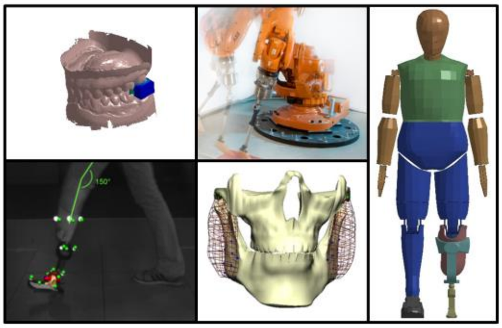
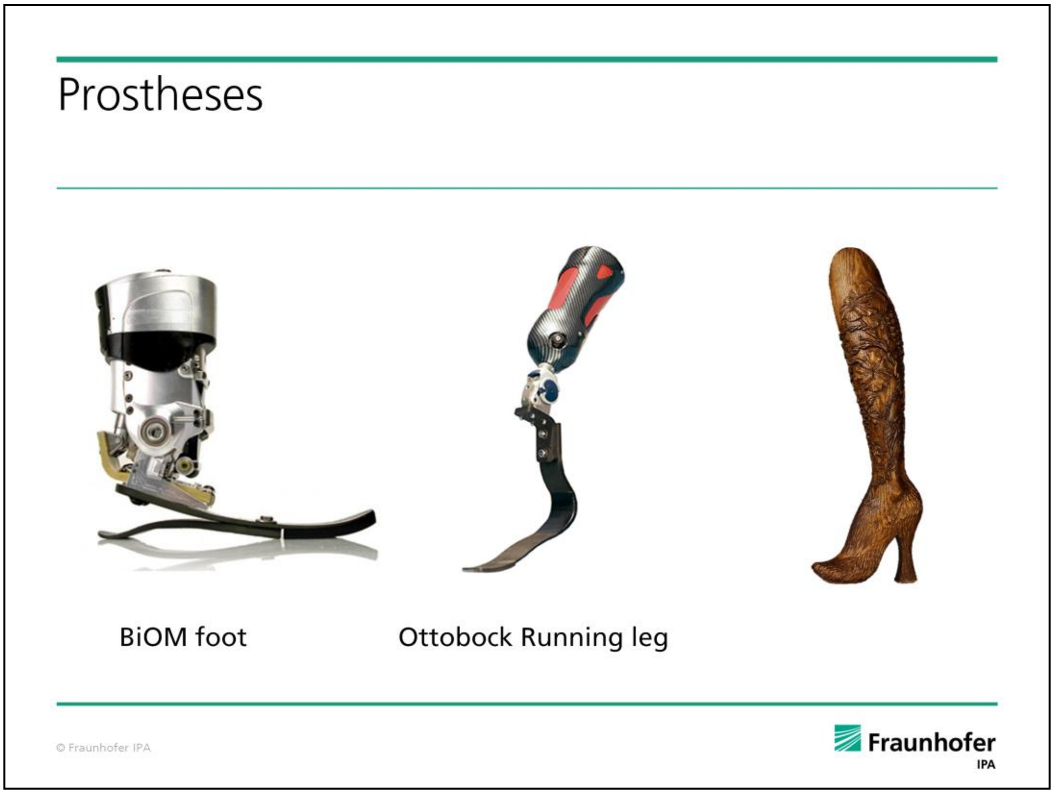
Simulation-assisted prosthetic design

Ellankavi Ramasamy, Beate Dorow, Urs Schneider, Oliver Röhrle





Prostheses

BiOM foot

Ottobock Running leg

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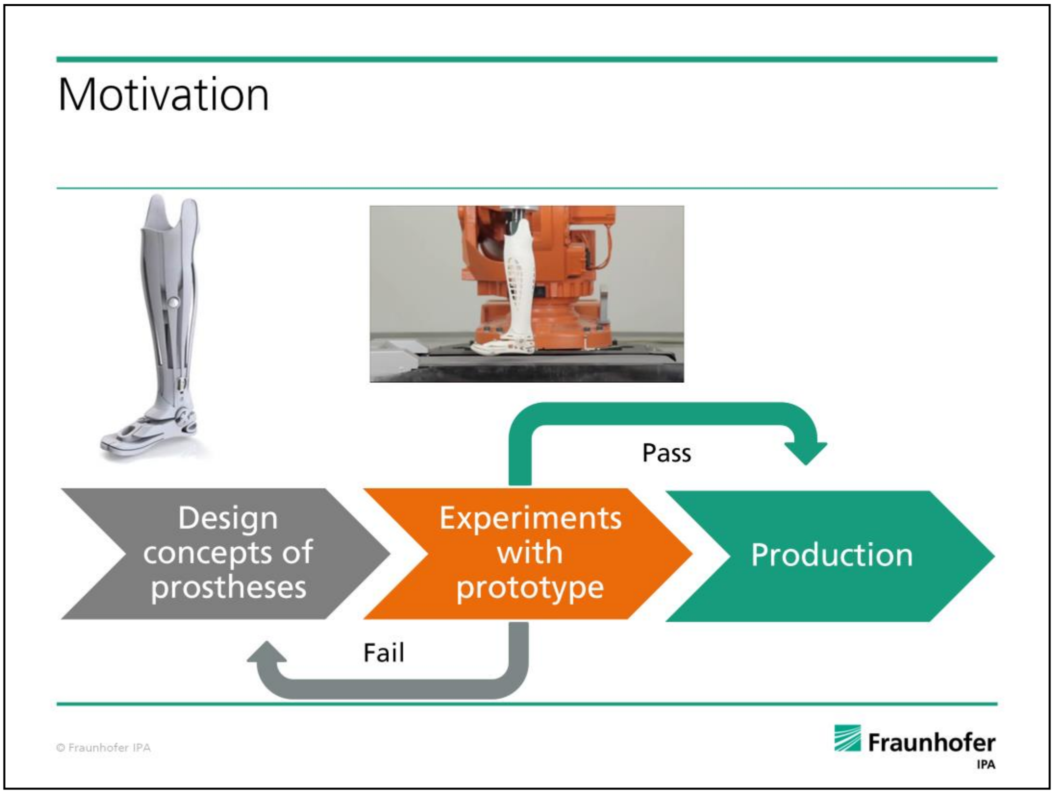
Prostheses must cater to different needs of people.

