Evaluation of a surrogate contact model of TKA.

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Introduction

- Since the calculation of joint contact forces is often carried out using expensive finite-element or elastic-foundation models, concurrent simulation of body-level dynamics and detailed joint mechanics is computationally demanding.
- Simulation time for a single activity of daily living may reach several hours, as shown in a recent Total Knee Arthroplasty (TKA) musculoskeletal (MS) model [1].
- To speed up the computation, surrogate modeling techniques have been proposed to replace the original contact model (OCM) with a faster surrogate model (SCM)[2,3].
- Overhead may also arise from the computation of muscle and ligament lines of action over obstacles, which require the solution of a contact problem. Simple wrapping conditions can be solved both analytically and numerically.

Objective
We developed and tested a surrogate contact model of TKA and we assessed its performance during gait simulation using both numerical and analytical wrapping algorithm.

Materials and Methods

- Sampling. 135.000 sample points were randomly generated using a multi-domain approach [3]. The OCM (Fig. 1) was created in the AnyBody Modeling System (AnyBody Technology A/S, Aalborg, Denmark) and used to calculate the TF loads resulting from the TF pose for each sample. Additionally, 20.000 samples were evaluated for testing.
- Training. Feed-forward artificial neural networks (FFANN) were trained until convergence to learn the implicit relations between TF loads and pose (Fig. 2) [2,3].
- Gait simulation. A gait trial from a publicly available dataset [4] was simulated using the OCM, the SCM, numerical and analytical wrapping algorithm¹. Simulation times were noted.

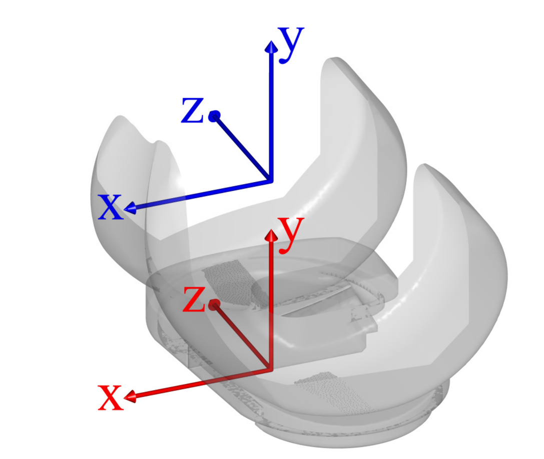

Figure 1. The original contact model used to evaluate sample points by repeated static analyses. The TF pose is defined by the relative position between the femur (blue frame) and tibial (red frame) component.

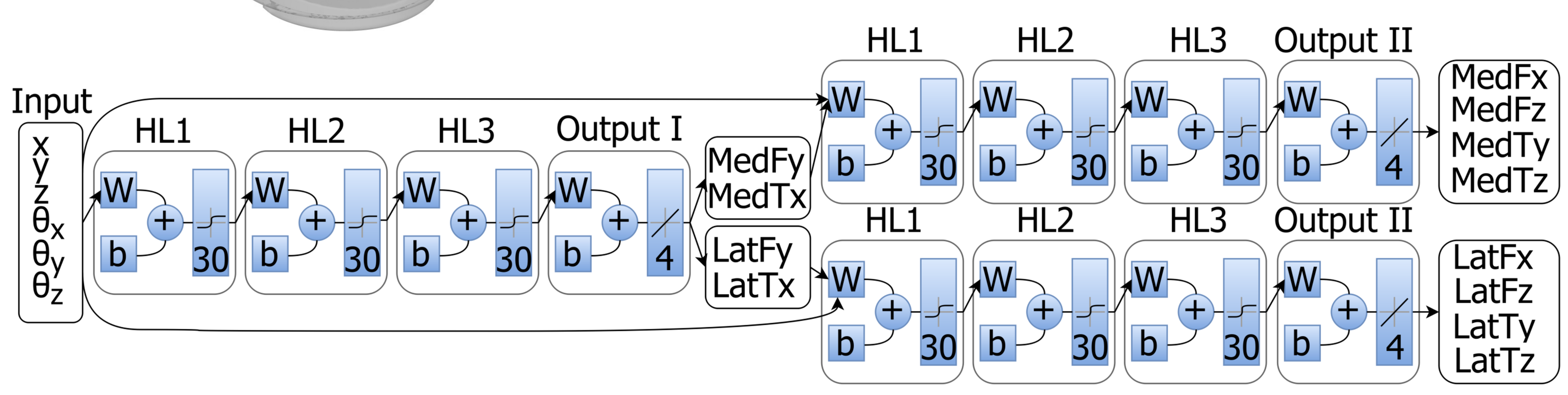

Figure 2. 2-stage FFANN used to learn the relations between TF pose (input) and TF loads (output). In stage I (left half) MedFy, MedTx, LatFy, LatTx were fit as functions of TF pose. In stage II (right half) the remaining TF loads were fit as functions of the TF pose and the TF loads of stage I. HL: hidden layer, W: network weight, b: network bias.

