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Musculoskeletal Multi-Body Modeling used for Hardware-in-the-Loop Simulations

Instabilities of artificial joints are prevalent complications in total joint arthroplasty. Due to the variety of influencing factors involving complex interactions between implant components and soft tissue structures, the actual process leading to artificial joint instability and adverse kinematics is not fully understood. As ethical and technical reasons discourage in vivo measurements, our research group follows a novel approach in the field of orthopaedic biomechanics to test instability scenarios of hip and knee endoprostheses under physiological boundary conditions. The approach consists of a Hardware-in-the-Loop (HiL) simulation where a musculoskeletal multi-body model interacts with an industrial robot. SIMPACK is used to generate the musculoskeletal multi-body model and to provide a realtime-capable standalone model for implementation into the HiL simulation.

CLINICAL BACKGROUND

One of the most prevalent reasons for total joint revision is instability of the artificial joint (see Fig. 1). With regard to hip endoprostheses, dislocation of the prosthetic head represents a major reason for revision surgery. Mechanisms linked to the dislocation process involve prior prosthetic or bony contact (impingement), and spontaneous separation due to dynamic forces. Similarly, instabilities and adverse kinematics in knee endoprostheses constitute one of the most important reasons for implant failure. As knee endoprostheses are, by design, less constrained than hip endoprostheses, instability mechanisms are caused by excessive relative movement between the joint partners resulting in damage of surrounding soft tissue and hence an unstable joint articulation.

Numerous clinical and biomechanical studies address the issue of instability pointing out several influencing factors. Soft tissue condition, implant design and positioning have each been frequently referred to as major factors. However, the process leading to an unstable artificial joint and the precise contribution of each influencing factor is not yet fully understood as in vivo measurements of instability-associated maneuvers are discouraged by ethical and technical reasons. Therefore, we follow a novel strategy to test total hip and knee endoprostheses in instability scenarios under reproducible, physiological boundary conditions.

The approach consists of a Hardware-in-the-Loop (HiL) simulation where the anatomic environment of the artificial joint is completely extracted into a musculoskeletal multi-body model generated in SIMPACK. The interaction with real implant components is ensured by an industrial robot used as an actuator system.

Fig 1: Radiographs of a dislocated hip endoprosthesis (left) and an unstable knee endoprosthesis (right).

"The approach consists of a Hardware-in-the-Loop (HiL) simulation..."

FUNCTIONAL PRINCIPLE OF TESTING INSTABILITY

The functional principle of the HiL simulation is based on complementary sets of free and constrained directions of artificial hip and knee joints. Considering hip endoprostheses, all three translational directions are mainly constrained due to contact between the prosthetic head and the acetabular cup, whereas all three rotational directions are free within the technical range of motion. Likewise, all three translations and the adduction/abduction rotation are fairly bounded within knee endoprostheses due to soft tissue restraints and bony contours, while the internal/external and flexion/extension rotations are free. These joint characteristics can be used in determining whether the joint of interest is unstable by considering potential movements in the constraint directions during an instability event. This requires the incorporation of predefined free and constraint directions within the musculoskeletal multi-body model which also affects the underlying control strategy of the industrial robot running in hybrid position-force control as illustrated in the following for testing knee endoprostheses.

Considering the spatial load case in the knee joint, the free directions are two rotations of

