

Entwicklung einer Hüftinterimsprothese (Spacer) mittels FE-Analyse unter Berücksichtigung der Muskel- und Gelenkkräfte aus AnyBody

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Summary

Within this project a new hip interims-prosthesis (spacer) made of antibiotic impregnated bone cement used in two-stage treatment of infected hip joints was developed and investigated. As the material strength of bone cement is limited, fractures occurred in the past and led to important complications, so that a reinforcement of titanium grade two (endoskeleton) was designed. Design loads (hip force and muscle forces) were determined for daily activities (one-leg standing, walking, going up/downstairs) by using the musculoskeletal modelling system of "AnyBody", in order to simulate physiological joint behaviour. Subsequently, the calculated loads were implemented into ANSYS Workbench to analyse the stress/strain behaviour of the spacer and the femur. The generated FE-model was validated by laboratory tests. Spacer with a titanium endoskeleton seem appropriate to provide a mobile and functional joint during the treatment course.

Keywords

AnyBody, FEM, musculoskeletal modelling, spacer

1. Development of a hip interims-prosthesis (spacer)

Two-stage reimplantation using an interval hip prosthesis (spacer) of antibiotic-impregnated bone cement has become a well-accepted method to eradicate hip-infection and prevent limb shortening [1,2]. As intraoperatively formed spacers are capable to eradicate the infections, complications include fractures of spacers (Fig. 1) [3, 4].



Fig. 1: Intraoperatively moulding form of a spacer (left) and fracture of an implanted spacer (right).

Within finite element analysis - performed with ANSYS Workbench - stresses and strains of nonreinforced spacers and spacers having an adapted endoskeleton when implanted into composite femurs are calculated. Hip joint loads and muscle forces are determined for common daily activities (one-leg-stand, walking, going up/downstairs) by using the musculoskeletal modelling system of "AnyBody". The final aim of this study can be concluded by designing an intraoperatively formed spacer, both, adapted to the patient situation and capable of resisting normal loading during those activities.

2. Musculoskeletal modelling using AnyBody

The AnyBody Modeling System™ is a software system to calculate muscle forces, joint forces and moments etc. during user-defined activities. Due to the fact that the direct measurement of the tension in muscles, the forces and moments transmitted by the joints of the human body is difficult, the "Inverse Dynamic" approach is used. Within the analysis of the inverse dynamic approach it is possible to determine the forces that cause a certain motion of the system, when the kinematical motion of the system is known. The human body is modelled as a kinematic chain, consisting of single bone segments which are connected by frictionless joints. The single bone segments are represented by rigid body elements. Each segment has six degrees of freedom (three translational and three rotational), whereas through the connection of two segments according to the kind of joint a certain number of degrees of freedom is restricted. Each single segment is loaded by muscle forces, forces of gravity and inertia, joint contact forces and external forces. As the musculoskeletal modeling system is a redundant system, meaning that the number of muscle forces exceed the number of degrees of freedom, optimization criteria to activate the muscles in a certain pattern are used. AnyBody uses the min/max muscle recruitment criterion, i.e. a minimization of the maximal muscle activity [5].

As the development of an accurate human body model is a complex and challenging task, we used the existing library of models in the "AnyBody Model Repository" [6]. Thus our model is based on the "Full-Body-Model" and the muscles of the lower extremity given in the Repository (Fig. 2).

