INTRODUCTION. Multibody dynamics has become an important tool in the analysis of musculoskeletal diseases and for implant development. The model-based estimation of inaccessible biophysical properties, e.g. muscle forces, joint loadings or neural activation patterns, in the musculoskeletal apparatus and their analysis in terms of clinically relevant questions contributed further information to established in vivo and in vitro testing procedures as well as clinical trials. Especially, the in-depth computational analysis of native or artificial joints requires mathematically challenging and computationally costly contact or contact surrogate modeling in order to represent the resulting joint dynamics that is majorly affected by the joint morphology and the forces exerted upon the joint partners by muscles and ligaments, see Figure 1 (A-C).

However, for model-based prediction of muscle forces a suitable calculation model has to be formulated, which is then used to provide the calculated muscle forces to the simulation model within inverse dynamic as well as forward dynamic simulations of motion maneuvers. It is emphasized here that these calculation models are inherently related to the quality of the in vivo state estimation, but have to be derived within an error-prone modeling process subject to numerous simplifications: State-of-the-art calculation models roughly represent the true kinematics and kinetics in the musculoskeletal system, since they approximate complexly shaped joint morphologies by ideal joints with fixed axes of rotation or rigid link mechanisms. As a consequence, commonly used calculation models suffer from a biased prediction of muscle forces leading to biased estimations of e.g. joint loadings. Herein, a novel modeling approach is presented that allows for computational prediction of muscle forces in complexly shaped joints by means of instantaneous screw axes (ISA).

METHODS. The novel approach represents the exact anatomical joint morphology, eases the modeling effort, and reduces the number of parameters required. Especially in the human knee joint, simulated kinematics and kinetics strongly depend on the representation of the articulating surfaces; thus, affect model-based prediction. In order to evaluate the calculation algorithm using ISA, a multibody simulation model was implemented into commercially-available multibody software environment (Simpack®, V.9.7, Simpack AG, Gilching, Germany). The simulation model comprised patient-specific bone and cartilage geometries (approved by ethics committee of University Medicine Rostock, reg. no. A 2014-0146) as well as relevant ligaments with nonlinear force-strain relation and Hill-type muscles spanning the knee joint.

For estimation of the muscle forces required to establish arbitrary knee motions, the ISA is calculated at each time instant solely by means of easily accessible kinematic measurements between the adjacent joint partners. Then, the equations of motion are derived with respect to the ISA and thereby reducing the dynamics of arbitrary open kinematic chains to force closure n-link pendulums. Finally, the resulting generalized torque that establishes desired motion around the ISA is distributed to the muscles using static optimization.

RESULTS. The calculation model based on newly presented computed muscle control (CMC) around ISA was compared to conventional CMC based on fixed axes of rotation in terms of muscle lever arm values of the relevant extensor muscles during active seated knee flexion and extension. The simulation data showed an underestimate of muscle lever arms of up to 56% for the considered load case and therefore overestimation of muscle forces necessary to drive the simulation model when using fixed rotation axes instead of ISA, see Figure 1 (D).

DISCUSSION. Simulation results verified the advantages of the novel modeling approach. The CMC with respect to ISA allows for high modeling fidelity even in complexly shaped joints and thereby offers a more general and less burdensome approach for model derivation. Muscle lever arms dramatically influence the force generating capacity of muscles and therefore significantly impact the resulting joint loading. Further simulation studies have to evaluate its estimation capabilities with respect to measurements obtained from instrumented implants, which is currently in progress. However, CMC-ISA offers versatile application fields as it reduces any articulating joint to a simple force closure pendulum without loss of generality, but increased modeling fidelity.

SIGNIFICANCE: The proposed approach for the prediction of muscle forces in musculoskeletal multibody models based on instantaneous screw axes can contribute to enhanced calculation accuracy in computer-based studies that have the estimation of inaccessible biophysical properties, e.g. muscle forces, under investigation. Thus, the novel modeling approach can significantly contribute to the quality of musculoskeletal multibody dynamics.

ACKNOWLEDGEMENTS: The authors acknowledge the internal funding program of University Medicine Rostock (‘Förderung zur Vorbereitung von Anträgen der Verbundforschung’) and the German Research Foundation (grant no. KL 2327/4-1 & BA 3347/11-1).

Figure 1. Model-based estimation of muscle forces. First, kinematic and kinetic data are captured in the gait laboratory, e.g. motion marker trajectories and force plate measurements (A). Second, the data is fed to the respective calculation model (B) in order to calculate the muscle forces that are necessary to drive the musculoskeletal simulation model (C) according to the desired maneuver. Simulation results (D) showed an underestimation of muscle lever arms and therefore overestimation of muscle forces necessary to drive the simulation model when using fixed rotation axis (red) instead of ISA (green).