The BiOM foot is a micro-processor controlled lower limb prosthetic foot. It provides natural propulsion similar to that of the normal ankle. However, it requires constant care and batteries for it to function normally.

The Ottobock Running Leg was designed for athletes for sprinting purposes. The blade, made of carbon fiber, is designed to be light but sturdy enough to take up high impact loads. It is also designed such that the high stresses produced do not affect the limbs of the athlete.

The prosthesis shown on the right is one that was used by a fashion model. It isn’t highly functional like the above two but serves its purpose of being fashionable!



Motivation

Design concepts of prostheses

Experiments with prototype

Production

Pass

Fail

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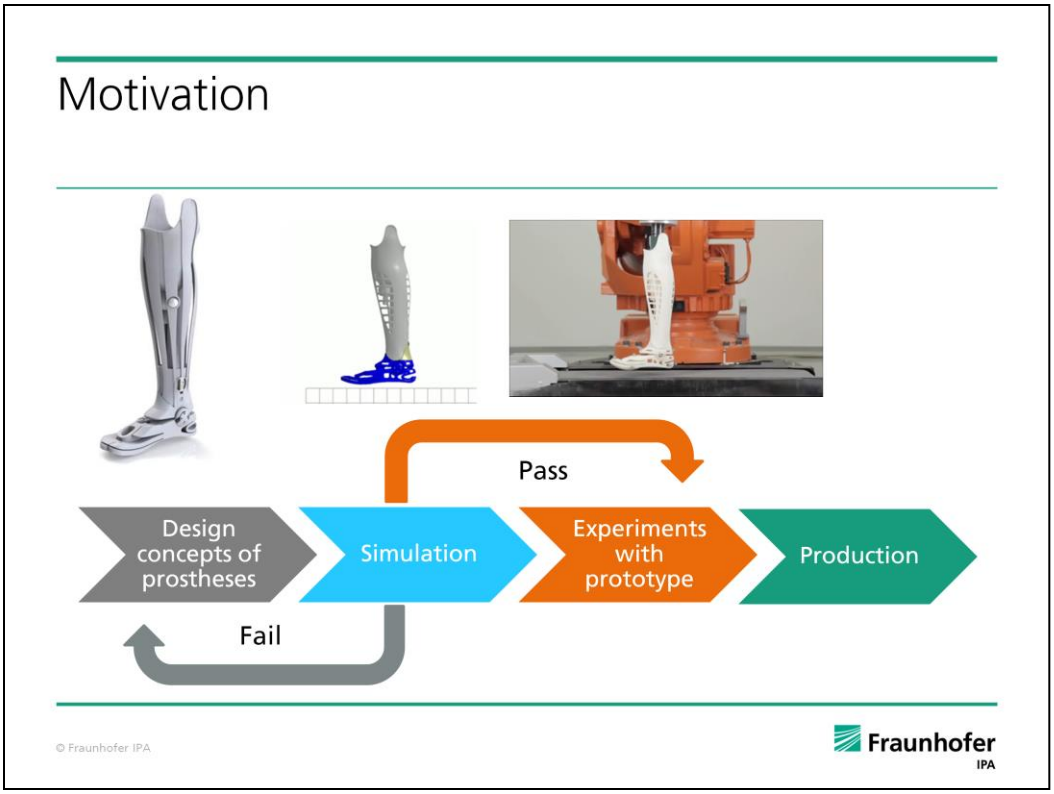
New concepts of prosthetic designs must be thoroughly tested for conformity to existing standards and for their quality. The current proof-of-design studies in the prosthetic industry involve prototype manufacturing and experimental testing.

The design prototype is tested, for example, according to ISO standards or with individual motion data in a robot for approximately 3 million cycles. If the prosthesis fails, it is re-designed and re-tested.

This cycle is rather time-consuming and should be avoided.