¹ The analytical wrapping algorithm was made available to us by AnyBody Technology A/S in a prototype version of the AnyBody Modeling System for the solution of a cylindrical wrapping case.

Results

Surrogate model accuracy

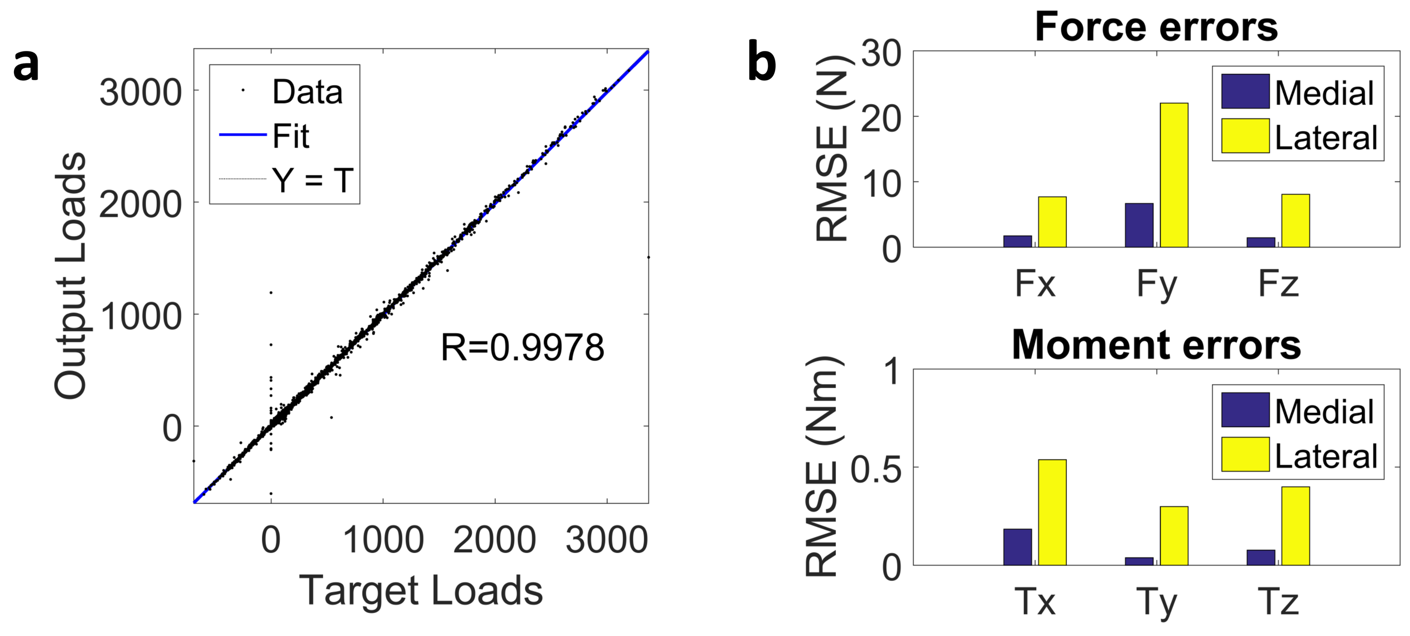

Figure 3. Accuracy of the surrogate model on a testing dataset of ca. 20.000 sample points. (a) Regression plot of output versus target loads and (b) root-mean-square errors of predicted medial and lateral forces and moments.