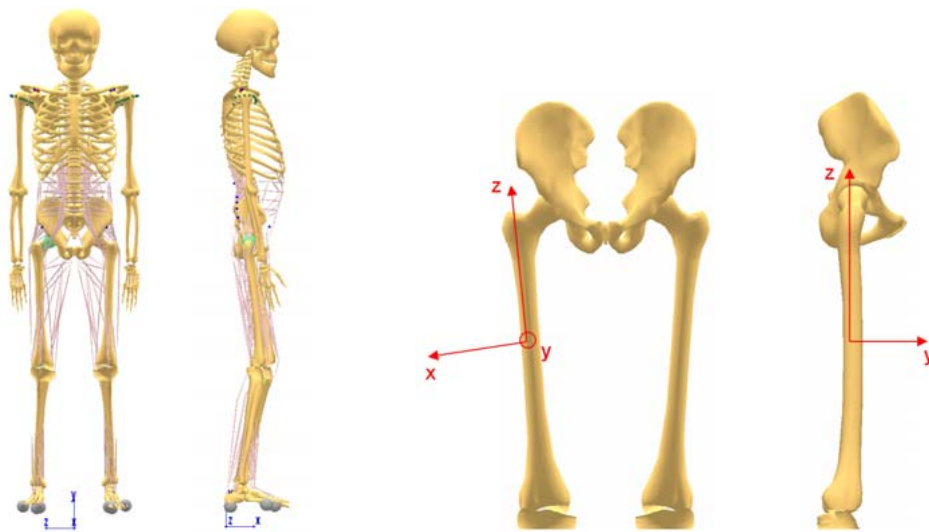


Fig. 2: „Full-Body-Model“ with muscles of the lower extremity (left) and local coordinate system of the right femur (right).

2.1 Analysis of daily activities

As mentioned before, with a given motion pattern and the analysis of the inverse dynamics, the calculation of the occurring muscle/joint forces can be realized. Supplementary to the existing walking model “Gait 3D” taken from the model repository, hip joint forces as well as muscle forces were determined during one-leg standing and during the gait cycle of going up/downstairs (Fig. 3, 4). At the beginning, motion data were therefor approximated by means of “Drivers” at the foot and supposed joint angles of the lower extremity. Conditional contact elements (“pushing muscles”) between foot and ground provide the necessary ground reaction forces. Within a defined radius-limit of the three “TargetObjects” (one point on the heel and two points, medial and lateral on the forefoot) to the “BaseObjects” on the ground (floor, stair etc.), contact forces are provided.

The AnyBody Modeling System contains three different muscle models, based on the classical work of Hill [7], which are ranging from simple (AnyMuscleModel – assuming constant strength of the muscle) to more complicated physiological behaviour (AnyMuscleModel3E – a three element model taking serial and parallel elastic elements into account along with fibre length and contraction velocity) [8].

The AnyMuscleModel3E is definitely the most advanced model and used quite a lot in the repository models [6]. It is good when dealing with passive forces or high velocity motion. The risk with this muscle model are the numerous parameters and the calibration needed. However, AnyBody provides those with reliable data [6, 8]. Altogether, the choice of the muscle model depends of what you want to investigate with your model. Within our task, the hip reaction forces for the AnyMuscleModel3E and the AnyMuscleModel (BodyModel) looks quite similar and thus the AnyMuscleModel provides a good alternative solution (Fig. 4).

