FE-Simulation of impact loads on the human body: Methodology for the development of tissue models

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1 Introduction

In human-robot collaboration, knowledge about the consequences of a potential collision between the robot and human is a prerequisite for reducing the risk of human injury through protective measures. For this purpose, the Fraunhofer IFF has conducted comprehensive collision tests with live test subjects to verify various biomechanical thresholds [1, 2] and reliably limit the consequences of a collision to the level of pain onset (Fig 1).

Fig. 1: Available impactor with impact surface 14mm×14mm (left) and the mechanical pendulum for examining verified limit values of dynamic contacts (right) [2].

Currently a measurement device is used to validate that an impact with a robot is below the biomechanical threshold for specific body parts. This method is expensive, time-intensive, and can only be applied after a complete robot application has been physically set-up. To improve this situation, we see great potential in finite element (FE)-simulation as a better and faster alternative for studying the consequences of impacts below the onset of injuries. This work describes three tissue models that we developed for the specific body parts of the lower arm bone, lower arm muscle, and upper leg muscle (Fig. 2).

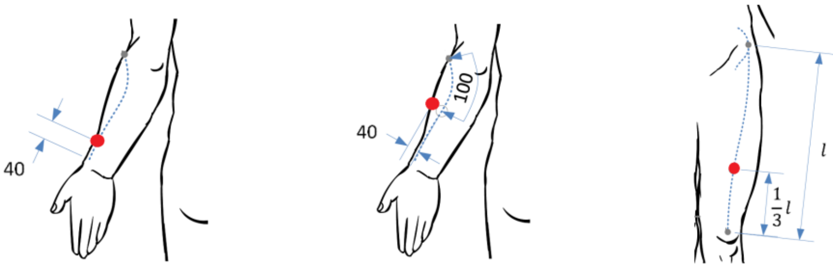

Fig. 2: Investigated body parts, lower arm bone (left) and muscle (center), upper leg muscle (right) [3]

2 Method

In our oral presentation we will demonstrate how the use of a FE-Model and simulation in LS-DYNA can reduce the time necessary assess the risks involved in collisions between humans and robots. For this purpose, FE-models for different human body parts were built in LS-PrePost. Each model precisely reproduces the biomechanical response from the real body part, simultaneously this was achieved by optimizing the model geometry and materials. This was achieved by simultaneously optimizing the model geometry and materials. The optimization of the parameters was done through adaptation of the parameters and a subsequent comparison between the real measurements data (contact forces and deformations) from the IFF's live subject studies and a FE-simulation. The measurement data of ten adults (Table 1) was used as the reference data for the optimization. Models for soft tissue (skin, fat and muscle tissue) and structural tissue (bone) were developed and reproduced as solid and tetrahedron bodies using the material MAT_SOFT_TISSUE_VISCO (MAT_092, soft tissue) and MAT_PIECEWISE_LINEAR_PLASTICITY (MAT_024, structural tissue). The data from the literature [4] were used as the starting values for the material parameters.

impact body parts	mean stature	mean weight	body mass index
lower arm bone	1.78m	80.7kg	25.46
lower arm muscle	1.76m	78.6kg	25.37
upper leg muscle	1.77m	75.8kg	24.2

Table 1: Subject data of the Fraunhofer IFF subject study (lower arm bone with five subjects, lower arm muscle with six subjects and upper leg muscle with five subjects).

The impact energy and impactor geometry (Fig. 1 left) from the subject study was used in the impact simulation. An MRI cross-section (Fig. 3 lower left) of the impacted body part was used to approximate the geometrical definition of the body part (Fig. 3 center image showing half cylindrical shape for the model geometry). The anatomical structure and mechanical characteristics of human tissue are difficult to reproduce properly in the FE-model in LS-PrePost, due to factors such as the exact geometry in longitudinal direction of the body segment and the relative movement between muscles during the impact.

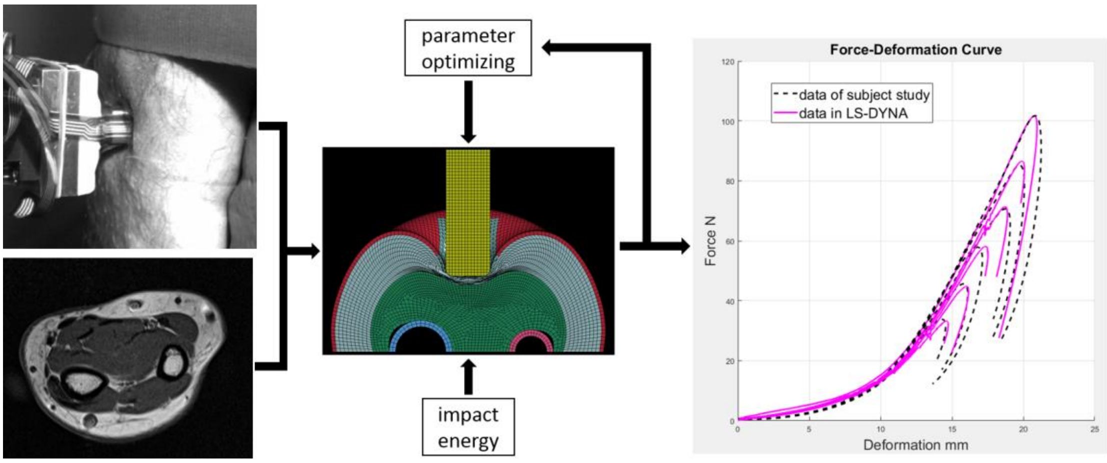

Fig. 3: Development of FE-simulation for the impact on tissue model in LS-DYNA, e.g. model for lower arm muscle with the impact energy from 0.23J to 0.48J and the impact mass 5.8kg.

