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TOOLS FOR NUMERICAL ANALYSIS: MOTION-ANALYSIS AND FEA SHOWN ON THE ABOVE-KNEE PROSTHESIS

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ABSTRACT
Motion-analysis and FEA can work together even though they are quite different. Motion-analysis software works with CAD assemblies. It starts by translating assembly mating conditions into corresponding kinematics pairs. It then calculates kinematics and dynamics data of the moving mechanism. Each component in mechanism, if viewed separately, is under balanced set of loads: joint reactions and inertial forces. Such isolated component behaves like structure, i.e. firmly supported object and FEA can deals with it. In short, motion analysis feeds FEA with data necessary to convert mechanism component into a structure- a form digestible to FEA.
These two numerical tools are applied on the above-knee prosthesis. The first, prosthesis assembly is made. Mating conditions are translated into kinematics pairs such as sliders, pin joints and fixed joints. Then, motion-analysis of prosthesis mechanism is done under subjected loads. The last, components in the foot assembly are remodeled, analyzed and optimized in FEA software, using reactions and inertial forces obtained from motion analysis.
Keywords: above-knee prosthesis, finite element analysis (FEA), motion-analysis software

1. INTRODUCTION
Motion analysis software calculates kinematics quantities of motion. Besides, it calculates joint reactions when outside loads are applied. It takes into account component weights, inertial forces and friction. This paper presents mechanism of above-knee prosthesis, which is analyzed in motion analysis software and results of analysis is used for a component optimization in FEA software.
First, static analysis of prosthesis was done by hand [1]. Prosthesis was split on above-knee part and below-knee part. Outside loads were reduced to the knee. Inertial and frictional forces were ignored. During analysis, forces in hydraulic actuators and reactions in joints were determined.
The same analysis was done in motion analysis software (i.e. SolidWorks 2006). This time it was in a few seconds. Inertial and frictional forces were taken into account. Comparison these two analyses showed similar results.

2. CONCEPTUAL DESIGN OF PROSTHESIS FOOT
Conceptual design of foot meant selection of components by which function of the prosthesis was accomplished. Prosthesis had a special purpose to help amputee to climb stairs, using external source

of hydraulic power [5]. During positioning on stair, foot of prosthesis had to be flexed dorsally. During ascending, tibia of prosthesis had to be raised continually. These tasks were accomplished by hydraulic actuator, which was positioned posterior to the ankle. Its range of motion and hydraulic pressure were determined by static analysis. Figure 1 shows initial 2D sketch of foot assembly.
Function of hydraulic actuator in the ankle can be best seen from Figure 2, where parts inside cylinder are simplified shown. When fluid pressure does not act on the piston, a spring pushes piston and piston rod moves outward. This flexes the foot dorsally around ankle joint (Fig. 1). When stair ascending begins, fluid pushes the piston, piston rod moves inward bringing the tibia of prosthesis in vertical position.