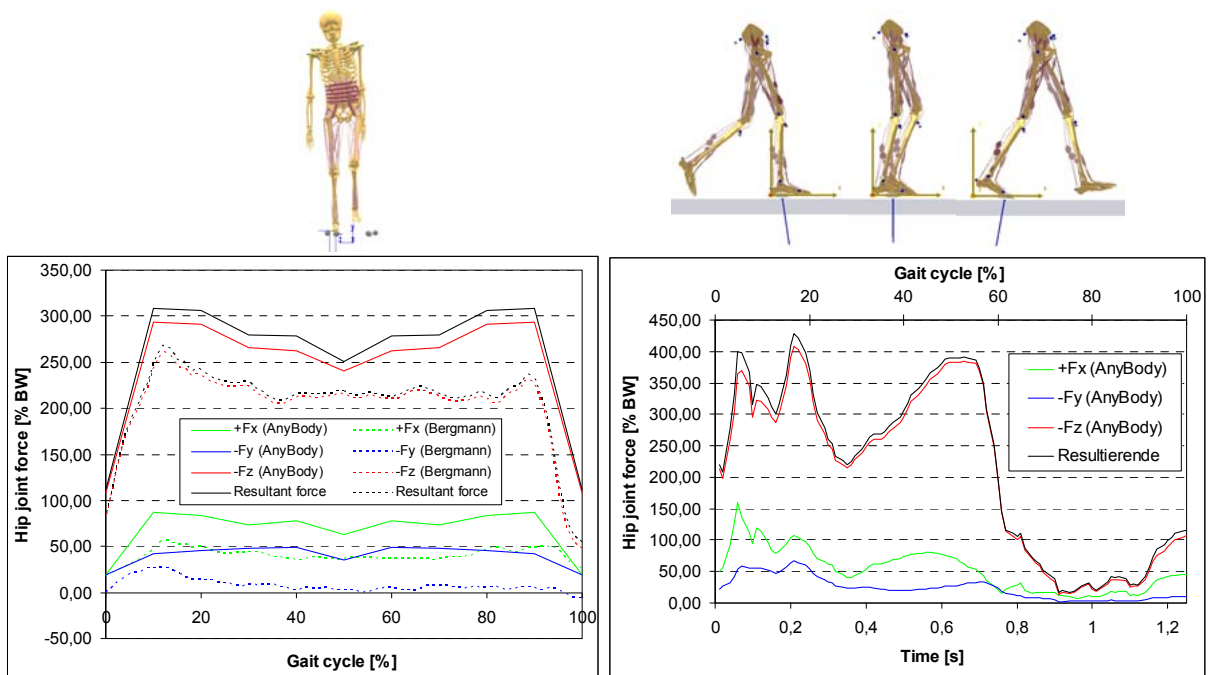


Fig. 3: Hip joint force during the activities „one-leg-stand“ (left) and walking „Gait3D“ (right).