3 Summary

The simulation shows that body parts with a thick layer of soft tissue result in a high deformation with low contact forces as expected and seen in the study data. In order to achieve stable results from the FE-calculation, it was necessary to vary the individual simulation and material parameters systematically. A particular challenge was ensuring that the response characteristic of the body parts were not influenced by the stabilization of the overall model. The simulation of impact loading on body parts with thick, soft tissue deviated less than 5% from the measured data from subject study (Fig. 3 right, hysteresis curve for the forces and deformation of the impact on lower arm muscle between the real measurements and simulation result). Simulations of the lower arm featuring bone and thin soft tissue, deviated by about 30% from measurements with regard to the contact forces and 4% for deformation. As a result, the FE-model replicates the real response of body tissue under slight impacts with stress consequences in the area of pain onset.

4 Literature

[1] R. Behrens, J. Saenz, C. Vogel, and N. Elkmann, “Upcoming Technologies and Fundamentals for Safeguarding All Forms of Human-Robot Collaboration,” *Proceedings of the 8th International Conference on Safety of Industrial Automated Systems*, 2015.

[2] R. Behrens and N. Elkmann, “Study on meaningful and verified Thresholds for minimizing the consequences of human-robot collisions,” *2014 IEEE International Conference on Robotics & Automation (ICRA)*, pp. 3378–3383, 2014.

[3] R. Behrens, “Biomechanische Belastungsgrenzen für Mensch-Maschine-Interaktionen in der kollaborativen Robotik,” Dissertation, TU Ilmenau, eingereicht 2018.

[4] C. Untaroiu, K. Darvish, J. Crandall, D. Bing, and J. T. Wang, “A finite element model of the lower limb for simulating pedestrian impacts,” *Stapp car crash journal*, vol. 49, pp. 1–25, http://worldcatlibraries.org/wcpa/oclc/173314221, 2005.

FE-SIMULATION OF IMPACT LOADS ON THE HUMAN BODY: METHODOLOGY FOR THE DEVELOPMENT OF TISSUE MODELS

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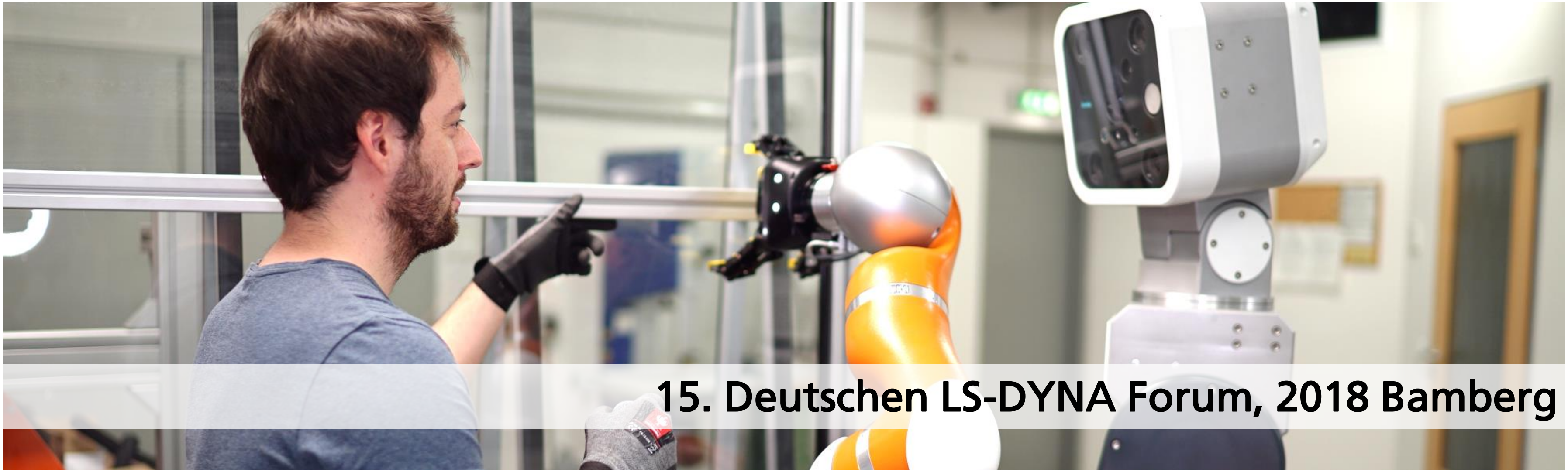
Fraunhofer IFF – Robot System



