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Friction-induced whirl vibration: Root cause of squeaking in total hip arthroplasty

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ABSTRACT

Squeaking is reported for ceramic-on-ceramic hip arthroplasty, and risk factors leading to this phenomenon have been investigated empirically in the past, this way giving hints to when this phenomenon occurs. The aim of this study is to present an experimentally validated explanation for the dynamical mechanism underlying the squeak, i.e. a description of what happens when noise is generated.

First the kinematics of the ceramic bearing couple in relative motion are reconsidered. The relative motion at the contact zone can be understood as superposition of relative rotation and translation. The relative weight of both components depends substantially on the instantaneous load vector, which primarily determines the position of the contact area, and the instantaneous relative rotation vector. For the investigated gait scenarios, both load vector and rotation axis vary strongly during the gait cycle.

Second, experimental vibration analysis during squeak is performed. A pronounced micrometer scale elliptical motion of the ball inside the liner is found. It is shown that the rotational component of the relative kinematics during gait indeed leads to friction induced vibrations. We show that a generic whirl type friction induced flutter instability, also known from similar (non bio-) mechanical systems, is the root cause of the emitted squeaking noise.

Based on the identified mechanism, the role of THA system parameters (materials, design), patient risk factors, as well as the role of the gait cycle, will have to be reconsidered and linked in the future to develop effective measures against squeaking.

1. Introduction

Squeaking of ceramic-on-ceramic total hip arthroplasty occurs in pain-free implants and usually causes no functional deficit (Stanat and Capozzi, in press; Swanson et al., 2010; Yeung et al., 2010). Although a large number of studies treat this phenomenon, the etiology, i.e. the risk or influence factors leading to squeaking remain not completely understood.

Among these risk factors, patient specific conditions were often target of speculations and empirical analyses. Some studies reported the patients with squeaking hips to be younger, heavier and taller than patients with silent hips (Sexton et al., 2011; Walter et al., 2007, 2010, 2011), however, other studies did not find any statistical significance when investigating factors such as age, sex, height, weight (Restrepo et al., 2010; Stanat and Capozzi, in press) and body mass index (BMI) (Restrepo et al., 2010). Recently, a higher body mass index (BMI) was found in a meta-analysis to be linked to a higher incidence of squeak (Stanat and Capozzi, in press). Preoperative diagnosis of rheumatoid arthritis was also linked to squeaking (Swanson et al., 2010).

Besides these patient factors, the implant itself was connected to squeaking. Stanat and Capozzi (in press) and Restrepo et al. (2010) showed that the type of stem used in vivo is of importance, they found a significantly higher rate of squeak with stems being made of beta-titanium, with a certain neck and stem design (Restrepo et al., 2010) or a particular combination of stem and cup (Swanson et al., 2010). Similarly, the stem design was shown to have an important influence when being tested in vitro (Hothan et al., 2011). Specific cups seem not to be of importance in vivo (Stanat and Capozzi, in press) or in vitro (Hothan et al., 2011). Also the implant's position was speculated to play a role in causing squeak (Sexton et al., 2011; Walter et al., 2007, 2010), other studies showed that mean anteversion and inclination of squeaking hip replacements were not statistically different from those of control groups (Jarrett et al., 2009; Restrepo et al., 2008; Stanat and Capozzi, in press).

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A third group of influence factors is related to the frictional contact. Roughening of the ceramic surfaces in form of stripe wear after edge loading (Restrepo et al., 2008; Taylor et al., 2007), particulate debris (Chevillotte et al., 2010; Corten and MacDonald, 2010; Walter et al., 2008) and metallic transfer (Chevillotte et al., 2010; Restrepo et al., 2008), often following from neck-rim impingement, also may play a role, for example through a disturbed fluid film lubrication (Chevillotte et al., 2010; Jarrett et al., 2009; Rieker et al., 1998) or increased friction forces (Hothan et al., 2011). Numerical techniques also suggest that primarily increased levels of friction are necessary to excite audible vibrations (Weiss et al., 2009, 2010).

Despite the large number of studies focusing on influence and risk factors, and some success based on corresponding empirical approaches, dominant factors to date do not seem to have been identified in a way such that designers or clinicians could a priori select validated strategies to avoid squeaking with certainty. The main reason for this deficiency seems to be the comparatively poor understanding of the mechanical, respectively dynamical processes underlying the sound emission.

Today there seems to be some consensus on attributing squeaking to friction-induced vibrations. Already Rieker et al. (1998) speculated some resonance or stick-slip mechanisms taking place between head and cup to be responsible for squeaking in metal-on-metal bearings following a deficiency of lubrication. A stick-slip mechanism is brought forward by Currier et al. (2010). However, from a vibration point of view, none of the presently available studies can truly be considered to result in solidly validated hypotheses.

In consequence, the present study was specifically designed to clarify the dynamical root cause of squeaking in total hip arthroplasty from a mechanics and dynamics point of view. Several mechanisms leading to such friction-induced vibrations are known (see Akay, 2002 for a survey), and the one actually occurring in THA was to be identified. Based on the findings of a reassessment of hip kinematics and kinetics, vibration measurements on specifically designed test rigs were to be conducted to reveal the mechanism behind the vibration dynamics during squeaking.

2. Methods and materials

The study is structured in three parts. First, characteristic human gait cycles are analyzed with respect to load vector and kinematic state to enable a conclusive test design. Second, the kinematic states are investigated experimentally by using an idealized test rig to uncover the nature of the emerging vibrations as a function of the decisive kinetic and kinematic parameters. Third, the findings from the idealized test rig are validated by using a full scale hip simulator.

