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Dynamic behavior of tripolar hip endoprostheses under physiological conditions and their effect on stability

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ABSTRACT

Tripolar systems have been implanted to reduce the risk of recurrent dislocation. However, there is little known about the dynamic behavior of tripolar hip endoprostheses under daily life conditions and achieved joint stability. Hence, the objective of this biomechanical study was to examine the in vivo dynamics and dislocation behavior of two types of tripolar systems compared to a standard total hip replacement (THR) with the same outer head diameter.

Several load cases of daily life activities were applied to an eccentric and a concentric tripolar system by an industrial robot. During testing, the motion of the intermediate component was measured using a stereo camera system. Additionally, their behavior under different dislocation scenarios was investigated in comparison to a standard THR.

For the eccentric tripolar system, the intermediate component demonstrated the shifting into moderate valgus-positions, regardless of the type of movement. This implant showed the highest resisting torque against dislocation in combination with a large range of motion. In contrast, the concentric tripolar system tended to remain in varus-positions and was primarily moved after stem contact. According to the results, eccentric tripolar systems can work well under in vivo conditions and increase hip joint stability in comparison to standard THRs.

1. Introduction

Total hip arthroplasty has become an established surgical intervention in case of hip osteoarthritis, aiming at pain relief and preservation of quality of life. Within general procedures, standard total hip replacements (THR) are implanted consisting of stem, head and cup. However, in recent years there has been an increased interest in tripolar hip endoprostheses.

In contrast to standard THRs, this type of hip replacement uses two articulating surfaces, so-called bipolar designs. Unlike former bipolar hip systems, the intermediate component of tripolar systems includes an additional articulation (outer bearing surface) which is located between the intermediate component and the acetabular cup or liner. The principal idea of tripolar systems is based on the use of the inner bearing surface for the majority of movements and the outer bearing surface for movements with a large range of motion (ROM). According to clinical studies [1–5] these systems tend to reduce the risk of dislocation. However, it remains unclear if these positive clinical outcomes with respect to joint stability are due to a large effective head size.

The tripolar implant designs used in clinical practice can be divided into concentric and eccentric systems. These variations are related to the arrangement of the rotation centers of the intermediate component with regard to the center of the artificial femoral head. Previous studies [6–8] analyzed the dynamic behavior of the intermediate component both theoretically and under in vitro conditions. However, these investigations were performed without consideration of physiological lubricant or alternating load situations as seen in vivo. So far, the in vivo effectiveness of these systems has been verified by radiographic or fluoroscopic imaging [8–11]. This kind of detection does not provide any information whether the component motion is caused by the implant dynamics itself or by impingement between the femoral neck and the rim of the intermediate component.

The main objective of the present study was to investigate the dynamics of tripolar systems under daily life conditions with lubrication and altering force and motion patterns. This should provide further insights in the in vivo performance of the intermediate component and its contribution to joint stability. Furthermore, we hypothesized that tripolar systems increase joint stability in comparison to a standard THR with an identical femoral head

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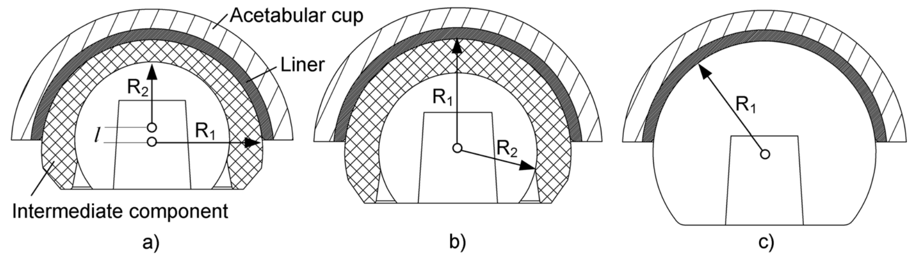

Fig. 1. Sectional view of the tested implant designs and their schematic construction, (a) eccentric design, (b) concentric design, (c) standard THR design.

diameter. Within the scope of this study an industrial robot was used to ensure the application of loads and motions of everyday life activities as well as crucial dislocation movements of the artificial hip joint. Throughout the experimental testing we differentiated between concentric and eccentric designs.