Fraunhofer
IFF

Motivation

safe human robot collabration with help of FE-methody

safe collabration

- risk of human injury
- limit of pain

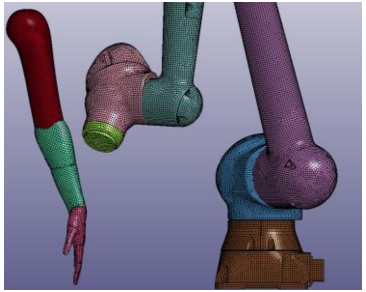
human-centered collaboration

human robot collabration

IFF subjects study

- 40 subjects
- 21 localization
- force-based limits
  ideal for simulating
  human-robot collisions

FE-Mode

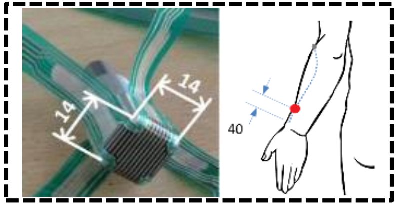


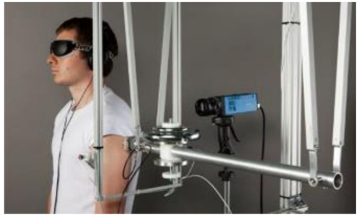
- biomechanics response
- experimental data