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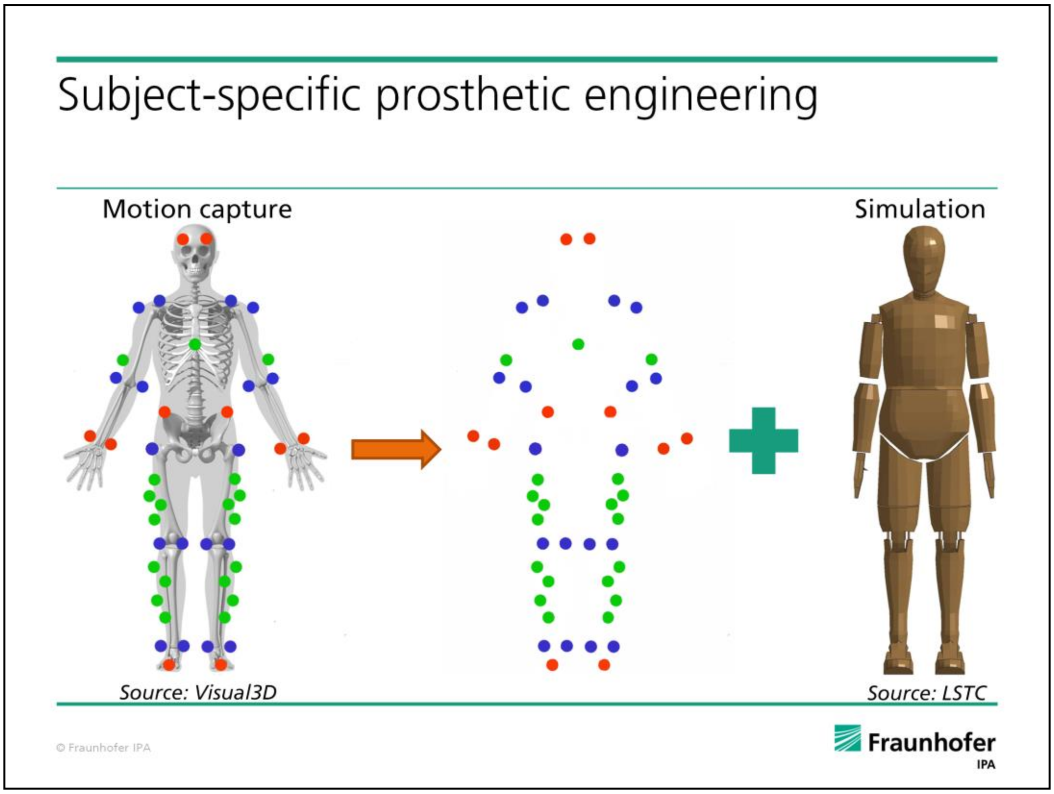
We propose to use simulations as a precursor to experimental tests to check if the design concept could fail. If the prototype fails in the simulation stage, it is re-designed until it passes the simulated test. This cycle (simulated test – prototype re-design) is short and a working prototype can be quickly realized.

When the prototype design passes the simulated test, it can then be experimentally tested. Simulated tests improve the chance of the prototype design passing the experiment.

We propose…

- To use computer simulations for assisting prosthetic technicians by
    - Designing and testing subject-specific prosthetics
    - Tailoring workflow techniques for prosthetic engineering
- To use intuitive visualization techniques



Subject-specific prosthetic engineering

Motion capture

Simulation

Source: Visual3D

Source: LSTC

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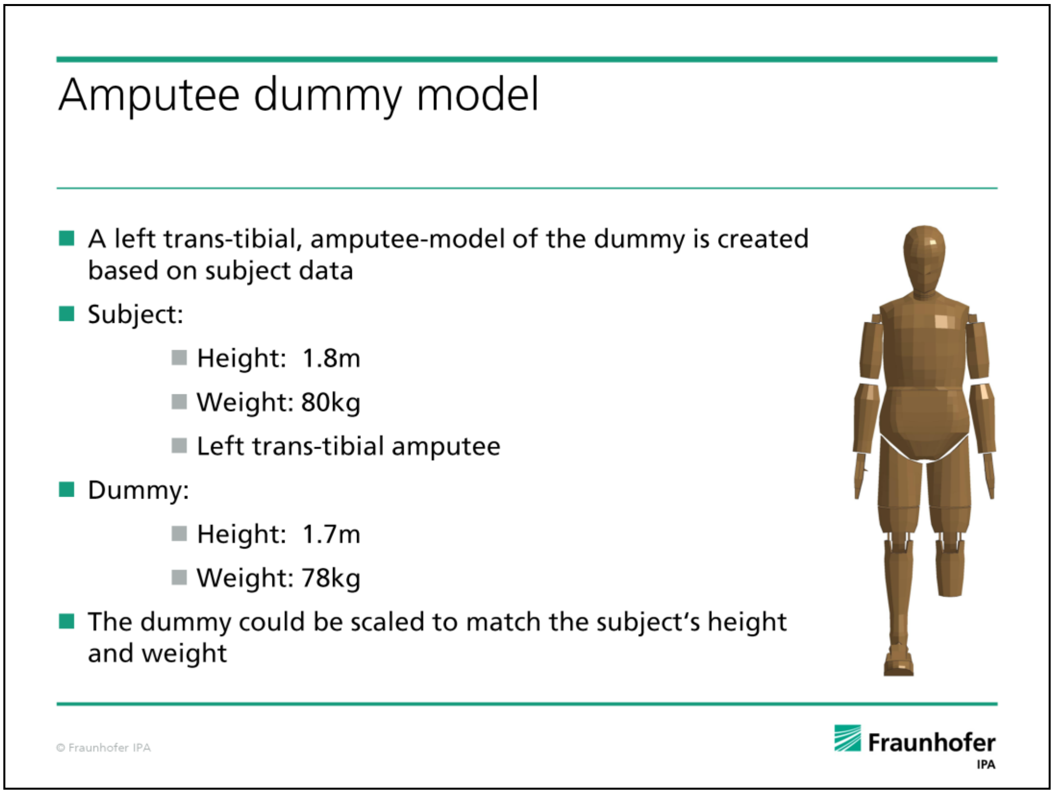
When it comes to subject-specific prosthetic devices, subject-specific parameters, in particular, the subject’s gait should be considered in the simulations.

