Andreas ALK[1], Tobias MARTIN[1], John BASSEY-NEEF[1], Jens BERGER[1], Josef KOZAK[1, 2]

AESCULAP AG (1),
AGH Akademia Górniczo-Hutnicza w Krakowie, Katedra Metrologii i Elektroniki (2)

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Smart Device Assisted Method for Rod Length and Rod Radius Measurement in Percutaneous Pedicle Screw Surgery

***Abstract**. In a percutaneous pedicle screw surgery the surgeon is faced with huge challenges because he has no direct view on the operating field. The screw positions and the required rod dimensions for the stabilizing connection are hard to define. In this paper a new method for a percutaneous pedicle screw surgery is described to record the positions of three pedicle screws with help of a mobile localizing system with passive markers and a tablet computer. The presented system calculates the required rod length and rod radius. The procedure is more convenient than mechanical measuring systems and it works without radiation load of the patient. The system is tested with an in-vitro test arrangement and first results are very promising with an accuracy of ±2 mm for the rod length.*

Streszczenie.** Dużym problemem dla chirurgów w zabiegach nieinwazyjnej chirurgii śrub pedikularnych jest brak oglądu na pole operacyjne. Z tego powodu określenie pozycji poszczególnych śrub oraz wymaganej długość prętu stabilizacyjnego może nastręczać trudności. W niniejszym artykule zaprezentowano nową metodę rejestracji pozycji śrub pedikularnych z wykorzystaniem pasywnych markerów optycznych, mobilnego systemu nawigacyjnego, oraz tabletu. Zaprezentowane rozwiązanie pozwala na obliczenie wymaganej długości oraz krzywizny pręta pedikularnego. Opisywana metoda jest wygodniejsza niż pomiar z wykorzystaniem systemów mechanicznych oraz nie wymaga naświetlenia pacjenta promieniowaniem rentgenowskim. Testy metody przeprowadzone w środowisku in-vitro wykazały dokładność pomiaru długości pręta stabilizacyjnego na poziomie ±2 mm co wydaje się być bardzo obiecującym rezultatem. **(Metoda pomiaru długości oraz krzywizny pręta stabilizacyjnego z wykorzystaniem urządzeń mobilnych w nieinwazyjnej chirurgii śrub pedikularnych)

Keywords: medical navigation, computer assisted surgery, mobile devices.
Słowa kluczowe: nawigacja medyczna, chirurgia wspomagana komputerowo, urządzenia mobilne

Introduction

In spine surgery pedicle screw systems are used for fixation of the spine in case of a degenerative disc disease and/or spondylolisthesis. The transforaminal lumbar interbody fusion, an open surgery method, is an iatrogenic traumatic procedure which causes soft tissue and muscle injuries. For a reduction of the surgical trauma a minimal invasive method was invented as described by Schwender et al. [1]. The minimal invasive transforaminal lumbar interbody fusion (MI-TLIF) appears to have the advantage of shorter hospital stays and decreased narcotic usage after surgery [2]. The percutaneous operation technique however presents the surgeon with many challenges like the placement of the pedicle screws, selecting a fitting rod or the positioning of the rod without a view to the pedicle screws.

Medical navigation systems are used in computer-assisted surgery (CAS) for knee replacement, total hip arthroplasty, spine- and neurosurgery. In orthopedic surgeries image free navigation systems like Aesculaps Orthopilot® are state of the art. They offer a navigation method to place the implants without radiation load which is different from the image based navigation systems. For this procedure active or passive markers on a Rigid Body are tracked by a stereo camera-system. A software calculates the position of the Rigid Bodies towards the camera with a 3D- reconstruction algorithm. Aesculap´s Orthopilot® with the NDI Polaris medical localizer is a very accurate navigation system but it's quite expensive and not mobile. Due to these facts a mobile localizer for Android and iOS smart-phones was developed by Aesculap. The mobile localizer is able to track the positions of two Rigid Bodies in reference to the camera in real time. With help of image processing algorithms the circle contours of the Rigid Body`s markers are identified in the video frame. The 2D position of the markers are reconstructed to 3D- space data by a reconstruction algorithm. The mobile medical localizer calculates the rotation and the translation of two Rigid Bodies to a camera coordinate system [3].

In this paper a method is proposed for recording the pedicle screws position with a mobile medical localizer and calculating the required rod length and rod radius. This information is necessary for connecting the pedicle screws by a fitting rod in a MI-TLIF surgery. Today´s standard for rod determination measurements are mechanical systems and x-Ray images [4]. To reduce radiation load and to replace inconvenient mechanical devices this method was developed. The system is based on low-cost components and offers a simple way to get information of the pedicle screw positions without having a direct view on the operating field. The system is able to calculate the required rod length and rod radius for different screw positions. The functionality of this method is described more precisely and the accuracy of the system is tested by an accuracy test arrangement as well in this work.