Concept

Methodology // develop of a stress tissue model

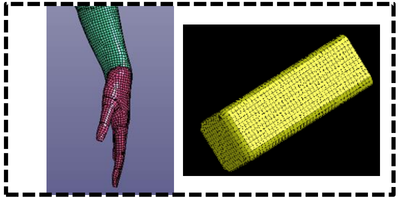
IFF





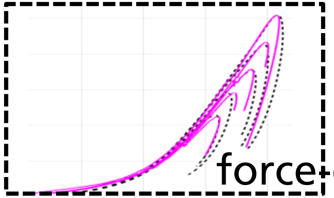
- 40 subjects
- 21 localization

tissue model



$F(N,mm)_{energy}$

validation



force-deformation curve

study

critical data

any contour

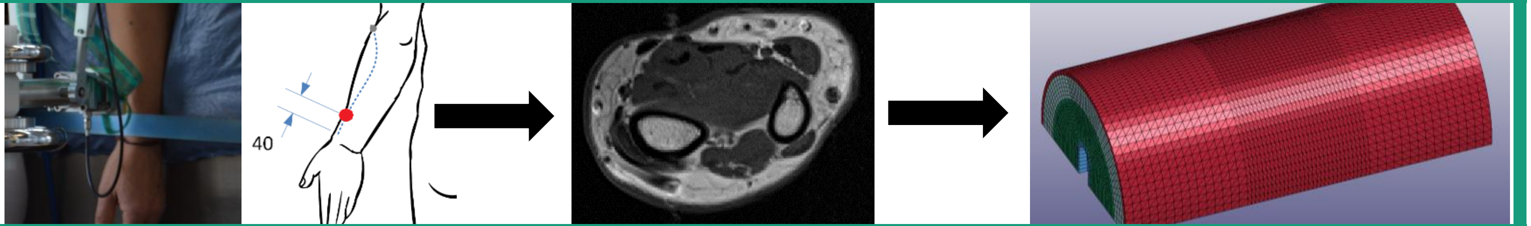
- forces
- stress
- energy

collabration

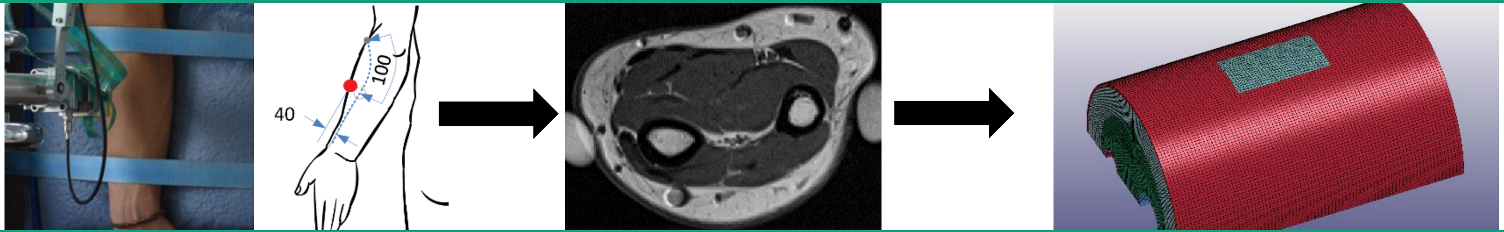
Tissue Model

stress models for the local impact body parts

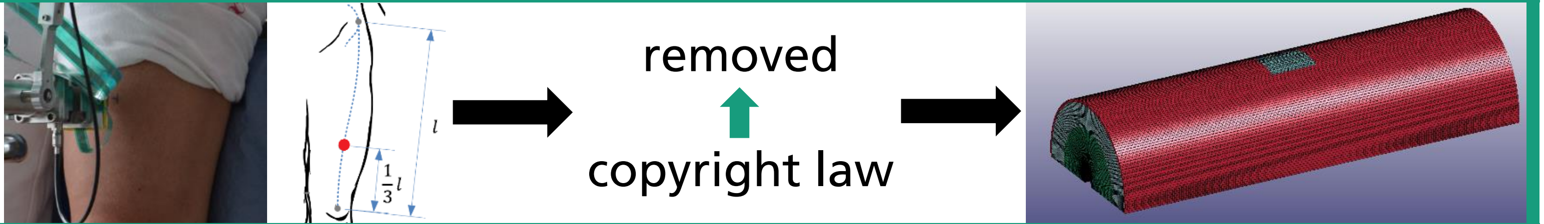
lower arm bone



lower arm muscle



upper leg muscle



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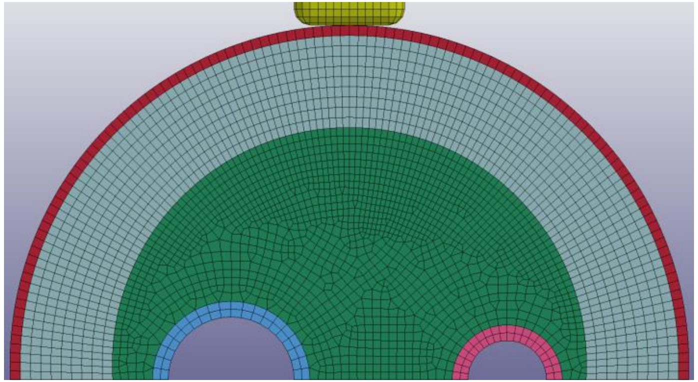
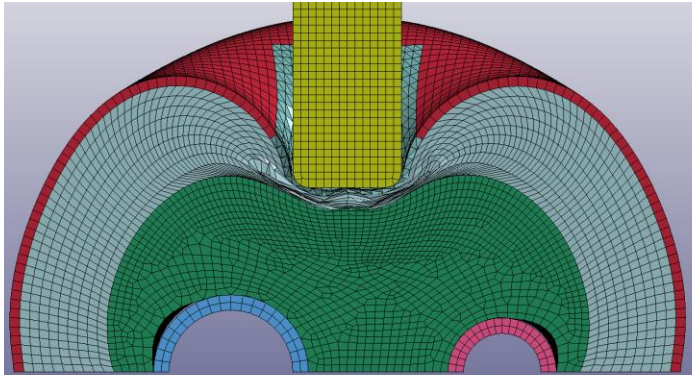
Tissue Model
Tissue models// lower arm muscle

CONTACT

- impactor head and skin
(AUTOMATIC_SURFACE_TO_SURFACE
- skin and fat
(TIED_SURFACE_TO_SURFACE)
- fat and muscle
(IED_SURFACE_TO_SURFACE)
- muscle and bone
(AUTOMATIC_SURFACE_TO_SURFACE)





Tissue Model

Tissue models// design concept

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TENDON

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MUSCULATURE

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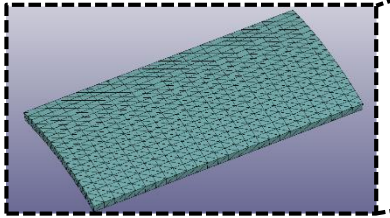
TISSUE MODEL

