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Does total disc arthroplasty in C3/C4-segments change the kinematic features of axial rotation?

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ABSTRACT

We analyze how kinematic properties of C3/C4-segments are modified after total disc arthroplasty (TDA) with PRESTIGE® and BRYAN® Cervical Discs. The measurements were focused on small ranges of axial rotation ($<0.8°$) in order to investigate physiologic rotations, which frequently occur in vivo.

Eight human segments were stimulated by triangularly varying, axially directed torque. By using a 6D-measuring device with high resolution the response of segmental motion was characterised by the instantaneous helical axis (IHA). Position, direction, and migration rate of the IHA were measured before and after TDA. External parameters: constant axially directed pre-load, constant flexional/extensional and lateral-flexional pre-torque.

The applied axial torque and IHA-direction did not run parallel. The IHA-direction was found to be rotated backwards and largely independent of the rotational angle, amount of axial pre-load, size of pre-torque, and TDA. In the intact segments pre-flexion/extension hardly influenced IHA-positions. After TDA, IHA-position was shifted backwards significantly (BRYAN-TDA: ≈8 mm; PRESTIGE-TDA: ≈6 mm) and in some segments laterally as well. Furthermore it was significantly shifted ventrally by pre-flexion and dorsally by pre-extension. The rate of lateral IHA-migration increased significantly after BRYAN-TDA during rightward or leftward rotations.

In conclusion after the TDA the IHA-positions shifted backwards with significant increase in variability of the IHA-positions after the BRYAN-TDA more than in PRESTIGE-TDA.

The TDA-procedure altered the segment kinematics considerably. TDA causes additional translations of the vertebrae, which superimpose the kinematics of the adjacent levels. The occurrence of adjacent level disease (ALD) is not excluded after the TDA for kinematical reasons.

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1. Introduction

Damage to intervertebral discs in the cervical spine is a frequently occurring and severe problem that can also affect young people. Fusion, which is the gold standard of treatment (Cloward, 1958; Smith and Robinson, 1958), is especially criticised because symptomatic adjacent level disease (ALD) is suggested to be a possible long-term complication (Anderson and Rouleau, 2004; Bertagnoli et al., 2006; Bohlman et al., 1993; Cunningham et al., 2003; Eck et al., 2002; Fritsch and Pitzen, 2006; Goffin et al., 1995; Hilibrand et al., 1999). Total disc arthroplasty (TDA) is reported to avoid ALD (Anderson et al., 2004; Bartels et al., 2008; Chang et al., 2007; Chung et al., 2009; Dmitriev et al., 2005). However, this hypothesis has not been definitively proven (Bartels et al., 2008; Beguiristain et al., 1994; Fritsch and Pitzen, 2006; Villas et al., 1994). Further supposed advantages of TDA are the possible maintenance of the segmental range of motion and the avoidance of donor site morbidity and pseudarthrosis (Puttlitz et al., 2004).

The segmental kinematics following TDA have not yet been explored, although they are considered to be important to the clinical outcome (Bartels et al., 2008; Chung et al., 2009; Fritsch and Pitzen, 2006; Sasso and Martin, 2011). Published data are usually related to rotational angle–torque characteristics (RATCs), range of motion (ROM), segment stiffness, and/or an averaged position of the rotational axis. However, such data are not kinematically significant because the

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real movement paths of the moved vertebra cannot be calculated by means of them (Mansour et al., 2004; Wachowski et al., 2009b).

Important kinematic features of segment motion are the instantaneous position and the direction of the instantaneous helical axis (IHA) and the instantaneous migration rate (IMR) of the IHA (Mansour et al., 2004; Wachowski et al., 2009b). These geometrically defined parameters usually depend on the rotational angle of the segment.