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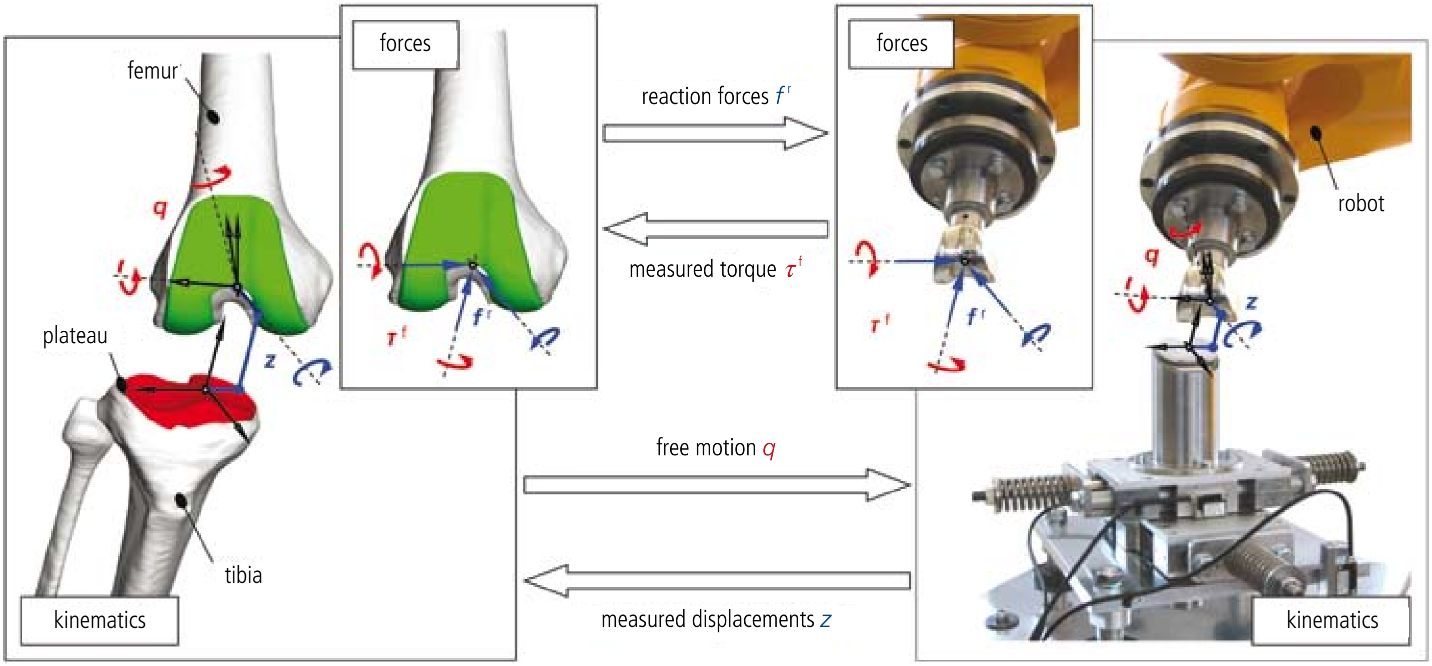

Fig 2: Functional principle of HiL simulation for testing kinematics and joint instability of knee endoprostheses with illustration of the exchanged variables between musculoskeletal multibody model (left) and the industrial robot (right) at the kinematic and force levels.

the femur with respect to the tibia plateau which correspond to internal/external rotation and flexion/extension movements (see Fig. 2). The three translational and remaining rotational direction are treated as constrained directions. For an actual time instant, the multi-body model delivers values of the joint coordinates q in the two free directions and joint forces/torque f^r in the four constrained directions which are transferred to the robot control. Hence, the robot rotates the femoral component into the desired position q and applies the joint reaction forces/torque f^r onto the endoprosthesis. In order to close the HiL control loop, the resulting displacements in the constrained directions, if any occur, are recorded and fed back to the multi-body model. Moreover, occurring torques τ^f in the two free directions are measured and transferred to the multi-body model. These torques could be caused by, for example, friction forces or impingement events.

The robot is able to apply the joint reaction forces/torque f^r as long as the endoprosthesis withstands these loads. However, an instability event is simulated when the joint is not able to bear the load application by the robot accompanied by increasing relative displacements in the four constrained directions.

EXAMPLE OF AN HIL SIMULATION

In order to illustrate the functional principle of the proposed HiL simulation, we simulated a rheonomically driven flexion movement of a so-called unconstrained knee endoprosthesis based on a simplified musculoskeletal multi-body model of the right lower extremity generated in SIMPACK (see Fig. 3). Within the multi-body model the patello-femoral joint is modeled with one degree of freedom. The tibio-femoral joint is represented by a kinematic sub-chain consisting of three orthogonal prismatic joints and three revolute joints with co-intersecting axes. Two revolute joints correspond to the free directions (flexion/extension and internal/external rotation) while the coordinates of the four other joints are constrained by the measurements