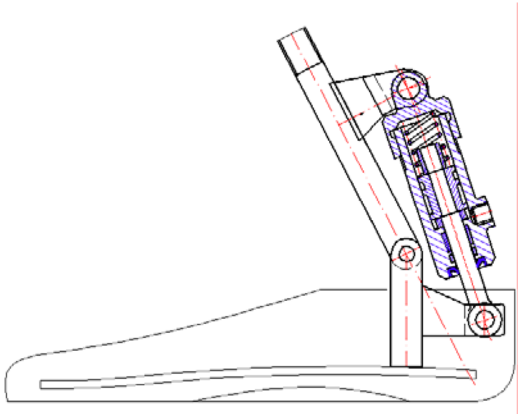

Figure 1 Conceptual design of foot

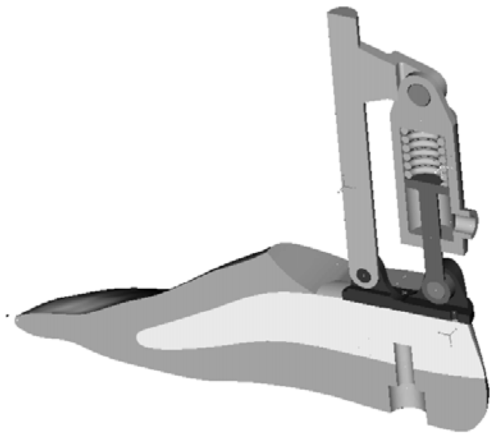

Figure 2 Function of hydraulic actuator

3. MODEL OF PROSTHESIS

Originally, the project of prosthesis development started from idea to replace hydraulic damper in SFEUK knee by active hydraulic actuator [5]. It was supplied by fluid from mobile hydraulic pump. Further, idea was to put one more actuator, this time in ankle. After conceptual design of foot with hydraulic cylinder in ankle, a task was to model foot assembly and to checked stress distribution in its components.
In I-DEAS 9, whole above-knee prosthesis was modeled (Fig. 3). 3D model was used to visualize motion of prosthesis when hydraulic actuators in the knee and the ankle were started. This model was also used to optimize the shape of foot components under acting loads and to choose their material. In order to determine stress distribution in components, foot assembly had to be rigid i.e. to become structure. This meant that all components had to be connected by command ‘’Join partition’’ or by applying gap elements [2]. When assembly was rigid, loads, obtained from static analysis, were applied. For every component was chosen appropriate mesh size and finite element analysis was performed.
This procedure didn’t seem like elegant solution. Making assembly rigid had been time consuming work and one could not be sure that boundary conditions were applied properly. Better way to analyze components of assembly was found in SolidWorks 2006.

4. ANALYSIS IN SOLIDWORKS 2006

Assembly of prosthesis had been imported in SolidWorks. Assembly was transformed in mechanism. This meant mating conditions of components were translated in corresponding kinematics pairs such as fixed joins, sliders and pin joints. Further task was to set motion for actuators. Linear function of displacement was chosen for both actuators. Loads were reduced to the knee joint: weight of amputee and pulling force of hand. Both forces were applied in knee together with moment of reduction (Figure 4).
Command ‘’Run Simulations’’ calculated kinematics and dynamics characteristics of motion: displacement, velocity, accelerations, reactions in joints and inertial forces during motion. Figure 5 shows reaction forces and moments that act on tibia component. Figure 6 shows plot of the force in

upper lug of tibia rod during time of prosthesis straightening. This force is equal to force that has to be produced by hydraulic actuator in the ankle.