Material and method

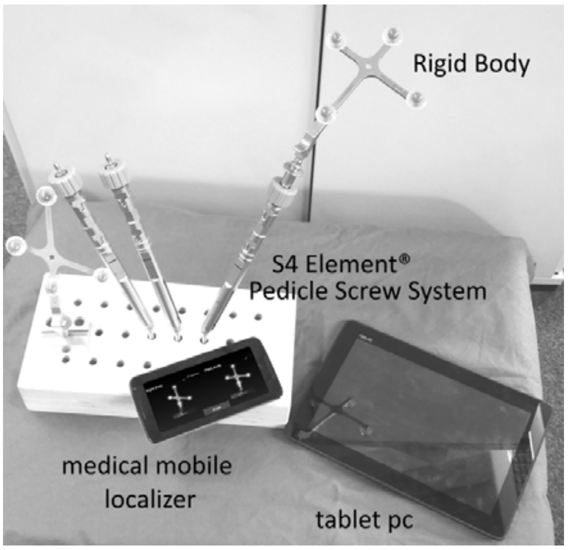

Fig. 1. Components of the rod assignment system

The hardware of the rod determination system consists of Aesuclap´s S4 Element® pedicle screw system for MI-TLIF surgery with special attachments for Rigid Bodies, two different Rigid Bodies, a medical mobile localizer and a mobile tablet computer with a custom developed application.

The S4 Element ® pedicle screw system is made up out of polyaxial pedicle screws. On top of the screws tubes are fixed for the minimally invasive surgery method. A prototype attachment for tracking the screws is created to fix a trackable Rigid Body on it.

Rigid Bodies are made up out of four retro reflective markers on a rigid cross. There are three different Rigid Bodies which differ in their geometrical form. The mobile medical localizer is able to detect the position of two different Rigid Bodies at the same time.

As mobile medical localizer a smart phone with Android as operating system is used. The tracking software is a custom developed software and is described by Daniol. [3].

For displaying the screw positions and the results of the rod determination a tablet computer is used. The tablet pc communicates with the medical mobile localizer via a Bluetooth connection.

System workflow

The purposed system is able to record the positions of three pedicle screws to a fixed reference. As reference a Rigid Body is positioned next to the pedicle screws and fixed on a golden plate. A second Rigid Body, which is called screw Rigid Body, is placed on top of the attachment of a first outstanding pedicle screw. The screw Rigid Body is moveable and is put on the attachment of every pedicle screw tube during recordings. The medical mobile localizer and the tablet computer are automatically connected over a Bluetooth connection after starting the applications. An assistant holds the mobile localizer and makes sure that both Rigid Bodies are visible. The localizer sends the position data of both Rigid Bodies continuously. The tablet computer records the position data of the Rigid Bodies with a click for each screw position. It calculates the necessary offsets and displays the screw in a frontal and sagittal view on the screen. After recording the first screw position the screw Rigid Body is moved to the second pedicle screw and so on. That way, all positions for three pedicle screws are recorded and displayed on the screen. During recording it is necessary that the reference Rigid Body and the patient should not be moved. Once all pedicle screw positions are recorded the tablet computer calculates the required rod length and rod radius for the recorded screw positions. When the radius is calculated greater than 150 mm, the radius is displayed straight because there are no rods available with a taller radius than 140 mm in the S4 Element System®. A straight rod fits in a situation with a radius greater than 150 mm [5].

Fig. 2. Pedicle Screw positions, calculated rod length and rod radius displayed on the tablet pc

Offset Calculation

In order to calculate the rod length and radius the positions of the pedicle screws are required. The mobile medical localizer makes it possible to get the translation vector and the rotation matrix of a predefined Rigid Body coordinate system towards the camera. The rotation matrix and the translation vector are combined in this transformation matrix.

$$T=\begin{bmatrix} R_{11} & R_{12} & R_{13} & tx \\ R_{21} & R_{22} & R_{23} & ty \\ R_{31} & R_{32} & R_{33} & tz \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

The Rigid Body coordinate system has got its absolute zero point on top of the trocar attachment. To get the right screw position in 3D-space it is necessary to calculate an offset to the absolute zero point of the trocar. For calculating the offset the coordinates from the zero point of the Rigid Body to the head of the screws has to be known.

$$T_{Offset}=\begin{bmatrix} 1 & 0 & 0 & x_{Offset} \\ 0 & 1 & 0 & y_{Offset} \\ 0 & 0 & 1 & z_{Offset} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