2. Materials and methods

2.1. General experimental setup

An unused concentric and eccentric intermediate component (custom-made, roughness of the articulating surfaces $R_a = 0.75$, OHST Medizintechnik AG, Rathenow, Germany) with an outer diameter of 40 mm in combination with a CoCr liner (ATF, Marignier, France) was used for the experiments (Fig. 1). The eccentric design considered a 2 mm offset l between the centers of rotation of the inner and outer articulation surface to create a certain amount of eccentricity. Both intermediate components consisted of UHMW-PE, combined with an unused 28 mm outer diameter ceramic head (BioloxForte, CeramTec, Plochingen, Germany) and a CoCr acetabular liner. For dislocation tests an unused standard 40 mm ceramic head (BioloxDelta, CeramTec, Plochingen, Germany) with an unused associated ceramic liner (BioloxDelta, CeramTec, Plochingen, Germany) was used as reference. A stem (SL-Plus standard stem cementless, Smith & Nephew Orthopaedics AG, Baar, Switzerland) as well as the acetabular cup (Exclusif, ATF, Marignier, France) was embedded with casting resin (RenCast FC 52, Huntsman Advanced Materials, Duxford, England) into a specific fixation device, which permitted definite implant positions.

The experimental setup consisted of a six-axis industrial robot (TX200, Stäubli, Bayreuth, Germany), an *X*–*Y*–*Z* cross table, a contactless stereo camera system (PONTOS, GOM mbH, Braunschweig, Germany) and a video camera (Fig. 2a). The hip stem was moved and loaded by the robot. The cross table was used to fix the acetabular implant component and allow force control by means of elastically constrained translations in three spatial dimensions. Every 4 ms three rotation angles (Cardan angles) and three force vector components were transferred to the robot. Within this time step, the robot controlled its position and force until the predetermined position and the desired force were reached. The data of the resultant forces and moments were continuously measured, using a 6D force torque sensor on the robot. All rotations were related to the rotation centers of the different femoral heads. For this purpose, the femoral heads along with the fixed stem were surveyed before any testing using a 3D-coordinate measuring machine (Prismo 7HTG, Carl Zeiss, Oberkochen, Germany) in order to determine the location of the center of rotation.

In order to preserve the clinical background all indicated angles for cup inclination and anteversion as well as stem anteversion referred to the projected representation onto the planes of the human body (sagittal plane, coronal plane, transverse plane). In order to use the projected angles for the robot, these angles had to be transformed into angles with an ordered set of elementary rotations about the co-moving axes in accordance with the definition of Cardan angles. Therefore, the orientation of the acetabular cup including inclination and anteversion corresponded to the radiographic definition according to Murray [12]. The indicated angles for the femoral orientation only considered anteversion, i.e. varus or valgus positions were not analyzed. That meant the stem axis pointed in the direction of the longitudinal axis in a frontal and sagittal view. For the physiological femoral movement the kinematic chain of the elementary rotations started with flexion/extension around a spatially fixed axis of rotation followed by rotational movements of abduction/adduction and internal/external rotation about the co-moving axes [13].

For the investigation of the dynamic behavior and dislocation stability two different test arrangements were carried out with the robot. Both test arrangements are described in detail in the following sections.

2.2. Analysis of the dynamic behavior of the intermediate component

In order to analyze the dynamic behavior of the intermediate component, different load cases were applied by the industrial robot. These load cases included everyday life activities such as walking, knee bending, stair climbing and a combination of sitting down and standing up from a chair.

For this purpose the in vivo motion and force data reported by Bergmann [14] were evaluated by means of analytical techniques. Based on reference points, the relative motion between pelvis and thigh was generated for different routine activities. Moreover, measured in vivo hip joint forces [14] were transferred into the pelvic coordinate system which was establised by using the reference points. In order to use the consistent parameter sets for simulating a sequence of consecutive smooth motion cycles in test benches, the data were interpolated by an eight-degree trigonometric polynomial to get a continuously cycle. The computations of the parameter sets were described in detail in [13].

In the present study, all load cases of the everyday life activities were based on the evaluation of the averaged motion data of the patient with the abbreviation PFL [14]. For this patient, specific initial position data of the acetabular cup (59° cup inclination, 18° cup anteversion) and the hip stem (23° stem anteversion) were present, which allowed a reproducible mounting position of the robot test device. Apart from the relative joint motion, the in vivo contact forces [14] were simultaneously applied for the selected activities to simulate a realistic dynamic behavior of the intermediate component. These calculated forces, however, were scaled to one quarter to prevent damage to the test device. After setting the initial position, each specimen was subjected to 100 load case specific motion cycles.

To ensure a postoperative lubrication film during consecutive motion cycles, the acetabular cup was permanently one quarter filled with calf serum, which required a horizontal arrangement