First, we reconsider the basic effects of two implant designs on the internal segmental kinematics. In intact segments the intervertebral discs mechanically represent a deformable synarthrosis. Because deformation of an elastic layer allows six kinematic degrees of freedom (DOF), a synarthrosis does not reduce the segmental number of DOF. This number is only restricted by the number of simultaneously guiding diarthroses. In cervical segments, the adjoining vertebrae are potentially linked by four diarthroses: two facet joints (FJs) and two uncovertebral joints (UCJs). For mechanical reasons the number of DOF is reduced by one by each single contact of the joints. When all four joints take over guidance a cervical segment has only two DOF.

Using in vitro measurements, we analysed how the kinematic properties of C3/C4-segments were modified after implantation of the PRESTIGE® Cervical LP Disc or the BRYAN® Cervical Disc. In implanting the prostheses, the UCJ bases were partially removed (Fig. 1) so that the UCJs become functionally annulled or considerably diminished (Kang et al., 2010a; Kang et al., 2010b). We focused our analyses on the small amplitudes of axial rotation ($<1^\circ$) to investigate physiologic rotations that frequently occur in vivo and to exclude possible guidance by the residual portions of the UCJs during extreme axial rotation.

PRESTIGE® is a "ball-and-socket joint" in which the socket is anteriorly/posteriorly elongated. Under force closure, which is enforced by an axially directed preload $\vec{F}_z$, the segment has four (three rotational and one translational) kinematic DOFs after PRESTIGE-TDA. In the BRYAN® Cervical Disc two metal shells embrace a lentoid elastic nucleus that has six kinematic DOFs similar to the natural disc (Patwardhan et al., 2010). BRYAN-TDAs do not produce the kinematic restrictions of the UCJs. The number of DOF of the PRESTIGE-TDA, however, is exactly the same as that of the removed natural structure consisting of intervertebral disc plus the UCJs. We hypothesised the following: in cervical segments, the natural kinematics is better reproduced by PRESTIGE-TDAs than by BRYAN-TDAs.

2. Material and methods

2.1. Materials

Eight human C3/C4-segments were used (68.7 ± 13.5 years), which were stabilised using a solution that minimally altered the hardness and the shape of the osseous structures (Fanghänel, 2009; Fanghänel and Schultz, 1962). Osteochondrosis, spondylarthrosis or injuries were excluded using CT scans.

2.2. Methods

A custom-made, well-established 6D measuring apparatus was used to determine the kinematic properties of the eight segments (Mansour et al., 2004). A cyclically varying, triangular-shaped, torque–time function $\vec{T}_z(t)$ (amplitude: 2.24 Nm; frequency:≈1 min^{-1}) and an axially directed constant force $\vec{F}_z$ (20 N) were applied to each C3 vertebra. The varying spatial C3-positions were recorded in relation to the reference (C4) with a spatial resolution of <1 μm for translation and $<10^{-3}$ deg for rotation. This measuring system was sufficiently precise to determine at least 400 "snapshots" of the varying C3-position within one cycle of $T_z(t)$. From this large set of successive C3-positions, the instantaneous position and the direction of the instantaneous helical axis (IHA) and its instantaneous migration rate (IMR) were calculated as functions of the rotational angle α.

This measuring programme was repeated when the amount or position of the axially directed pre-force F_z was changed to alter the constant flexional/extensional and/or lateral/flexional pre-torque. The entire programme was also applied after PRESTIGE-TDAs and then after BRYAN-TDAs (Fig. 1). Because less bone resection was necessary, PRESTIGE-TDAs were performed first. The correctness of the implantations was verified using X-rays in multiple projections.

To reach biomechanically comparable measurements for the eight segments, identical starting conditions of the respective initial C3-position were experimentally adjusted. For it, the movable (C3) and the fixed (C4) coordinate systems were simultaneously defined by translating the line of the axially directed force F_z until segment C3 finally tilted neither in lateral flexion nor in flexion/extension. Then, the F_z-line met the centre of resistance and defined the z-axis. The x-axis lay in the segment's sagittal plane of symmetry. The position of the origin of the coordinate system was defined by the 6D-measuring system. Fig. 2 illustrates the initial position of segment D and the initially coinciding coordinate systems.