We use Qualisys motion capture system to record the subject’s gait. The gait trajectory is obtained from the markers on the subject.

An LSTC crash test dummy (Hybrid III) was used to represent the subject. The captured marker trajectories are transferred to this dummy model.

Simplifying the dummy model

- The LSTC crash test dummy (Hybrid III 50th percentile) has 115 parts
- It is neither necessary nor possible to provide motion capture data to each part
- The LSTC dummy is reduced to consist of 5 parts – arms, torso and legs
- The rigid body trajectories are imparted to these parts



Amputee dummy model

- A left trans-tibial, amputee-model of the dummy is created based on subject data
- Subject:
  - Height: 1.8m
  - Weight: 80kg
  - Left trans-tibial amputee
- Dummy:
  - Height: 1.7m
  - Weight: 78kg
- The dummy could be scaled to match the subject‘s height and weight

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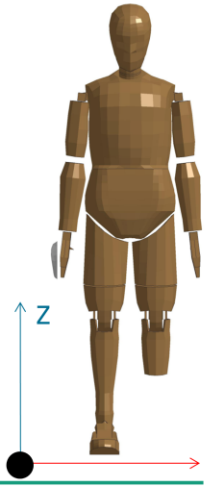
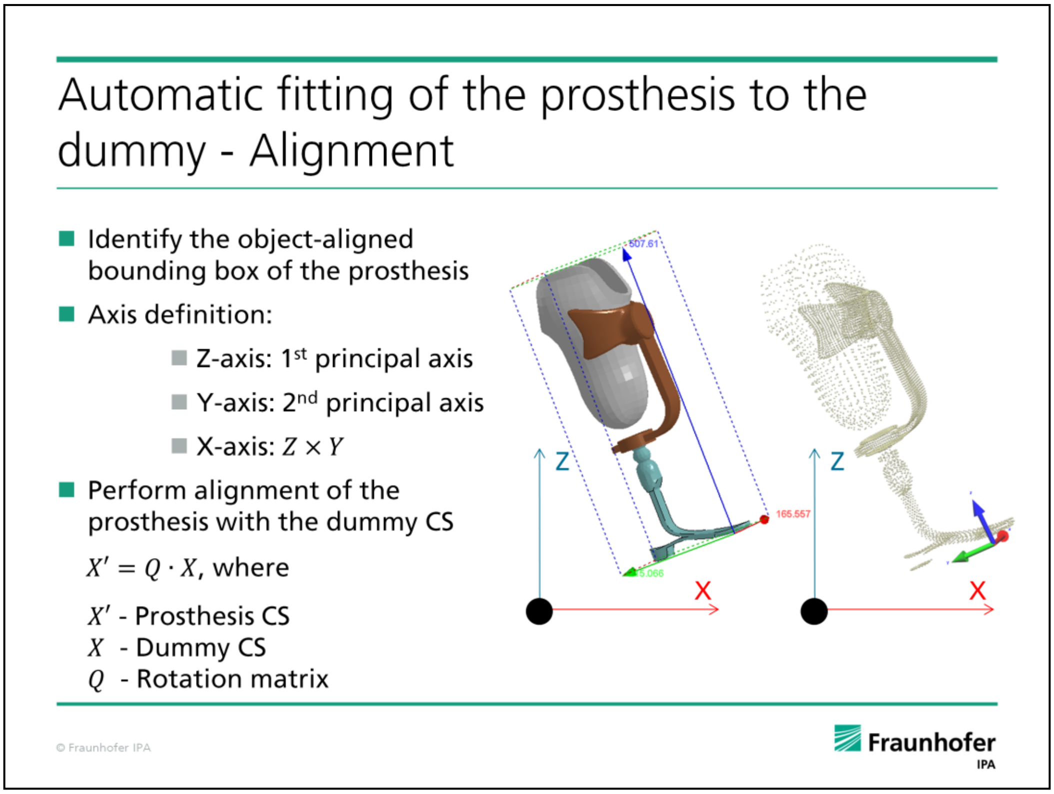
The chosen LSTC dummy matched the weight and height of the subject. The dummy could be scaled (anthropometrically) to match the subject’s parameters if necessary.