low energy

⬇

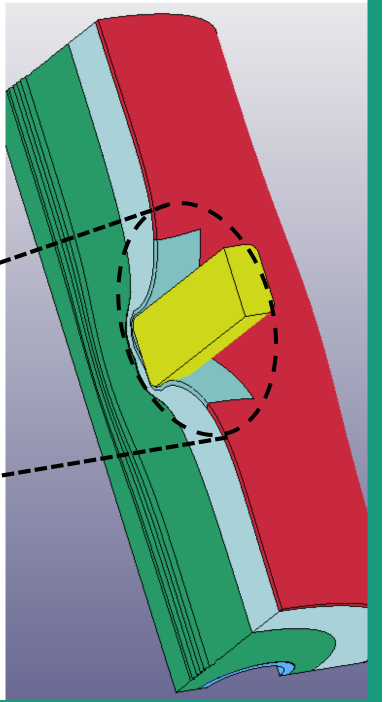
high deformation
low force



tetrahedron

⬇

stability

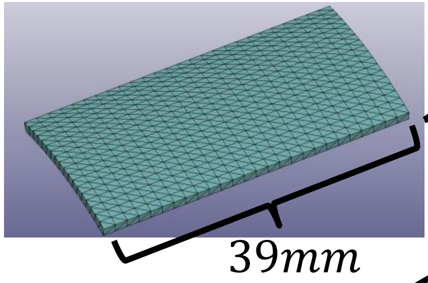


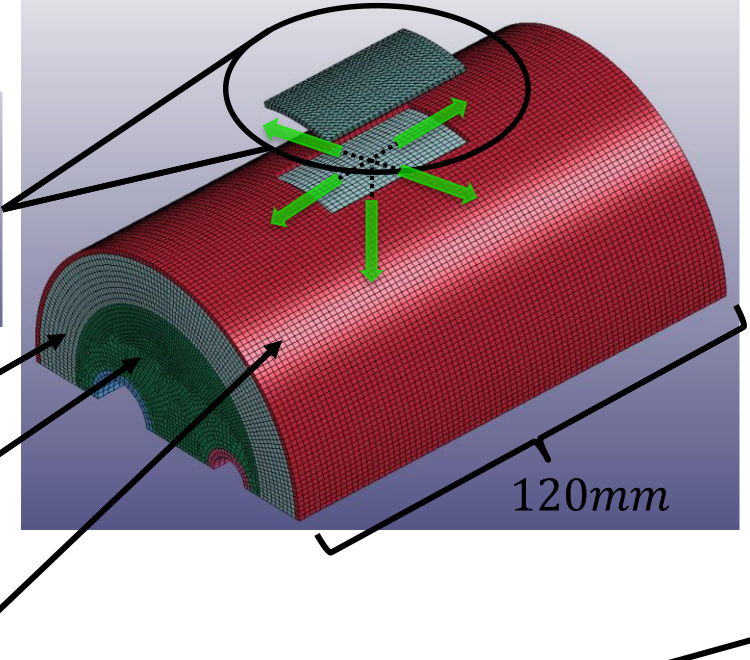
Tissue Model

Tissue models// lower arm muscle

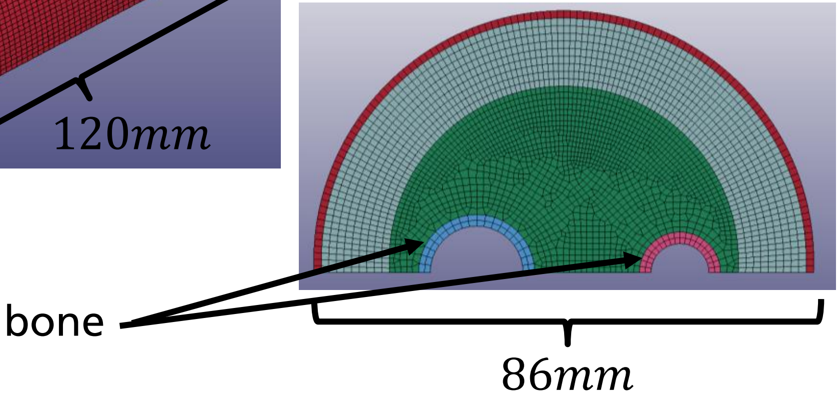
skin contact area

SECTION_SOLID_ERFORM_13





soft tissue	bone
ERFORM_-1	ERFORM_1
*MAT_092	*MAT_024



Tissue Model

Tissue models// lower arm muscle

- frictionless