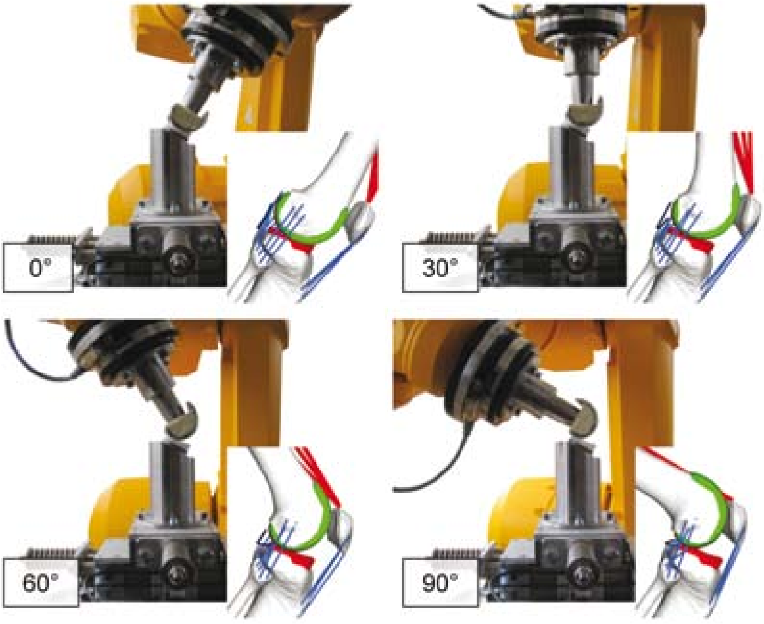

Fig 3: HiL simulation of an unconstrained knee endoprosthesis showing simultaneous positioning of the musculoskeletal multibody model and the industrial robot at different flexion angles.

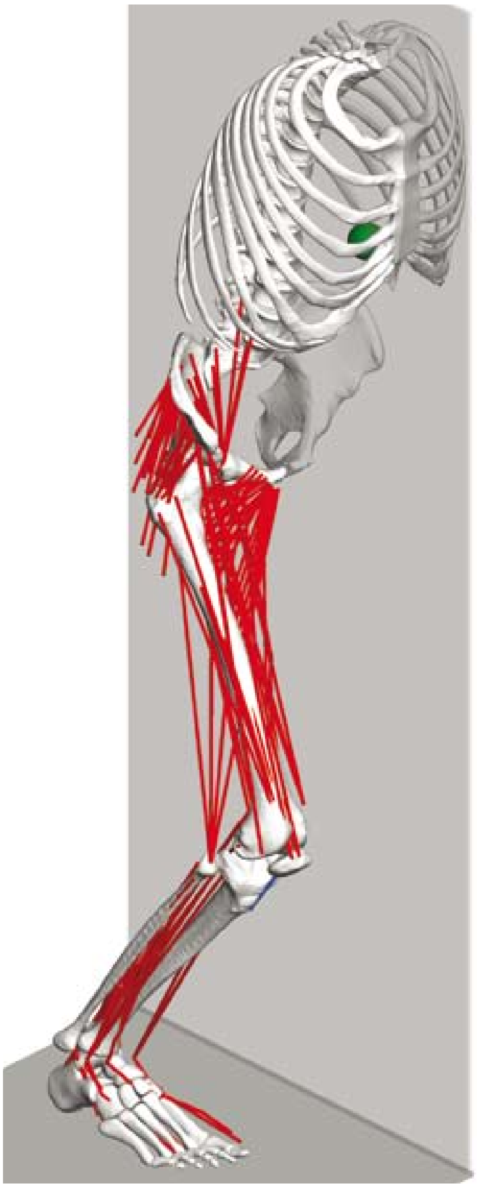

Fig 4: Full-leg musculoskeletal multi-body model with a simplified trunk developed in SIMPACK incorporating detailed modelling of soft tissue structures.

provided by the robot. Major ligament and muscle structures are incorporated as nonlinear spring-damper combinations following force-displacement characteristics. In order to implement the multi-body model into the HiL control loop, input and output interfaces are defined which enable communication with the robot controller. Finally, the multi-body model is exported into a standalone model using the code export function of SIMPACK generating real-time capable machine code for HiL applications.