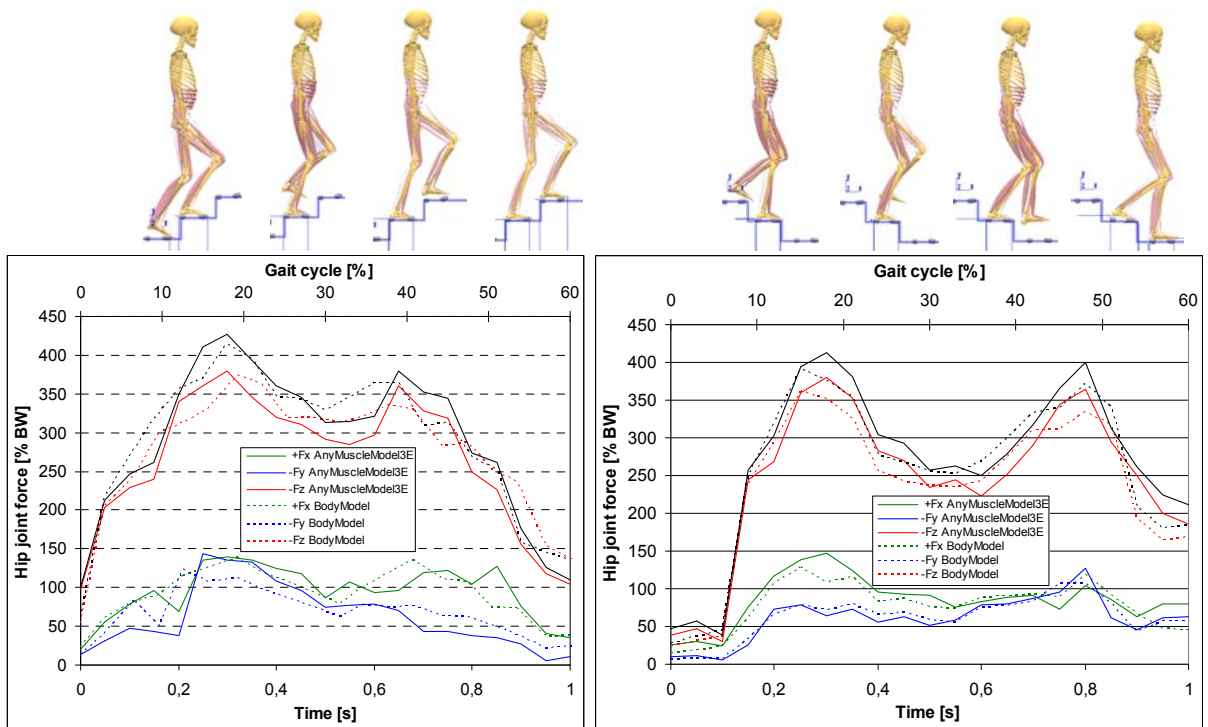


Fig. 4: Hip joint force during the activities „going upstairs“ (left) and „going downstairs“ (right) with the different muscle models.

Since Bergmann et al., 2001 [9] measured in vivo hip joint forces with simultaneously recording the motion pattern of common daily activities, those kinematic data were furthermore used as input values for our model. The model was scaled in body size and weight to match the anatomical data of the individual patient. The conditional contact elements have been switched of and the experimental measured ground reaction forces were applied as external forces. Fig. 5 shows the hip joint forces calculated with AnyBody compared to the measured data by Bergmann et al. [9].

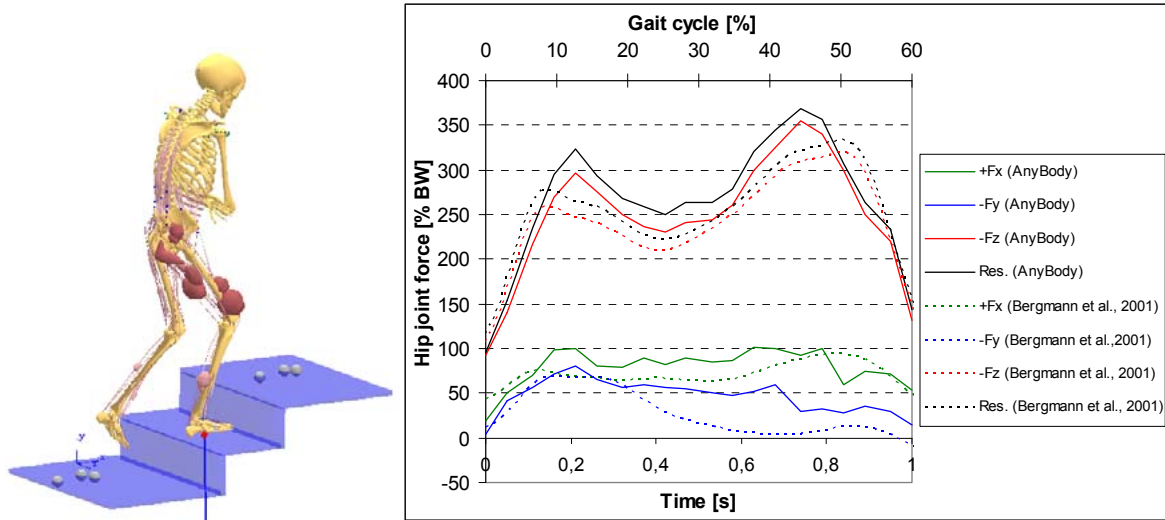
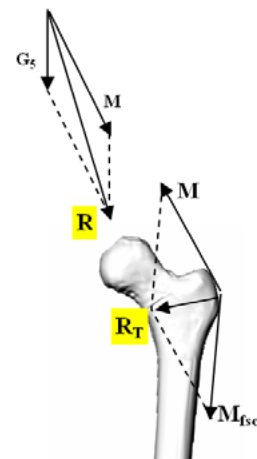


Fig. 5: Comparison of calculated and measured hip joint force for the patient K. Walter / Trial 1 [9] when “going upstairs”.