- without the heat loss

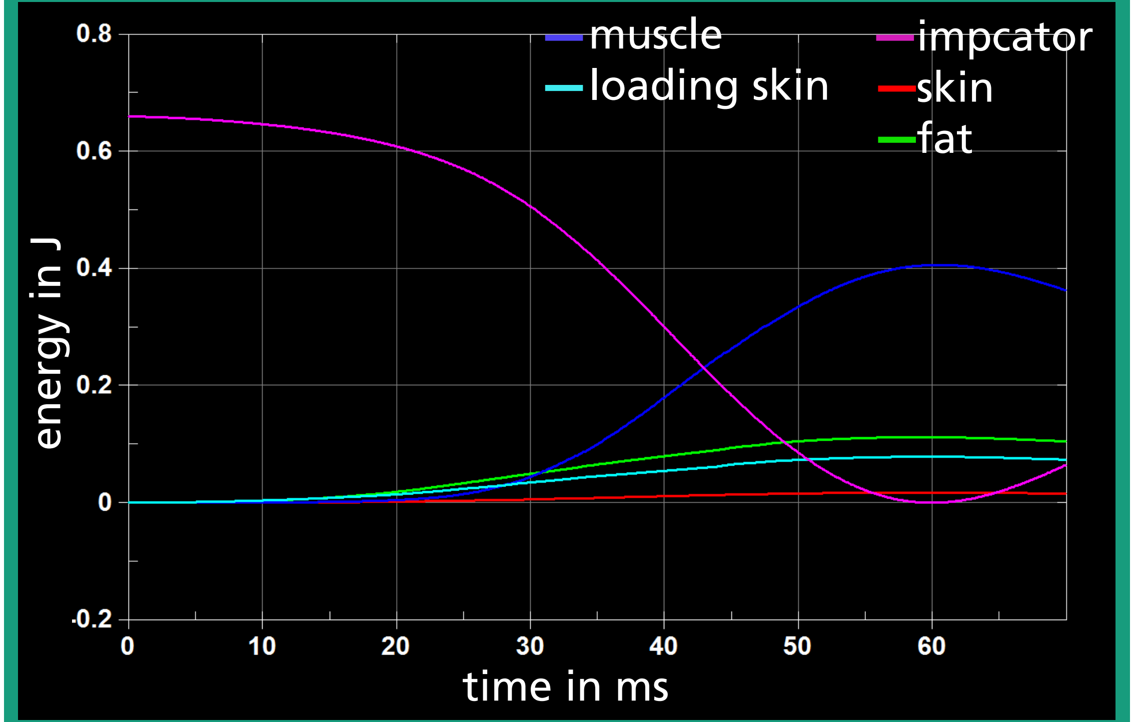
⬇

$$E_{k\_impact}$$

$$\downarrow$$

$$E_{i\_tissue}$$

ENERGY



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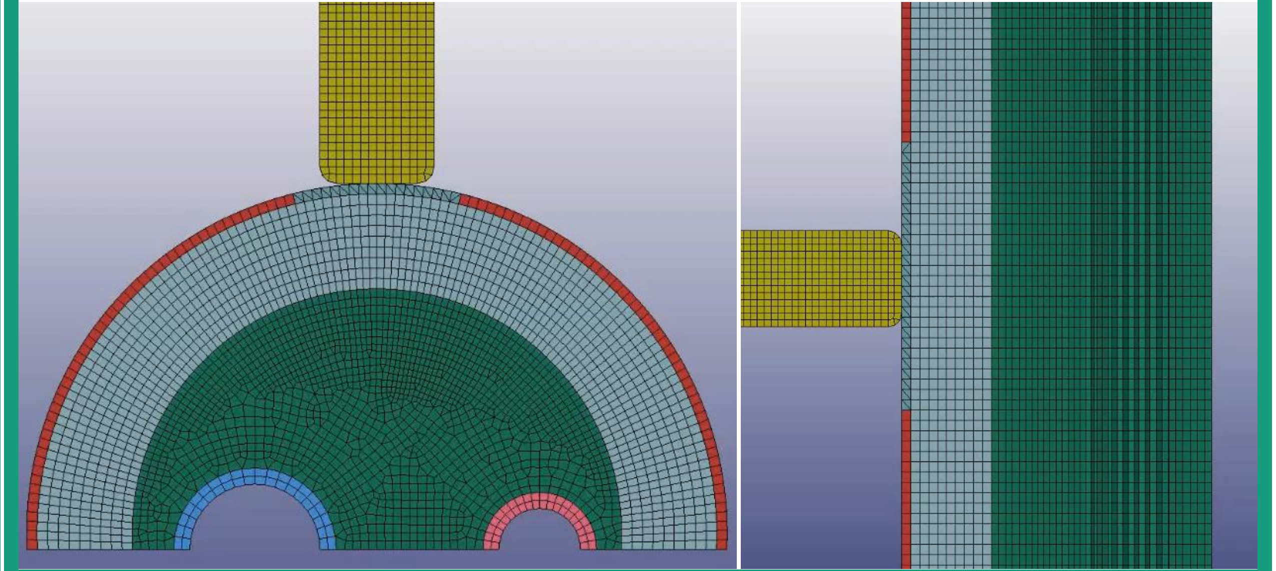
Tissue Model

Video// IFF study and simulation in LS-DYNA

IFF STUDY

SIMULATION IN LS-DYNA



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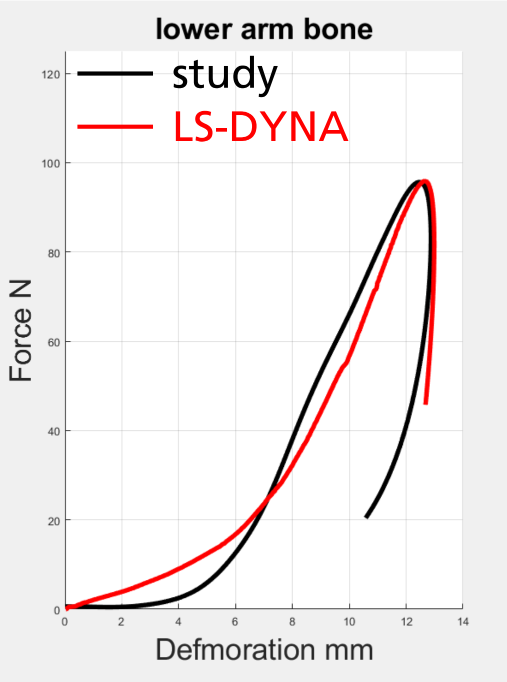
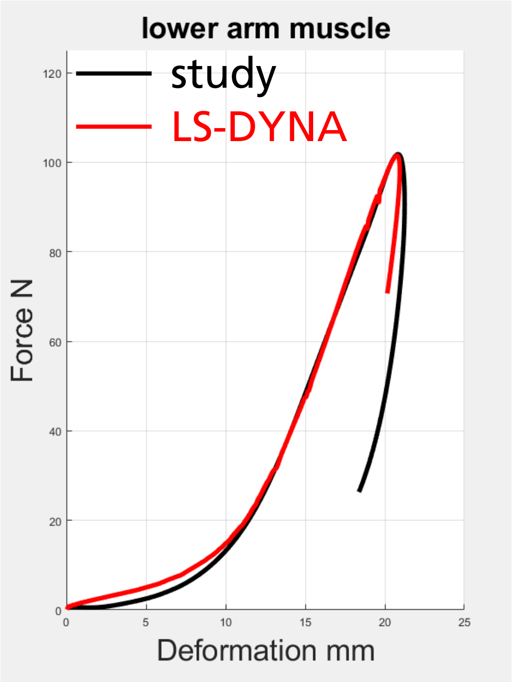
Results