The LSTC dummy was ‘amputated’ approximately at the same location as that of the subject.

Automatic fitting of prosthesis to dummy

- The standing model of the LSTC dummy is aligned in its local coordinate system (Dummy CS)
- If the prosthesis is not aligned in the dummy's coordinate system, a proper transformation of the prosthesis in the Dummy CS is required.





Automatic fitting of the prosthesis to the dummy - Alignment

- Identify the object-aligned bounding box of the prosthesis
- Axis definition:
    - Z-axis: 1st principal axis
    - Y-axis: 2nd principal axis
    - X-axis: $Z \times Y$
- Perform alignment of the prosthesis with the dummy CS

$X' = Q \cdot X$, where

X' - Prosthesis CS
X - Dummy CS
Q - Rotation matrix

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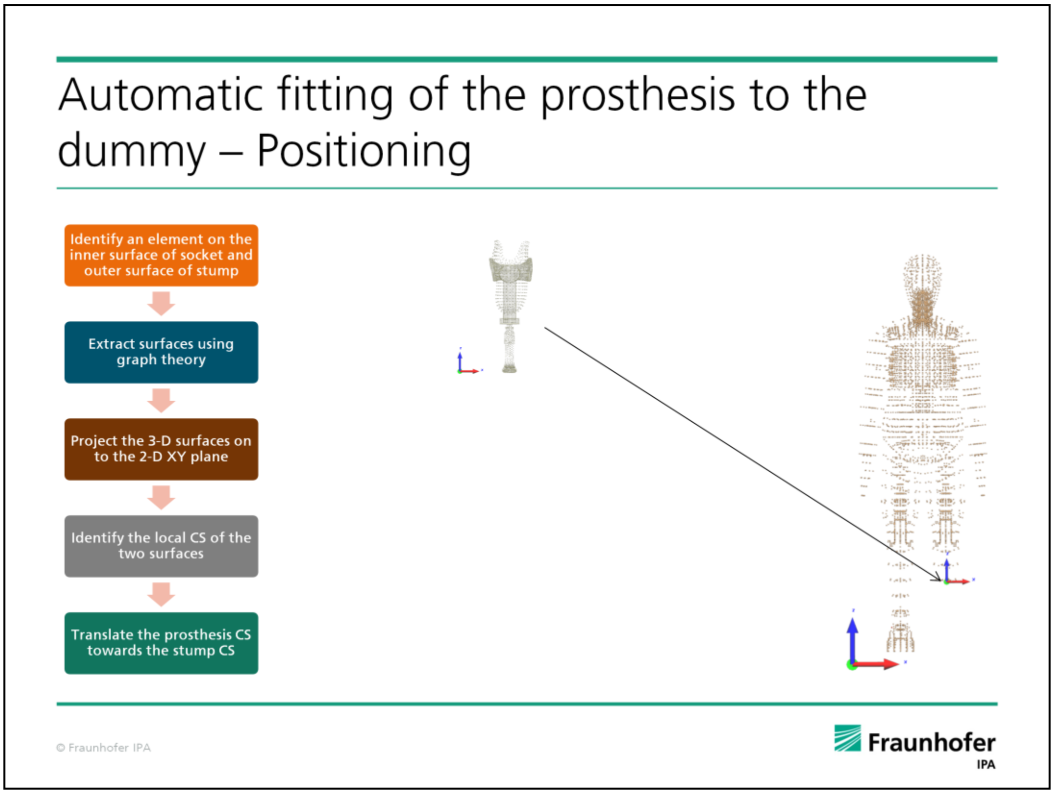
The prosthetic limb need not necessarily be aligned with the residual limb of the dummy in the dummy coordinate system (CS). To automatically align the prosthetic limb with the dummy's residual limb, we align the object-aligned bounding box of the limb in the dummy CS.