Gait simulation

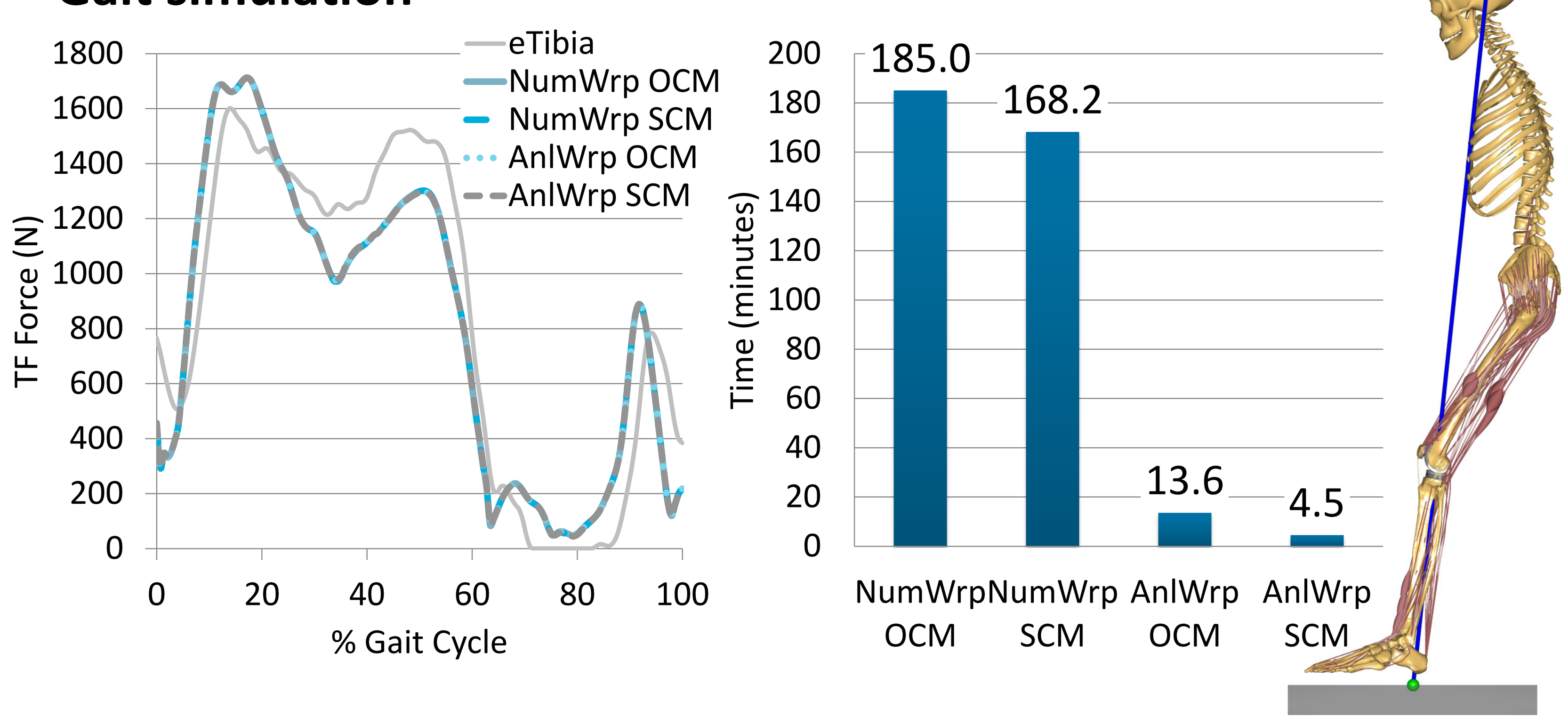

Figure 4. Left: proximo-distal component of tibiofemoral force predictions during gait. Right: simulation times and the musculoskeletal model used.
Legend: eTibia: experimental TF force; NumWrp, numerical wrapping; AnlWrp, anlytical wrapping; OCM, original contact model; SCM, surrogate contact model.

Discussion and Conclusion

- Approximately 213 hours were necessary on an Intel® Core™ i5-4570 quad-core computer with 16 gigabytes of RAM for the creation of the surrogate model. This time was paid up front and could be reduced using parallel-computing.
- There were no substantial differences in predicted versus experimental TF forces during a gait simulation using either contact models and wrapping algorithms (Fig. 4).
- The SCM provided the largest acceleration in conjunction with the analytical wrapping algorithm (Fig. 4). The latter is preferable over the more general numerical algorithm when computation time is a concern.

Conclusion
When used together with an analytical wrapping algorithm, our surrogate contact model could reduce simulation time by 67%.

[1] Marra et al., "A Subject-Specific Musculoskeletal Modeling Framework to Predict in Vivo Mechanics of Total Knee Arthroplasty", J Biomech Eng. 2015 Feb 1;137(2):020904; [2] Eskinazi and Fregly, "Surrogate modeling of deformable joint contact using artificial neural networks.", Med Eng Phys. 2015 Sep;37(9):885-91; [3] Lin et al., "Surrogate articular contact models for computationally efficient multibody dynamic simulations.", Med Eng Phys. 2010 Jul;32(6):584-94; [4] Fregly et al., "Grand challenge competition to predict in vivo knee loads.", J Orthop Res. 2012 Apr;30(4):503-13

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