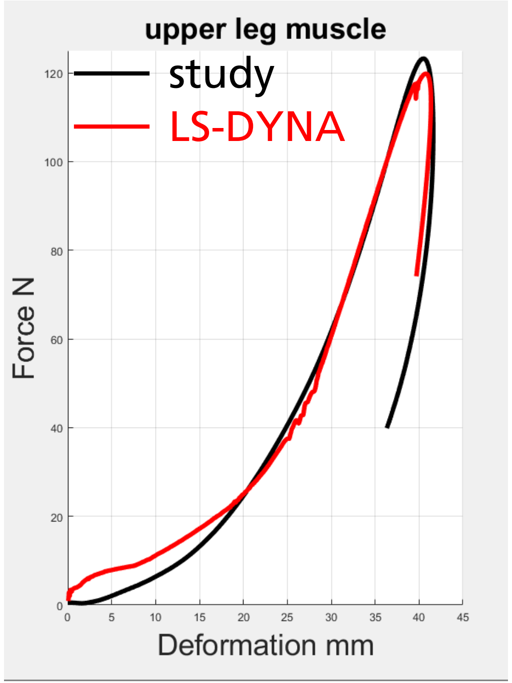
Optimization of tissue model



$Diff < 3\%$



$Diff < 3\%$



$Diff < 3\%$

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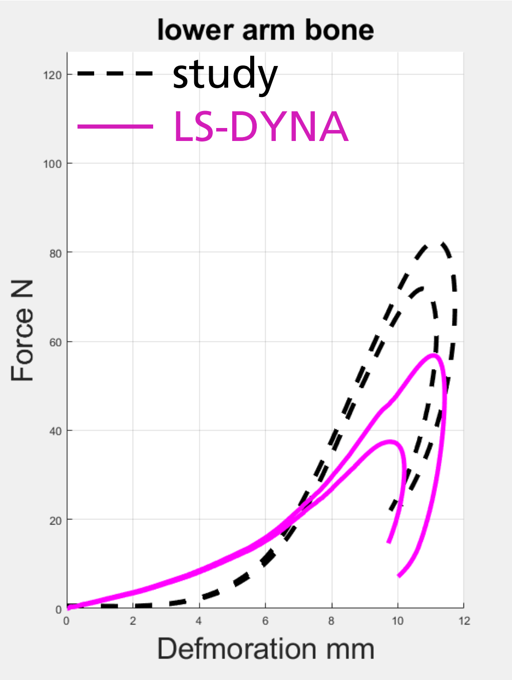
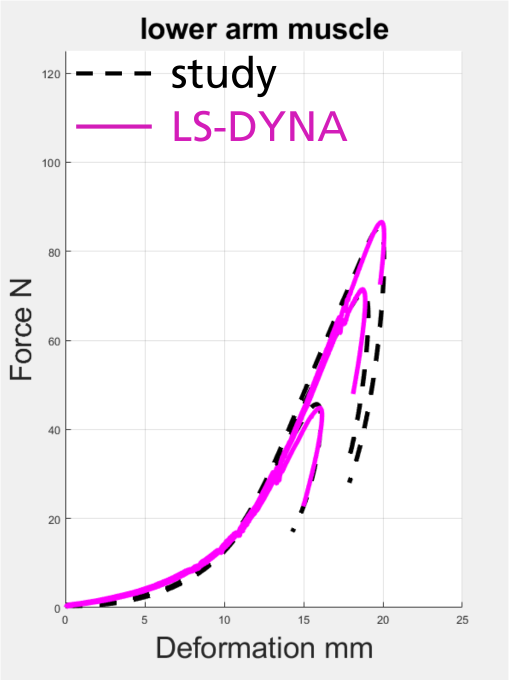
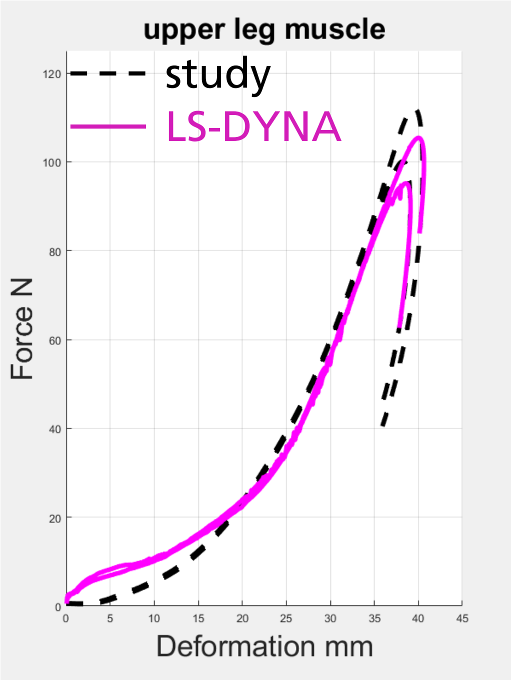
Results

Validation of tissue model







$Diff_N < 30\%$ $< 5\%$ $<\approx 5\%$

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Tissue Model
Tissue models//limitations

1. body information related to each tissue model.