Automatic fitting of the prosthesis to the dummy – Positioning

Identify an element on the inner surface of socket and outer surface of stump

Extract surfaces using graph theory

Project the 3-D surfaces on to the 2-D XY plane

Identify the local CS of the two surfaces

Translate the prosthesis CS towards the stump CS

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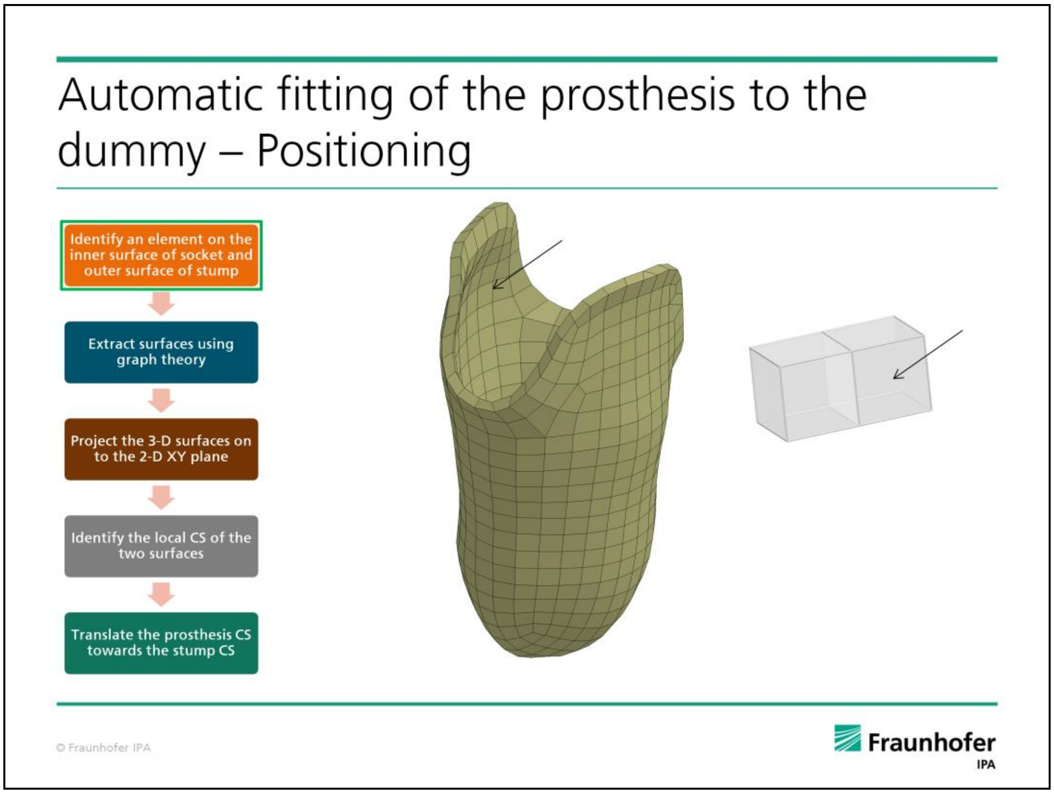
Once aligned, the prosthetic limb could be located anywhere in the dummy CS and should be translated and positioned over the residual limb of the dummy.



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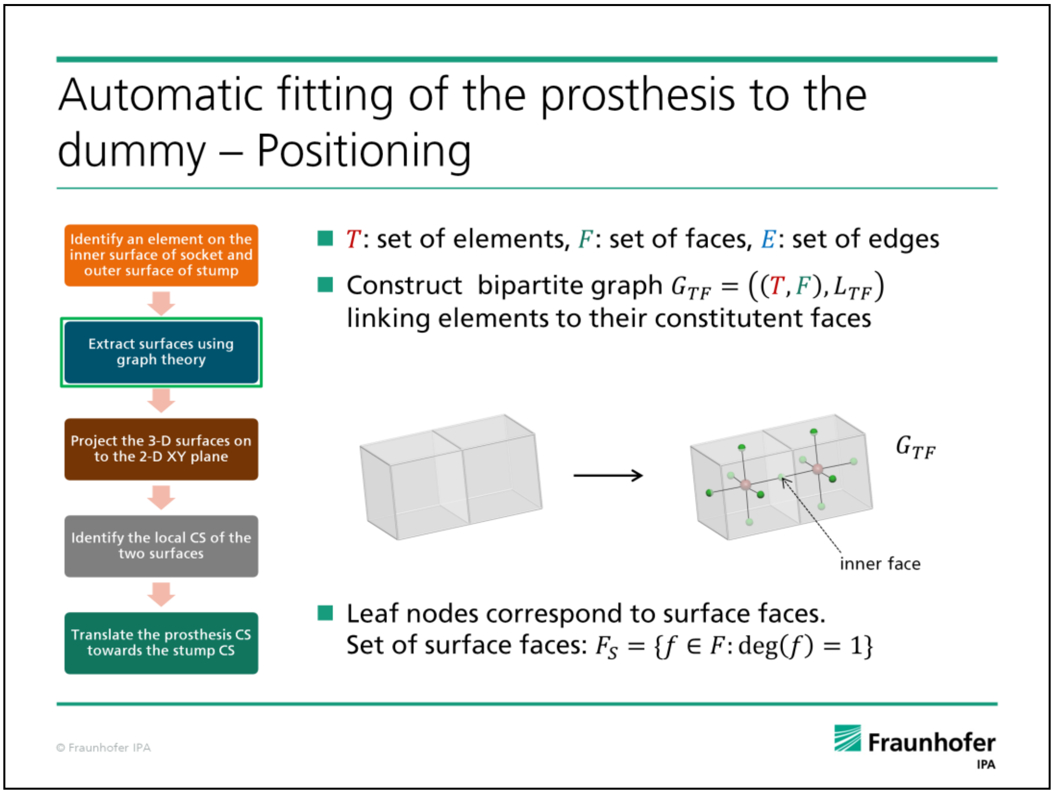
By ‘translating the prosthetic limb’ we match the inner surface of the prosthetic socket and the outer surface of the dummy’s residual limb.

In order to match the surfaces of the residual limb and the socket, these surfaces should first be extracted. A set of nodes (of an element) on the surface to be extracted is required for the extraction.

The extraction methodology is explained with the help of two cubes that share a common face.