Table 1 summarizes the here calculated hip joint forces and the most significant muscle forces of the proximal part of the femur. M represents the abductor muscle forces (gluteus minimus, gluteus medius and the proximal part of the gluteus maximus and tensor fasciae latae) whereas M_{fsc} represents the traction of the iliotibialtract (distal part of the gluteus maximus and tensor fasciae latae) and the force exerted by the knee extensors (vastus lateralis and vastus intermedius) [10].

Tab. 1: Summary of the calculated hip and combined muscle forces of the proximal femur.

Activity	Hip resultant force (R) [x BW]	Muscle force (M) [x BW]	Muscle force (M_{fsc}) [x BW]
AnyBody Modeling System™			
One-leg stand	3,0	1,7	1,6
Walking (Gait 3D)	4,0 – 4,2	2,6	1,4
Going downstairs	4,1	2,4	3,1
Going upstairs	4,3	2,5	3,3
Calculation with motion capture data and ground reaction forces by Bergmann et al. [9]			
H.Sonke (Trial 1)	3,3	2,2	2,7
K.Walter (Trial 1)	3,7	2,3	2,9
K. Walter (Trial 5)	3,2	2,3	2,4



3. FE-Model of the prosthesis and femur

A finite element model of the prosthesis (spacer) and femur was developed to analyze stresses. The analysis was performed using ANSYS Workbench. The standardized femur was used as a basis for a finite element model of a composite femur [11]. An IGES file of the spacer with/without endoskeleton was placed within the composite femur geometry. Meshing was conducted by the element 186, a hexahedral solid element with quadratic displacement behaviour (Fig. 6). For modeling the contact and sliding between femur-spacer interface, CONTACT 174 and TARGET 170 elements were used. The material properties are given in Table 1. The femur is separated into two materials, cortical and cancellous bone. The bone materials were assumed to be isotropic and homogeneous (Tab. 2).

Tab. 2: List of the material properties used for the analysis.

Material	Young's modulus [MPa]	Poisson's ratio (ν)	Tension		Compression strength [MPa]
			Yield strength [MPa]	Ultimate strength [MPa]	
Cortical bone	16,000	0.26	-	107	154
Cancellous bone	150	0.30	-	-	-
PMMA	2,500	0.35	-	35	85-100
Titanium grade 2	110,000	0.34	$R_{p0.2}=325$	430	430