impact body parts	mean stature	mean weight	body mass index
lower arm bone	1.78m	80.7kg	25.46
lower arm muscle	1.76m	78.6kg	25.37
upper leg muscle	1.77m	75.8kg	24.2

$$\left.\begin{array}{l}\text{body stature}\\ \text{body weight}\end{array}\right\} \xrightarrow{\text{change}} \text{scale vector} \left\{\begin{array}{c} V_{longitunidal} \\ V_{transversal} \\ V_{sagittal} \end{array}\right.$$

2. range of the impact energy

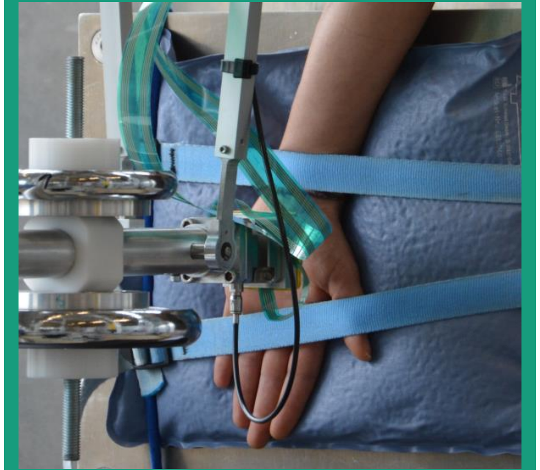
- research on the threshold for the appearance of pain without injury
- the change of the impactor geometry

Tissue Model
Tissue models//limitations

3. simple model design for local body part with a thick layer of soft tissue

- geometry in model with higher similarity to the real tissue
- whole deformation incl. bone

HAND STUDY



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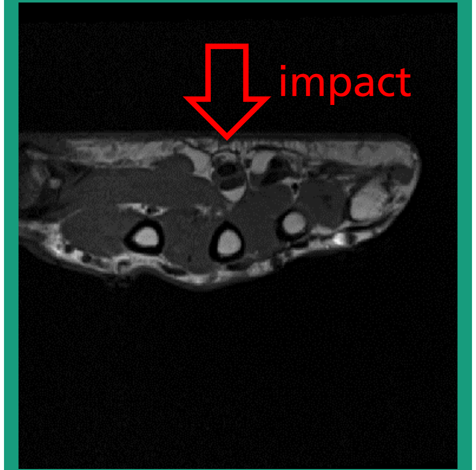
MRI



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Tissue Model

Tissue models//hand tissue model

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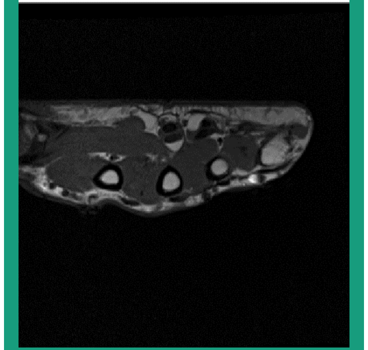
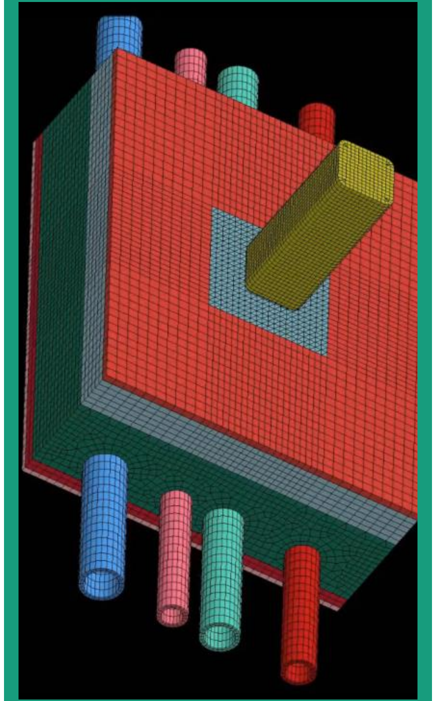
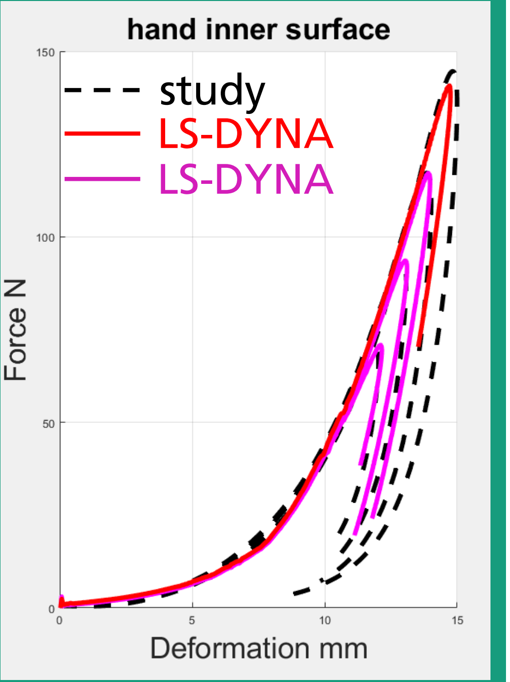


SIMULATION



RESULT



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