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- T: set of elements, F: set of faces, E: set of edges
- Construct bipartite graph $G_{TF} = \big((T, F), L_{TF}\big)$ linking elements to their constitutent faces

- Leaf nodes correspond to surface faces.
  Set of surface faces: $F_S = \{f \in F: \deg(f) = 1\}$

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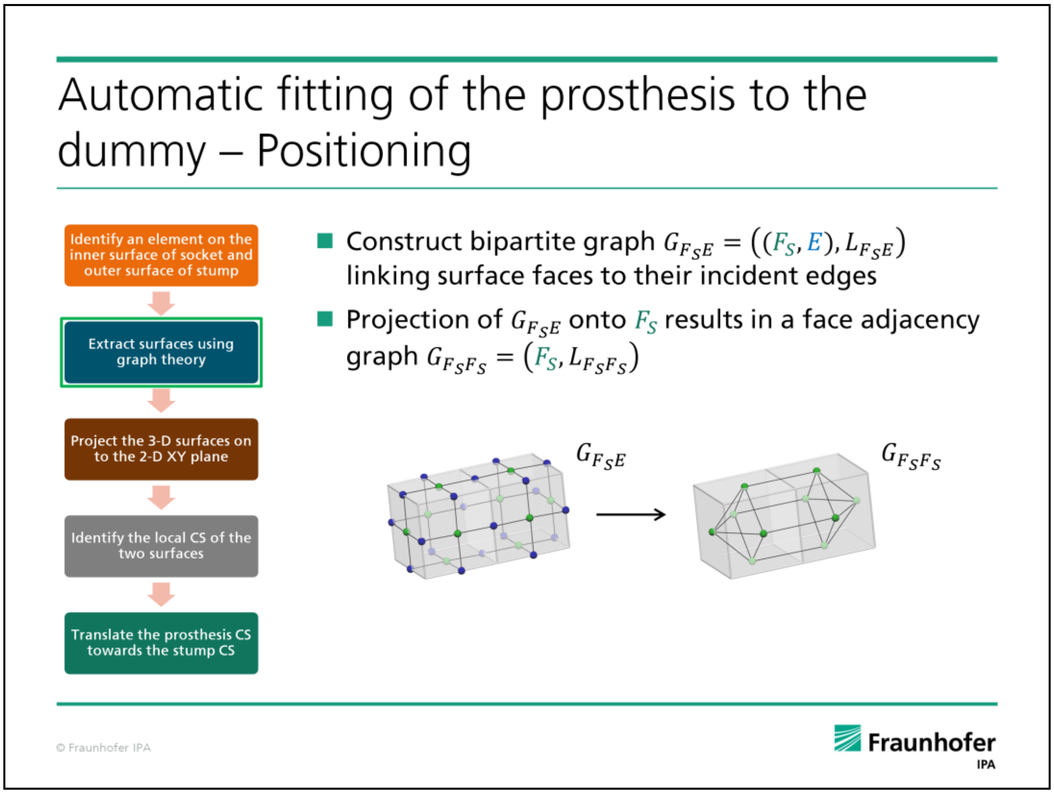
Surface extraction is done using graph theory.

As an example, consider two cubes sharing a common inner face. Let T be the set of elements in the geometry, F be the set of faces and *E* be the set of edges. A bipartite graph connecting the set of elements to the set of faces is constructed $G_{TF} = \big((T, F), L_{TF}\big)$.

In the figure on the right, the elements are represented by pink balls and the faces by green balls. L_{TF} are the links connecting the element to its constituent faces.

From this graph, we extract only those faces (green balls) which connect to only one element (pink ball).