2.1. Analysis of the role of the gait cycle in squeaking

Activities related to squeaking are exercising, bending, stair-climbing, sex, putting on pants, and predominantly walking or prolonged walking (Jarrett et al., 2009; Walter et al., 2007). Although squeaking may sometimes occur continuously during the entire gait cycle (Glaser et al., 2008), it is typically observed as an intermittent phenomenon during certain physiological ranges of motion, only, for instance at the limit of flexion, when picking up a heavy load (Buergi and Walter, 2007), or during mid range motion while the bearing is loaded as in a simulated stair climb (Jarrett et al., 2007). In the present study the gait cycle is thus analyzed with respect to those kinematic and kinetic properties that lie at the heart of the vibration excitation mechanism.

In general, due to the nature of a ball-joint, the relative motion of the ball and the socket can instantaneously always be described as a pure rotation, and in the course of the gait cycle the corresponding axis of the momentary rotation changes its direction.

To analyze friction self-excited vibrations, the friction characteristics at the contact zone are decisive. Therefore, the link between the friction forces in the contact zone and the momentary relative rotation of ball and socket has to be determined. To do this, the instantaneous load vector has to be considered in addition, since the load vector determines – together with the relative orientation of the components – the momentary location of the contact-area between the surfaces of ball and socket. This contact area lies generally near the pole of the hip replacement's ball (cf. Bergmann et al., 2001).

While the load vector determines the contact area, the momentary rotation determines the friction forces inside the contact area; below we will show that these friction forces govern the dynamic behavior of the bearing partners. In the first part of the study selected characteristic gait cycles are thus analyzed correspondingly: It will turn out that for the present purpose the decisive quantity is the angle between the momentary load vector and the momentary axis of relative rotation between ball and socket. When the angle approaches zero, drilling type friction results, while angles approaching 90° result in straight sliding type friction, and angles in between can be understood as superposition of both. The angle between load vector and axis of relative rotation was thus derived for datasets from the Hip98 database of Bergmann et al. (2001).

The database already includes the time-evolution of the load vector. The axis of relative rotation of ball and socket had to be determined from the data. For that purpose position values of measurement-points from the hip and the femur segments were extracted from the database, and the momentary axis of rotation was calculated from the relative motion, viz. instantaneous relative velocity vectors. The axis of relative rotation of the ball inside the socket was then determined on the basis of the cross-products of the normalized velocity vectors and the normalized relative position vectors of the selected points. Based on the results, the angle between load vector and axis of rotation was determined.

2.2. Experimental investigation with an idealized test setup

To investigate the influence of load vector and kinematics on squeaking, an idealized test rig was builit (Fig. 1a,b), where both load vector (in magnitude and direction) and relative rotation axis and rate can be chosen independently. In the present study all those parameters are kept constant throughout a run, by that rendering a local model to any phase in the gait cycle to be considered. The acetabular group with the ceramic liner was firmly fixed on a rotating shaft, while the ceramic ball was mounted on a stem replacement with idealized dynamic properties (Fig. 1b); the stem is expected to play a major role in the excitation of audible vibrations with total hip arthroplasty (Hothan et al., 2010) and influences the prevalence of squeaking in vivo (Restrepo et al., 2010; Stanat and Capozzi, in press; Swanson et al., 2010). A 28 mm ceramic bearing couple (Ceramtec AG, Plochingen, Germany) was used. While the acetabular side was set into rotation, the stem replacement was subjected to different loads.

Our base setup is similar to that of Chevillotte et al. (2010), who did reproduce squeaking with lubrication only when metal transfer was present on the ceramics,

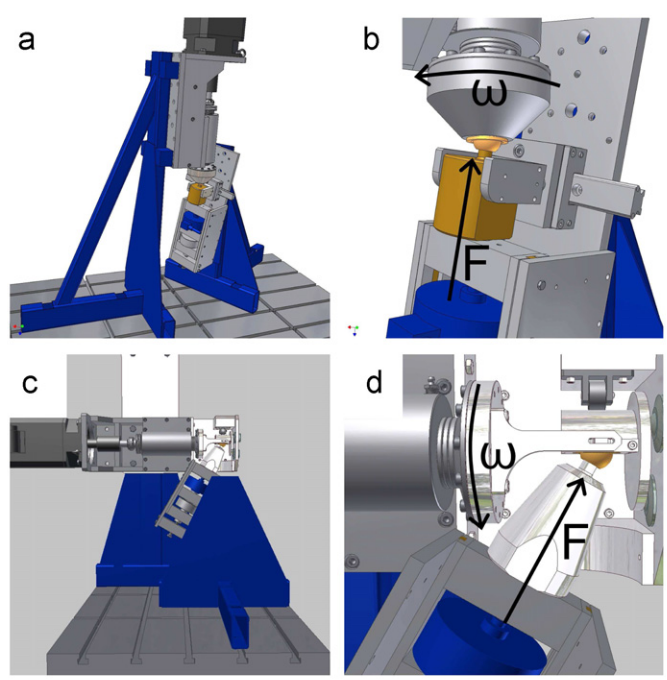

Fig. 1. (a) Schematic sketch of the test rigs used with the abstracted experiment and small angles (0°–50°). (b) Close-up of the ceramic components. The ball is mounted on a stem replacement (metal). Note that the stem replacement and the lower part of the test rig can be tilted to adjust the load axis (force *F*) independently from the axis of rotation. (c) Modified test rig used with large angles (60°–90°). (d) Close-up of the ceramic components and stem replacement.