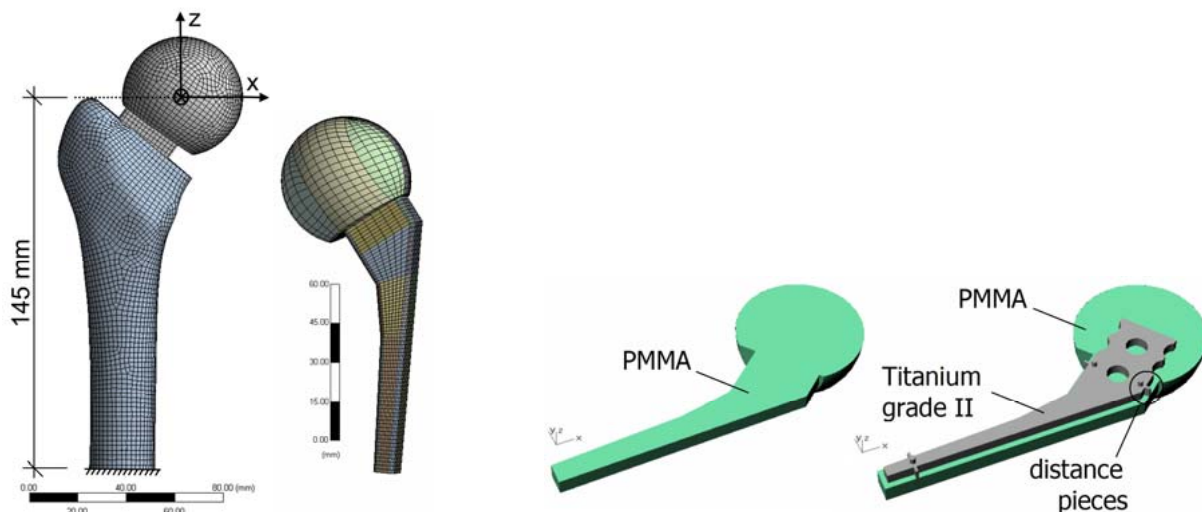


Fig. 6: Finite element mesh of the implanted spacer (left) and longitudinal cut of a non-reinforced and reinforced spacer (right).

Loading was based on the results out of AnyBody, i.e. the calculated joint and muscle force vectors from AnyBody were implemented into ANSYS. The activity which causes the highest joint and muscle forces (going upstairs) was simulated. Either simply the hip resultant force R or the hip resultant force R plus the muscle forces, which causes a more physiological stress pattern in the distal femur diaphysis, were simulated (Fig. 7).

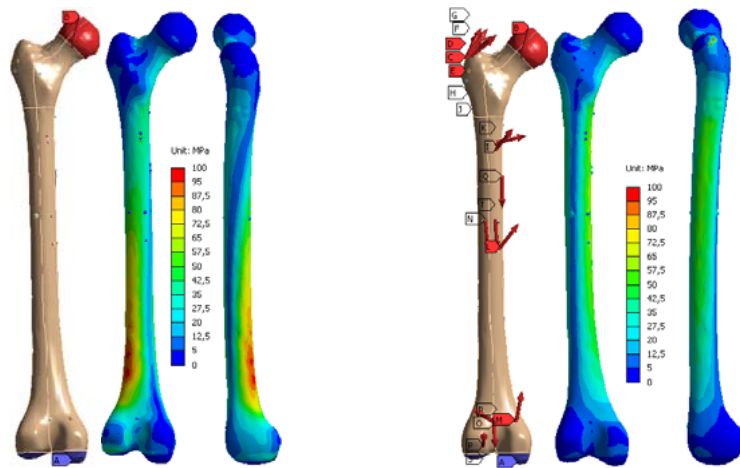


Fig. 7: FE model of the femur loaded either with the hip joint force (left) or hip joint force + muscle forces (right) for the activity “going upstairs”.

In case of the implanted spacer, stresses on Femur and Spacer are decreased by an existing reinforcement made of titanium grade two. The stresses in the proximal part of the femur are not highly influenced by the additional presence of the muscle forces, whereas the bending stresses in the distal femur diaphysis are again considerably reduced (Fig. 8, 9).

