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ORIGINAL ARTICLE

Influence of joint kinematics on polyethylene wear in anatomic shoulder joint arthroplasty

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Background: Despite the positive results in total shoulder arthroplasties (TSAs), a higher revision rate is documented compared with total hip and knee replacements. Wear is the possible main cause of TSA failure in the long-term. This study investigated the effect of joint kinematics and the influence of the rotator cuff on the polyethylene wear performance in an anatomic TSA.
Methods: Lifting a load of 2 kg with an abduction/adduction of 0° to 90° was simulated for 2×10^6 cycles as a primary motion using a fully kinematic joint simulator. A combined rotation in anteversion-retroversion of ±5° and ±10° was also simulated. The force in the superior-inferior direction and the axial joint compression were applied under force control based on in vivo data of the shoulder. A soft tissue restraint model was used to simulate an intact and an insufficient rotator cuff.
Results: The highest wear rate in the intact rotator cuff group was 58.90 ± 1.20 mg/10^6 cycles with a combined rotation of ±10°. When an insufficient rotator cuff was simulated, the highest polyethylene wear rate determined was 79.67 ± 4.18 mg/10^6 cycles.
Conclusions: This study confirms a high dependency of the polyethylene wear behavior and dimension on the joint kinematics in total shoulder replacement. This can be explained by an increasing cross-shear stress on the polyethylene component. The results obtained indicate that additional combined kinematics are an indispensable part of wear tests on anatomic shoulder replacements.
Level of evidence: Basic Science Study; Biomechanics

Keywords: Anatomic total shoulder arthroplasty; joint kinematic; superimposed motion; cross-shear; rotator cuff; wear rate

Although anatomic total shoulder arthroplasty (aTSA) is associated with improved function and range of motion,[5,31] registry data[2] reveal that revision surgery occurs more frequently compared with total knee and hip replacements. Complication-related revision rates of between 1% and 19% occur within the first 2 years.[2,16,28] According to the Australian Orthopaedic Association National Joint Replacement Registry, the dominant reasons for revision surgery in shoulder arthroplasties at 9 years are loosening and lysis.[2]

Polyethylene (PE) wear in arthroplasty plays an essential role in the development of periprosthetic osteolysis, which results in aseptic loosening and is therefore considered to be a fundamental reason for bone degradation.[4] PE wear-related

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osteolysis is frequently reported in knee and hip replacements, but there is no clear evidence of such a causal relationship concerning total shoulder prostheses. However, histologic evaluations of the interface membranes surrounding total shoulder prostheses compared with failed total hip prostheses that were removed due to progressive osteolysis concluded, based on a similar pathogenesis, that PE wear also provokes proinflammation and osteolysis in shoulder joint replacements.[37] Therefore, understanding the PE wear processes is important, and its relevance should be emphasized in TSA.

PE wear performance in aTSA has been investigated in 2 in vitro studies using multistation simulators.[22,38] However, the joint kinematics in these studies were set to a single type of motion cycle without varying the joint kinematics. In this context, it should be remembered that the shoulder joint allows a large range of motions and, compared with the other big joints of the human body, has the greatest range of motion. In case of shoulder arthroplasty, the glenohumeral joint is replaced. The anatomy of the glenohumeral joint is characterized by a low conformity between the humeral head and the glenoid. This configuration allows the major rotations (eg, abduction-adduction) but also small translations (eg, superior-inferior sliding) of the head relative to the glenoid cavity.

The joint is stabilized by the rotator cuff. Implantation of an aTSA requires an intact rotator cuff.[39] However, a rotator cuff insufficiency (RCI) may also occur and progress after replacement of the joint.[19,23] According to joint registry data, RCI is the second most common reason for revision surgery in aTSA.[2] The main causes for RCI are the incompetence of the soft tissues surrounding the prosthesis, bony insufficiencies, or an incorrect component placement during surgery.[9] RCI mainly results in a superior-anterior instability of the glenohumeral joint.[19,23] Therefore, higher contact kinematic (in terms of translations) between the humeral head and the glenoid must be expected in the case of RCI compared with an intact rotator cuff.[33]

The present study investigated the effect of the applied joint kinematics and the influence of the rotator cuff on the PE wear performance in an aTSA. The questions addressed were:

1. How are PE wear rate, particle size, and particle morphology influenced by the magnitude of joint kinematics?
2. Are glenohumeral translation and PE wear rate increased if an insufficient rotator cuff is simulated?

Materials and methods

Complex joint simulators are generally used for wear tests in joint arthroplasty. With these wear simulators, the joint-specific kinematics and loading conditions of the natural joint are reproduced as well as the surrounding fluid and temperature. In contrast to hip and knee wear tests, no international standards are available to determine the wear rate of aTSAs. However, a scenario for wear testing of aTSA proposed in a previous study was used for the present study.[22]

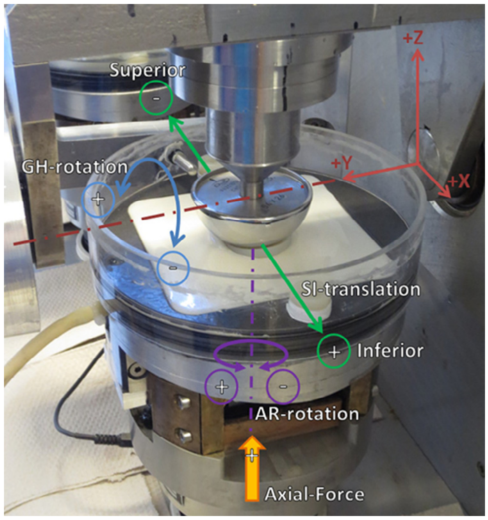

Figure 1 Test setup with the axis of rotation and translation of the humeral head and the glenoid component: *z*-axis: axial-force and axis of anteversion-retroversion (*AR*) rotation; *x*-axis: superior-inferior (*SI*) translation and axis of glenohumeral (*GH*) rotation.

Testing setup

Kinematics, loading, and a simulation of the surrounding ligament structures need to be implemented to realize an anatomic reproduction of the shoulder motion. All of these parameters should represent the anatomic situation as closely as possible; therefore, the wear analysis was done using a joint simulator with a freely programmable virtual soft tissue model[18] (KSD-6-1000; Advanced Mechanical Technology, Inc., Watertown, MA, USA). The servohydraulic joint simulator consists of 3 wear stations and 1 axial loaded soak control station. Each station has 4 controllable degrees of freedom (Fig. 1). A detailed description of the testing setup has been published by Mueller et al.[22]

Influence of joint kinematics

To study the influence of different kinematics, a representative and well-defined multidirectional joint motion was chosen[22]; therefore, several simultaneous motions were applied to the glenohumeral joint. In addition to a superior-inferior (SI) translation and the glenohumeral (GH) rotation, a superimposed rotation in anteversion-retroversion (AR) was also simulated. Previous wear studies simulated the AR rotation (arm forward-flexion/extension) in the sagittal plane between ± 8° and ± 10° in magnitude.[22,38] Within this study, 3 different magnitudes in AR rotation were considered: 0°, ±5°, and ±10°. All other kinematics and loading parameters (GH rotation, axial force, and SI force) were kept comparable and in accordance with the previous testing conditions.[22]

Influence of the rotator cuff

An SI translation of the humeral head relative to the glenoid is clinically observed in healthy shoulders during arm abduction.[21] The translation is limited to a few millimeters by the soft tissue restraint of the rotator cuff, glenoid conformity, and ligaments. Healthy shoulders achieve an excursion of approximately 2.1 mm during the