An offset to the Rigid Body center can be added by multiplying these two matrices [6]:

$$T_{Trocar}=T \cdot T_{Offset} \quad (3)$$

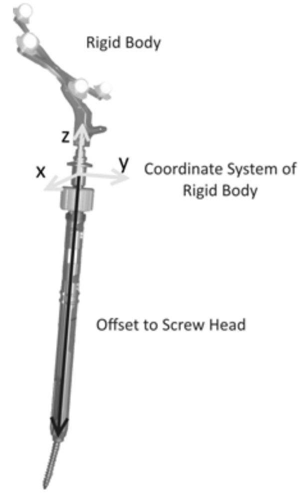

Fig. 3. Offset from Rigid Body to Screw Head

Referencing

The position of the screws must be recorded to a fixed reference Rigid Body. The reference is necessary to get a relative vector to a fixed position because there is a movement of the medical mobile localizer in between the recordings. In Fig.4. the method of referencing is shown.

To get the position regarding to the reference Rigid Body coordinate system, the transformation matrix of the reference has to be inverted and multiplied with the transformation matrix of the tool Rigid Body [3].

$$T_{screw}=T_{ref}^{-1} \cdot T_{tool} \quad (4)$$

T_{screw} = Transformation matrix of screw head in reference coordinate System

T_{ref} = Transformation matrix of Reference Rigid Body towards Camera

T_{tool} = Transformation matrix of Tool Rigid Body with screw head offset

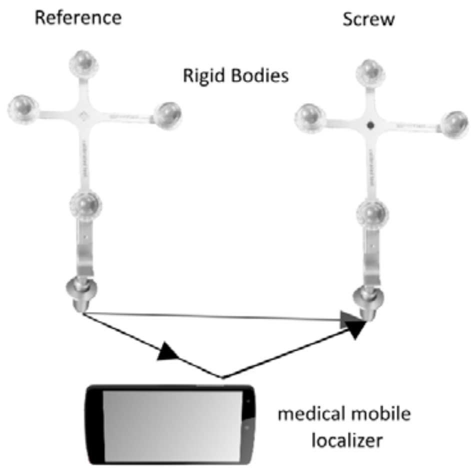

Fig. 4. Referencing: Transformation of Screw Rigid Body is calculated to the Reference Rigid Body

Recording screw positions

All screw positions are recorded in the referencing coordinate system. For all screw positions you get a vector from the reference absolute zero to the screw head. With these vectors we can calculate the vectors between the screw heads displayed in Fig. 5. This is necessary for the following rod length and rod radius calculations.

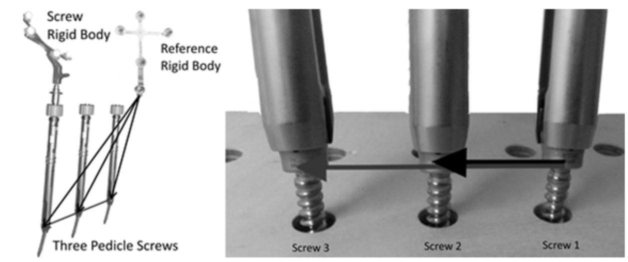

Fig. 5. Recording screw position to get vectors from first screw to second and third screw

Calculating rod length and radius for three screws

After all screw positions are recorded, the application on the tablet computer calculates the rod length and the rod radius as displayed in Fig.6.

The rod length is calculated with the magnitude of the vector (c), which shows from the first screw head to the last one.

$$Rod\ Length = |\vec{c}| \quad (5)$$

For the rod radius calculation of the screw positions the algorithm uses the circumcircle of a triangle which is defined by the position data of the three recorded screw positions. For the radius the magnitude of the vector (a) which shows from the second screw to the last one and the angle between vector c and b has to be calculated.

$$Radius = \frac{|\vec{a}|}{2 \cdot sin(\alpha)} \quad (6)$$

To get the angle between two vectors the scalar product of two vectors has to be divided by the product of the vectors magnitude.

$$cos(\alpha) = \frac{\vec{b} \cdot \vec{c}}{|\vec{b}| \cdot |\vec{c}|} \quad (7)$$

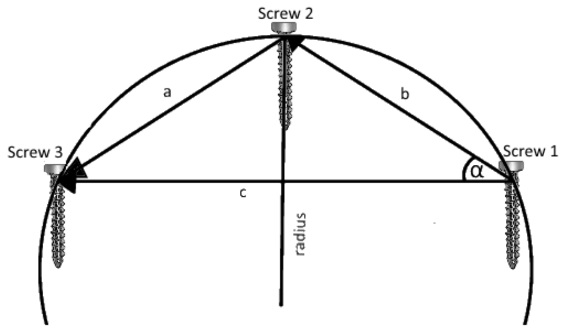

Fig. 6. Calculation of rod radius

Accuracy Experiment

For testing the accuracy of the proposed rod determination system a test arrangement with three pedicle screws was built.