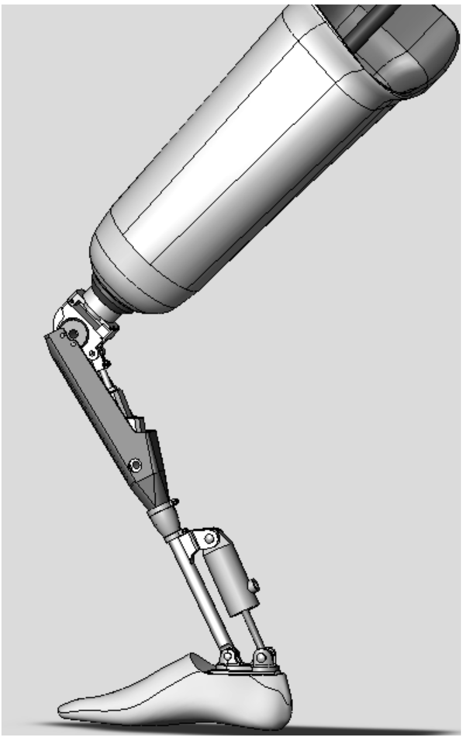

Figure 3. 3D model of prosthesis

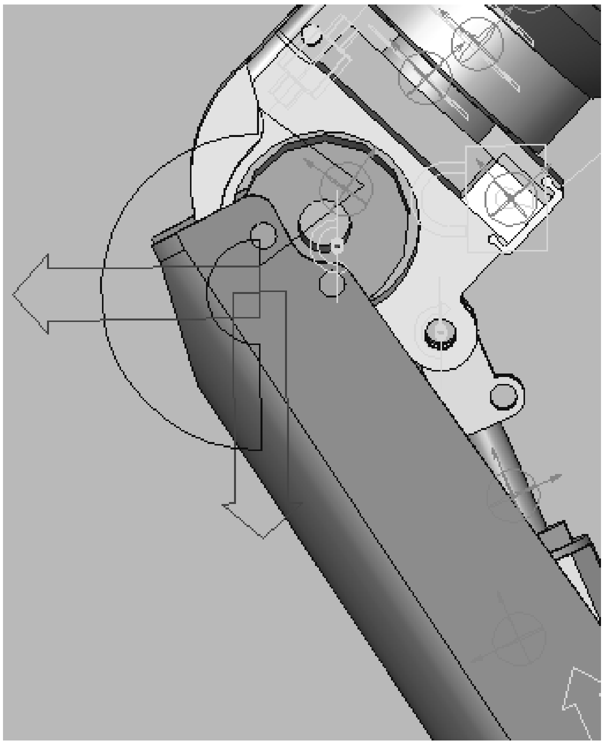

Figure 4. Forces Q i F_p reduced in the knee

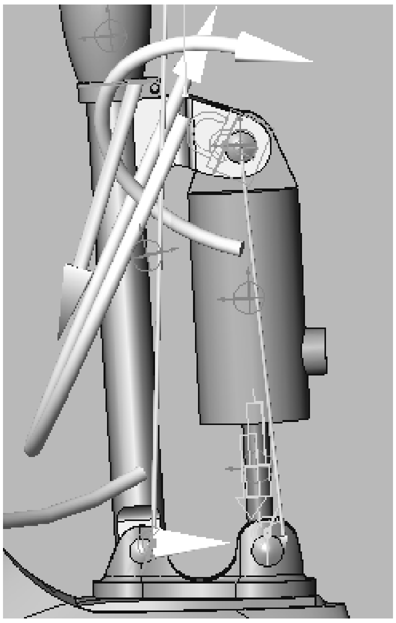

Figure 5. Reactive forces and moments in the tibia comonent

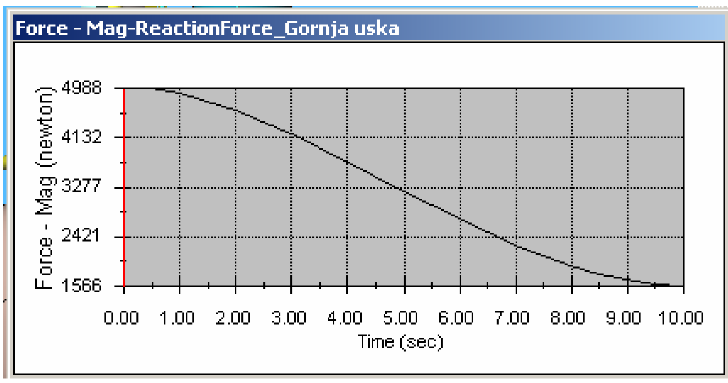

Figure 6. Force that has to be produced by actuator in ankle during time of lifting

After kinematics analysis, command ''Import motion loads'' was used to assign reaction and inertial forces to selected component. By definition, under these loads, the component was in balance. So component behaved like solid structure and finite element analysis (FEA) on component could be applied. Figure 7 shows component of tibia rod on which acting join reactions and inertial forces.

FEA analysis started by command ''Run design scenario''. Component was automatically meshed and boundary conditions were applied. In a few second, as a result one could get plots showing stress, strain, and deformations.
The analysis on tibia component (Figure 8) gave colorful stress distribution with clearly pointed places with concentrated stress. Maximal stress was σ_{max} = 346 MPa, when yield stress for selected material was σ_T = 505 MPa.

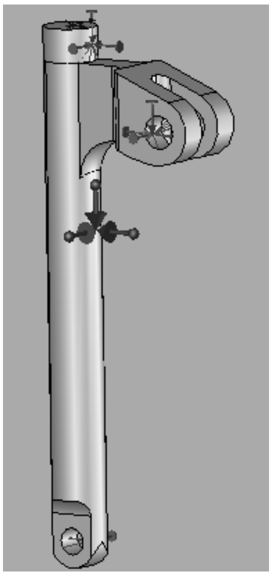

Figure 7. Tibia component with imported loads

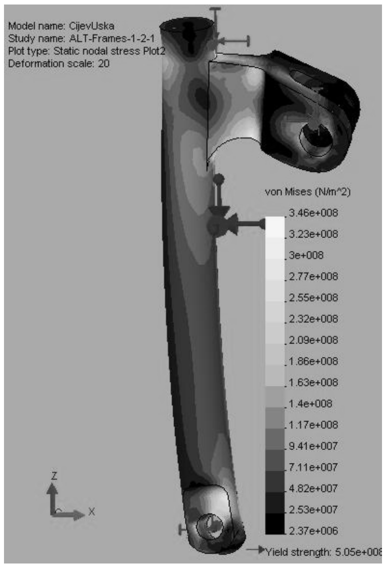

Figure 8. Stress distribution in tibia component

5. CONCLUSION

CAD geometry is the starting point for motion analysis and FEA. Both of these are easiest to use when they run as add-ins to CAD [3] (found in SolidWorks 2006). These numerical tools are quite different. Motion analysis software works with CAD assemblies. Assembly consists of components that can move without experiencing deformations. On the other hand, FEA is a tool for structural analysis. A structure is an object with firm support and can still move a bit under loads, because loads cause deformations.
Even though these tools are different, they can work together. First, motion analysis translates assembly in mechanism. Then, within range of motion it calculates kinematics and dynamics quantities. Each component, if viewed separately, is under balanced set of loads: joint reaction and inertial forces. So when component is isolated from assembly, software for finite element analysis (FEA) thinks that component is structure and can calculate stress-strain distribution.
This procedure is performed on above-knee prosthesis. Forces from amputee are reduced to the knee. Analysis of mechanism gives forces in joints and inertial forces that are used for stress calculation in foot components. Stress distribution helps to eliminate highly stress areas by modifying shape and to appropriate selection of component material.

6. REFERENCES

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