The outcome of the HiL simulation shows that the robot rotates and loads the implant components according to the angles and joint forces/torques provided by the multi-body model at each time step. By feeding back the measurements the components are simultaneously shifted and orientated in the constrained directions within the model. This is accompanied by changed elongations of the incorporated ligaments altering the load situation within the artificial joint for the next time step.

> ***“Muscle force estimation is incorporated within a user force element by applying inverse dynamics for given instability-associated movements.”***

FULL-LEG MUSCULOSKELETAL MULTIBODY MODEL

One of the major goals of the musculo-skeletal multi-body model is to provide joint forces in the considered artificial joint for instability-associated movements. Moreover, it has to account for the complex soft tissue response during an instability event which requires detailed modeling of capsular and ligament structures surrounding the artificial joint. As these structures are governed by force-displacement characteristics incorporated into force elements, the key problem remains the estimation of active muscle forces to be resolved by the multi-body model.

Therefore, we generated a full-leg multi-body model containing all relevant body segments starting from the foot to the trunk where muscles comprising several joints are also included (see Fig. 4). Muscle force estimation is incorporated within a user force element by applying inverse dynamics for given instability-associated movements. This approach leads to the distribution problem of muscle forces which is resolved by minimizing a physiologically reasonable cost function.

The muscle forces obtained are then applied to the body segments according to their respective attachment points. Hence, the desired hip and knee joint forces can be calculated for various instability scenarios including all soft tissue forces (see Fig. 5).

CONCLUSION

The present concept of HiL simulations provides a highly flexible, state-of-the-art test system in the field of orthopaedic biomechanics. The universal approach enables analysis and comparison of various artificial joints with respect to their behavior in case of instability under physiological and reproducible load conditions. This is ensured by extracting the anatomic environment into musculoskeletal multi-body models developed in SIMPACK allowing for generation of real-time capable machine code by use of the code export function. Subsequently, HiL simulations can give recommendations to enhance future endoprosthetic designs, preoperative planning, the choice of appropriate implant components, and surgical treatment for specific bony and soft tissue structures in the event of primary, revision and tumor surgery.

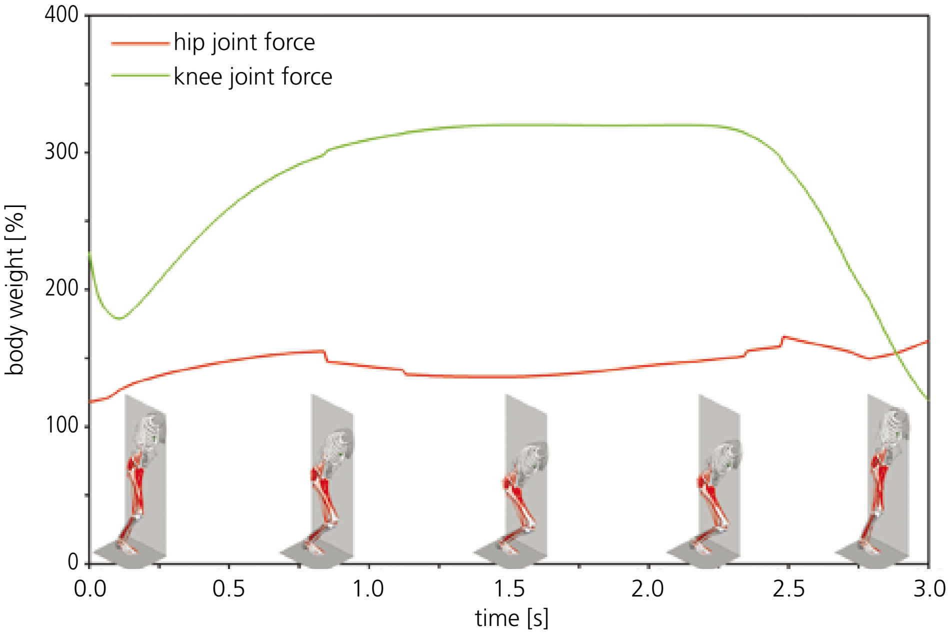

Fig 5: Example of calculated resultants of hip and knee joint forces for a deep knee bend based on a full-leg musculoskeletal multi-body model.