In order to have a ground truth data for pedicle screw positions a reference plate was used. The reference plate is made up of wood with 24 drilled holes ordered vertically and horizontally with the same distance to each other. To position the pedicle screws at the same height an attachment with a thread for the screws was built out of polyactide (PLA). Three S4 Element® pedicle screws were placed at the same height side by side as shown in Fig. 5. The distance between two pedicle screws is 30 mm. The expected rod length is twice the distance of two pedicle screws which is 60 mm. The expected rod radius should be displayed straight, because the screw positions were ordered in a line at the same height. The reference Rigid Body was placed next to the pedicle screws on the wooden plate. The positions of the screws were recorded as shown in the topic system workflow. Ten measurements of the rod length and rod radius were performed.

Results

In table 1 you can see the results of the rod assignment measurement. In ten measurements of the rod length we got a mean value of 59.9 mm with a standard deviation of ±1.91 mm. The real rod length was 60 mm. The range of the values was between 58 mm and 63 mm.

Table 1 Results of rod length and radius measurements

Measurements	Rod length (60 mm)	Rod radius (straight)
1. Measurement	63	straight
2. Measurement	60	straight
3. Measurement	60	straight
4. Measurement	59	straight
5. Measurement	58	straight
6. Measurement	63	straight
8. Measurement	60	straight
9. Measurement	60	straight
10. Measurement	59	straight
Mean:	59.9 mm	
Standard deviation:	±1.91 mm	

For a clinical use the rod length has to be chosen larger because a too short rod cannot be fixed in the pedicle screws. Because of this the rod length has got a clearance of +5 mm length. But if the rod is more than +5 mm long, there is a high risk that the rod can injure nerves and the surrounding tissue. The accuracy of the rod length measurement is exact enough for a clinical use because the range of all calculated rod lengths was always in the clearance of 5 mm. The rod radius was always displayed as a straight line.

In Aesculap´s S4 Element System the largest rod radius is 140 mm [5]. On that account every radius was displayed straight because it was measured taller than 150 mm. In the test arrangement the pedicle screws were ordered in a line and the expected radius should be infinity. The proposed rod was always displayed by the application properly and fitted to the pedicle screws test scenario. To make a statement about the rod radius accuracy some tests with different radii are necessary.

In Further work the system will be optimized for a clinical use because there is a point which has to be improved. The reference Rigid Body has to be fixed during recordings and there shouldn't be movements between the reference and the patient. Also the reference Rigid Body shouldn´t stand too far away from the second Rigid Body, because the accuracy of the medical mobile localizer is worse when the distance is too high. On the operating table the reference Rigid Body cannot easily be placed next to the pedicle screws. An alternative method with a fixed Rigid Body on top of a pedicle screw tube could also conduce as a reference Rigid Body. With a reference on top of pedicle screw movements of the patient don`t have influence on the measurements because all screws move relatively. The referencing Rigid Body would also be closer to the second Rigid Body.

Conclusion

In this paper we developed and tested a procedure for smart devices to measure the rod length and radius in a pedicle screw surgery without radiation load for the patient and the surgeons. A medical mobile localizer tracked two Rigid Bodies, which are placed on top of the trocars of the pedicle screw. A tablet computer received this data and calculated the required rod length and the rod radius for the positions of the pedicle screws. In a test arrangement the results for the rod length measurement test seem to be very promising with an accuracy of ±2 mm. In further work the system will be improved for clinical usage and the accuracy for rod length and radius will be evaluated in more in-vitro test scenarios.

***Authors**: M.Sc. Andreas Alk, AESCULAP AG, DE-78532 Tuttlingen, E-mail: andreas.alk@aesculap.de; M.Eng. Tobias Martin, AESCULAP AG, DE-78532 Tuttlingen; B.Sc. John Bassey-Neef, HAW Hamburg, Berliner Tor 5, DE-20099 Hamburg; Dipl. Ing. Jens Beger, AESCULAP AG, DE-78532 Tuttlingen; dr hab. Inż. Józef Kozak, prof. nadzw. AGH, AGH Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie, Katedra Metrologii i Elektroniki, Al. A. Mickiewicza 30, 30-059 Kraków, AESCULAP AG, DE-78532 Tuttlingen, Niemcy, E-mail: josef.kozak@aesculap.de.*

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