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HiL simulation in biomechanics: A new approach for testing total joint replacements

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ABSTRACT

Instability of artificial joints is still one of the most prevalent reasons for revision surgery caused by various influencing factors. In order to investigate instability mechanisms such as dislocation under reproducible, physiologically realistic boundary conditions, a novel test approach is introduced by means of a hardware-in-the-loop (HiL) simulation involving a highly flexible mechatronic test system. In this work, the underlying concept and implementation of all required units is presented enabling comparable investigations of different total hip and knee replacements, respectively. The HiL joint simulator consists of two units: a physical setup composed of a six-axes industrial robot and a numerical multibody model running in real-time. Within the multibody model, the anatomical environment of the considered joint is represented such that the soft tissue response is accounted for during an instability event. Hence, the robot loads and moves the real implant components according to the information provided by the multibody model while transferring back the position and resisting moment recorded. Functionality of the simulator is proved by testing the underlying control principles, and verified by reproducing the dislocation process of a standard total hip replacement. HiL simulations provide a new biomechanical testing tool for analyzing different joint replacement systems with respect to their instability behavior under realistic movements and physiological load conditions.

1. Introduction

One of the most prevalent reasons for total joint revision is due to instability of the artificial joint. From a clinical point of view, joint instability describes any excessive relative movement between joint partners often accompanied by damage of implant components or adjacent soft tissue. As a consequence, the load-bearing capacity of the artificial joint is limited or not assured at all.

As regards instability of total hip replacements (THRs), dislocation of the femoral head represents a major reason for revision procedures [1,2]. Mechanisms linked to subluxation and final dislocation of THRs involve impingement events where the femoral head is levered out of the cup due to prosthetic or bony contact [3]. Another mechanism is described by

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spontaneous separation where the head is distracted in translational directions due to dynamic forces [4]. In this context, geometry [5] as well as positioning [6] of THR components have been frequently considered as significant factors for the risk of dislocation. A lack of restoration of the femoral offset and the neck length leads to lax soft tissue with higher dislocation risk [7,8]. Moreover, Kwon et al. [9] identified an increased relative dislocation risk for the posterior surgical approach if no capsular repair had been carried out. These studies underline the important role of the soft tissue with respect to THR stability.

Instability of total knee replacements (TKRs) is one of the most reported reasons for implant failure [10–12]. As TKRs are by design less constrained than THRs especially in translational directions, relative movement between joint partners is governed by restraining ligament and muscular forces. Therefore, instability mechanisms are given by excessive relative movement between the femoral and tibial component resulting in damage of surrounding soft tissue and hence a non-load-bearing or unstable articulation. Cases of subluxated or even dislocated TKRs have also been reported [13]. A clinical study conducted by Graichen et al. [14] revealed that primary instability is caused by implant malposition and ligament insufficiency or imbalance, respectively. Fehring and Valadie [15] refer to surgical failures in bone resection as well as inadequate implant design as causes for instability. Additionally, Berger and Rubash [16] connected rotational instability with rotational malalignment of the implant components. Most studies noted that instability of TKR often involves a combination of different reasons.

Hence, there is a variety of causes associated with failure due to joint instability of THRs and TKRs. Soft tissue condition, implant position and design are each frequent reasons. Nevertheless, a deep understanding of the underlying mechanisms of artificial joint instability is essential in order to take appropriate countermeasures and treatments. This involves, in particular, an understanding of the interaction between soft tissue structures and implant components. However, in vivo measurements of instability inducing movements and maneuvers are not available.

The objective of the present work is to introduce a novel approach which allows for testing of total joint replacements with respect to occurring mechanisms associated with joint instability. The approach is based on a highly flexible mechatronic test system. In this work, we present the underlying concept and implementation of required units. The major goal is to enable comparable investigations of different THR and TKR designs with respect to instability under reproducible, physiological-like boundary conditions which accounts for the soft tissue response during instability scenarios.

2. Background

Testing of implant components is usually focused on the mechanical behavior such as fatigue strength, frictional and slip properties as well as wear behavior [17,18]. Bader et al. [19] developed the first mechanical test device which allowed the determination of the range of motion until impingement and dislocation of THR, while measuring the occurring resisting moment. Thus, parameters such as implant design, position and load situation could be tested mechanically regarding their influence on dislocation on the basis of reproducible test procedures. In a subsequent study the relevance of head and neck geometry on stability was surveyed [5]. Following these experimental investigations, Kluess et al. [20] developed a finite-element model of the impingement and dislocation process, analyzing the influence of head size and implant position of THRs. A recent study from Kliewe et al. [21] demonstrated a fully analytical determination of the range of motion of THRs with consideration of multidirectional, superimposed movements.

Other researchers in the field focused mainly on the assessment of range of motion and the importance of orientation of THR components. Amstutz et al. [22] constructed a three-dimensional protractor. Subsequently, a couple of parameter studies were conducted on the basis of the same device regarding for instance the influence of head diameter and neck length [23], the effect of elevated-rim acetabular components [24] and the effect of larger head sizes [25] on instability. Guyen et al. [26] used an automated hip simulator instead of a protractor for the evaluation of tripolar hip implants with respect to the in vitro range of motion to impingement. A comparable approach to Bader et al. [19] was followed by Kiguchi et al. [27] using a hexapod platform with hybrid position-force control as mechanical test device for THR stability. Considering activities which might induce dislocation, they studied the effect of the femoral head diameter [28].

Regarding instability of TKRs, Luger et al. [29] assessed laxity and stability characteristics of condylar replacements on the basis of a knee simulating machine applying loads on anatomical and prosthetic knee joints. They evaluated parameters such as dishing of the tibia component, the placement of the components and the retention or resection of the cruciate ligaments. Utilizing a six-degree-of-freedom force-controlled knee simulator DesJardins et al. [30] emulated a walking cycle to determine the effect of implant design on TKR mechanics. They integrated a passive restraint system simulating the in vivo capsular restraint condition. Stukenborg-Colsman et al. [31] used a knee simulator where flexion–extension motion of mounted specimens could be carried out under isokinetic conditions. They examined mobile bearing knee prostheses with respect to the range of motion and the effect of rotational malalignment of the tibia baseplate. Using a robotic force–torque sensor test system, Woo et al. [32] studied current reconstruction techniques of the anterior cruciate ligament with respect to instability of the native knee joint. Maletsky and Hillberry [33] developed a five-axis simulator where either cadaveric knee specimens or TKRs mounted on fixtures could be tested under realistic dynamic loading.

In summary, previous test devices of THRs [22,26] were limited to range of motion analyses, neglecting the influence of the actual load situation. Recently developed mechanical test devices [19,27] were able to consider actual loading conditions on THRs. However, those could not take into account soft tissue tension during the dislocation process. Most test devices of TKRs were designed for conducting studies based on cadaver specimens [29,31–33]. Due to the decay, time-independent and reproducible parameter studies could not be conducted on the basis of these approaches. Moreover, a time-dependent