coronal/sagittal plane during surgery (Lou et al., 2002; Lafon et al., 2009, 2010). Therefore, in order to know the rotational deformation of the rod during surgery, a different approach from that of existing methods is required. However, no study has been presented that estimates the amount of rotation of the rod in real time. It is expected that when methods from a previous study which measure the angle between two segments of the human body are applied, then the rotational angle of the rod coupled with the vertebral bodies can be estimated during surgery.

According to Kingma et al. (1996), the angle between two segments can be measured with an accuracy of more than 90% in all plane by applying trajectory data of markers that is obtained from a three-dimensional motion analysis system using the Euler angles, and these results were verified using a cadaver. If such a method is applied during rod derotation surgery, an estimation of the rotational angle of the rod can be obtained with a high degree of accuracy. However, the three-dimensional motion analysis system depends on a camera view has a very crucial limitation in that the marker can be hidden while performing a surgery, when the patient is surrounded by 5–6 people (Zhu and Zhou, 2004; Sabatini, 2011). In order to solve this problem, it is possible to apply such a method to measure the movement of the body segment by attaching small, portable sensors, such as inertial measurement units (IMU), to the body, as proposed by O'Donovan et al. (2007). According to O'Donovan et al. (2007), the angle of the ankle joint can be calculated using nine-axis IMU data (each of the direction vectors from tri-axial accelerometer, tri-axial gyroscope, and tri-axial magnetometer) attached each to two adjacent body segments (foot and shank). However, since the data from magnetometer is affected by ferromagnetic material or magnetic field (Cooper et al., 2009; Seel et al., 2014), an error occurs when this method is applied within an operating room (Favre et al., 2008). In an attempt to avoid environmental restrictions due to external interference from magnetic sources, Favre et al. (2008), Cooper et al. (2009), and Seel et al. (2014) estimated the joint angle of the two adjacent segments (ankle or knee joint angle) by using only six-axis IMU data (tri-axis acceleration, tri-axis rate gyro), excluding the magnetic data.

In previous studies, the angles between the neighboring segments were calculated under a simple assumption that the IMU sensor coordinates and human body segment coordinates were aligned with each other (Zhu and Zhou, 2004; Favre et al., 2006; Liu et al., 2009). In order to achieve the maximum alignment between both coordinate systems (segment coordinate system and sensor coordinate system), two IMUs were attached strictly on the corresponding orthogonal segment planes in a designated direction. However, when the IMUs were attached on the human body to calculate the segment angle, the manner with which the IMU was attached on the orthogonal plane in a pre-defined direction and the impractical assumption that the IMUs and segment coordinates were coincident might lead to a problem in the accuracy (Seel et al., 2014). In order to calculate the precise angle between the segments by using the IMU, sensor-to-segment calibration is surely required (Seel et al., 2014). Recent studies used an IMU attached to calibrate the sensor and segment coordinate system in the required alignment procedure for rotational movement, such as knee flexion/extension or hip abduction/adduction in predefined ranges between 45° and 180° for each degree of freedom (Favre et al., 2008; Brennan et al., 2011; Jakob et al., 2013). However, when the methods of these prior studies are applied to a spinal correction, a significant limitation may occur in that it is not possible to move at a level of 45–180° degrees during surgery, like in previous studies, due to the absence of the degree of freedom once the IMU is attached to the rod, so the application of the same alignment procedure as in previous studies is impossible. Since the alignment procedure and the assumption of coordinate system are coincident and magnetic data cannot be applied, the measuring method has to be replaced with another method so that the