Though rotational angle–axial torque characteristics (RATCs) do not have direct kinematic significance, we used RATC for the biomechanical assessments of the kinematic data. When the periodic triangular-shaped torque–time-function $T_z(t)$ was applied to a segment, a transient process was simultaneously stimulated that superimposed on the periodic response, the angle–time-function $\alpha(t)$ (Meyer and Guicking, 1974). Once the transient process was ended the response function $\alpha(t)$ became periodic such that the time-independent function $\alpha(T_z)$ could now be calculated from $\alpha(t)$ and $T_z(t)$ (=RATC, Fig. 3). When the sign of the constant inclination $dT_z(t)/dt$ of the triangular-shaped function changed $T_z(t)$ further transients periodically influenced the function $\alpha(t)$. These transients were reflected in the non-linear tr-segments of $\alpha(T_z)$. In the nl-segments of $\alpha(T_z)$, however, the transients faded away (Fig. 3). This non-linearity revealed that the torque and rotational angle did not follow Hooke's law for the C3/C4-segments. Note that exactly these angle ranges without transients ($\alpha \geq 0$ for rotation to the left and $\alpha \leq 0$ for rotation to the right, Fig. 3) were used to assess the kinematic data such as the IHA-position and the IHA-direction or IMR.

3. Results

To confirm that only data that correspond to physiological motions are presented we focussed exclusively on small ranges of axial rotation ($-0.8^\circ \leq \alpha \leq +0.8^\circ$).

3.1. IHA-direction

The constancy of the IHA-direction was found to be a general feature of each segment. The IHA-line was shifted parallel in the eight segments during axial rotation and remained almost parallel to the z–x-plane (deviations: $<5^\circ$). However, the directions of the stimulating torque vector $T_z(t)$ and the direction of the IHA-lines did not coincide. The IHA-lines were rotated backwards in the z–x-planes (Figs. 4 and 5). The IHA-direction was statistically observed to remain at an inclination of approximately -69° on average and was independent of TDA or the size of pre-torque or pre-load (Table 1). Therefore, the segments generally performed the same type of motion.

3.2. IHA-migration and IHA-position

For segment D, in flexional/extensional and in the right/left neutral state, the succeeding intersections of the migrating IHA with the x–y-plane of the fixed coordinate system are shown in Fig. 6 for the axial rotation to the right within an angular range of $\pm 0.8^\circ$. The lengths of the intersection lines were approximately 8 mm for the intact segment and for the segments after PRESTIGE-TDA or BRYAN-TDA. Compared to the intact segment the intersection lines were shifted backwards after both TDA types (Fig. 6). After BRYAN-TDA, the intersection line was shifted an additional amount to the right side. The lengths of the displacement vectors ($\Delta\vec{r}_{pin}(0^\circ)$, and $\Delta\vec{r}_{bin}(0^\circ)$) of the intersection at the rotational angle $\alpha=0$ were approximately 10 mm. The displacement vectors $[\Delta\vec{r}_{pin}(0^\circ)=(\Delta y_{pin}, \Delta x_{pin})=(y_{pn}(0^\circ)–y_{in}(0^\circ), x_{pn}(0^\circ)–x_{in}(0^\circ))$ and $\Delta\vec{r}_{bin}(0^\circ)=(\Delta y_{bin}, \Delta x_{bin})=(y_{bn}(0^\circ)–y_{in}(0^\circ), x_{bn}(0^\circ)–x_{in}(0^\circ))]$ of the central point of the intersection lines approximately reflected the displacement vectors of any point along the respective IHA-lines (Fig. 6). Therefore, it was possible to display these displacement vectors in the x–y-plane of the fixed co-ordinate system (Fig. 7). As a result only the backward shifts of the IHA-lines were statistically significant ($p<1\%$). Additionally, the difference in

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