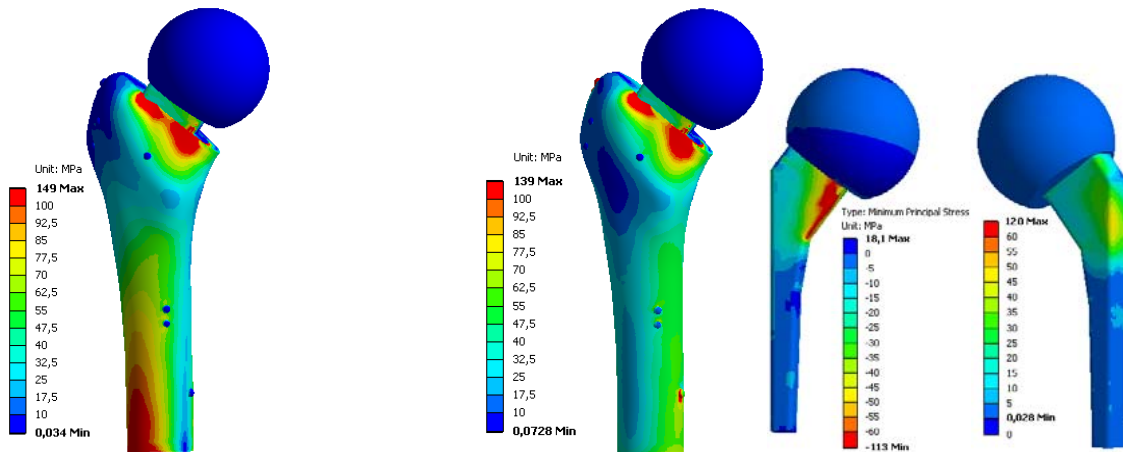


Fig. 8: Non-reinforced spacer implanted into the femur loaded either with the hip joint force (left) or hip joint force and muscle forces (right) for the activity “going upstairs”.

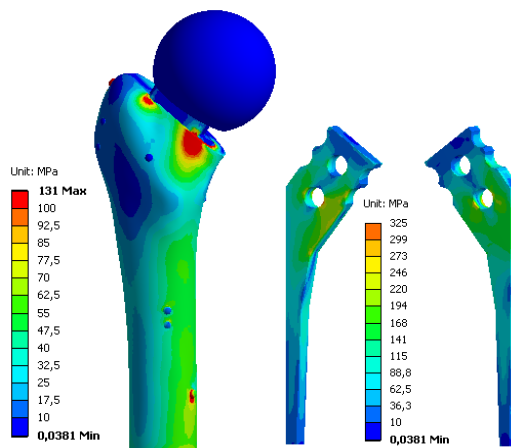


Fig. 9: Spacer with endoskeleton implanted in the femur and loaded with the hip joint force and muscle forces for the activity “going upstairs”.

The calculated stress-strain patterns and deformations were validated by means of laboratory tests. The hip joint force was applied through the femoral head of the spacer, where shear loads were eliminated by means of a ball bearing cup. To keep friction as low as possible, the interface between cup (POM, $d = 120 \text{ mm}$) and spacer head (PMMA) is furthermore lubricated (Shell 138 Retinax CS 00). Muscle forces were neglected in this experimental test device (Fig. 10).



Fig. 10: Experimental test-setup for validation.

4. Conclusions

The AnyBody Modeling system allows for calculating joint and muscle forces with available kinematic data and ground reaction forces within a close range of anticipated force values. As muscle modeling is a complex task, the output depends highly on the input values (bone geometry, insertion and origin points of the muscles, kinematic data etc.), the optimization criterion to recruit the single muscles and the muscle model which describes the physiological muscle behaviour. Nevertheless, the here calculated joint reaction forces are between 3-4 times body weight and thus close to measured values found in the literature [9]. Comparison of calculated muscle forces to in-vivo measurements is not thoroughly possible. EMG measurements allow rather for prediction of muscle force activity than force magnitude. However, combinations of single muscles into muscle groups, according to their tasks (abductors, adductors etc.), can give further evidence. Altogether, AnyBody provides a musculoskeletal modeling system to calculate reasonable joint reaction forces and muscle forces during a gait cycle of a user-defined activity. Furthermore, a sensitivity analysis can show how the forces are influenced by changing the input parameters.

As AnyBody uses rigid bone segments to simulate the human body, a stress-strain analysis isn't possible within this software. However the output values (force magnitudes and directions) can be implemented into ANSYS, either by the interface Any2Ans-software or by manual output into a text file, in order to conduct a FE analysis. In this study, a non-reinforced and a reinforced spacer stem were investigated. The implant design and the solid femur model was imported from CAD. The implant was analyzed under physiological relevant boundary conditions that correspond to specific activities of daily living. Results showed good mechanical characteristics for the reinforced spacer under physiological joint behaviour. Again, a sensitivity analysis allows for further evaluation of the bone-implant assembly. This will save time for the design, prevent any permanent damage caused by increased bone defect and save money in order to avoid costly laboratory tests.

5. References

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