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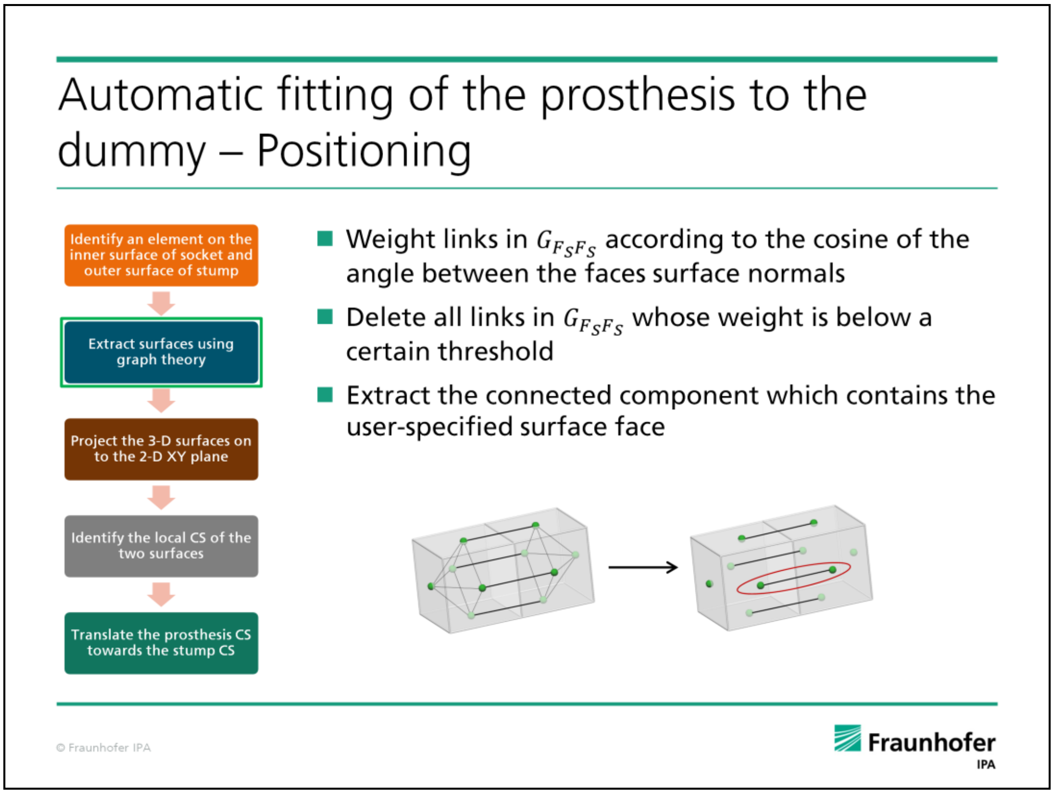
- Construct bipartite graph $G_{F_S E} = \left((F_S, E), L_{F_S E}\right)$ linking surface faces to their incident edges
- Projection of $G_{F_S E}$ onto F_S results in a face adjacency graph $G_{F_S F_S} = \left(F_S, L_{F_S F_S}\right)$

A second bipartite graph is constructed between the above set of element faces and their edges. The edges are represented as blue balls.

Two faces that are connected by an edge implies connected surfaces. Such faces with shared edges are linked resulting in a face adjacency graph (figure on right).



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- Weight links in $G_{F_S F_S}$ according to the cosine of the angle between the faces surface normals
- Delete all links in $G_{F_S F_S}$ whose weight is below a certain threshold
- Extract the connected component which contains the user-specified surface face

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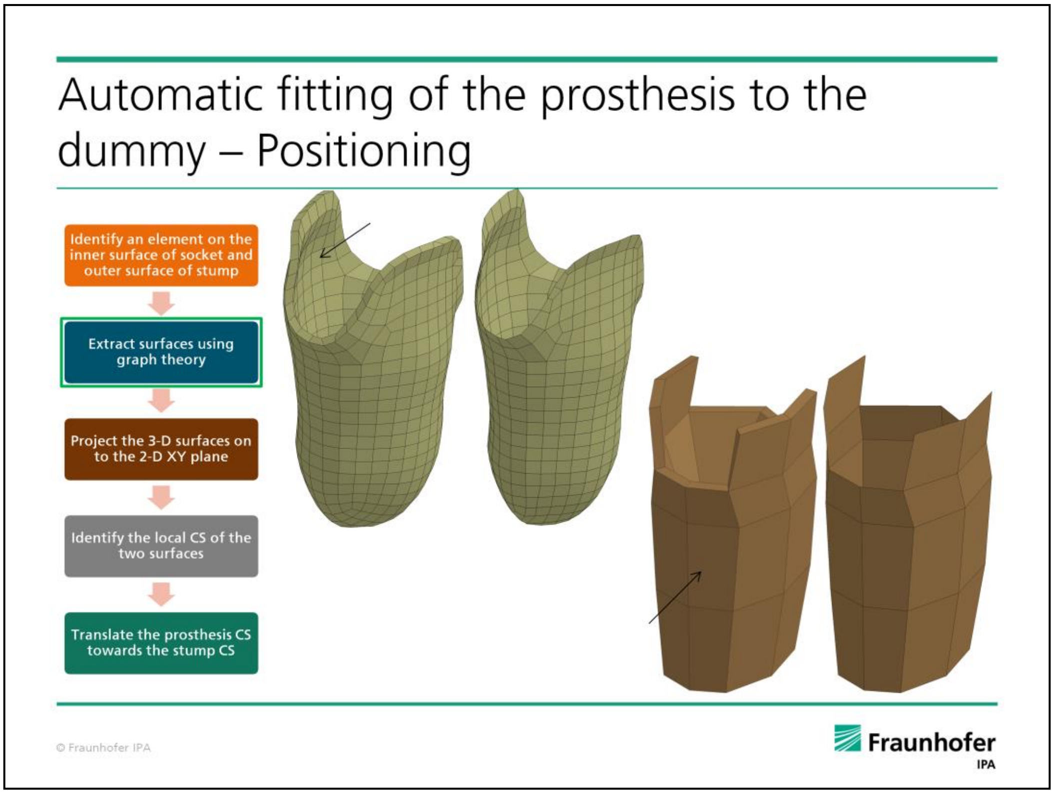
In this face adjacency graph, we assign weights to the links. The weight is the cosine of the angle between the face normals of any two connected surfaces.

Links between those faces whose weight is below a certain threshold value are deleted and the graph decomposes into several subgraphs (shown in the figure on right).

The subgraph containing the user-defined element nodes yields the desired surface.



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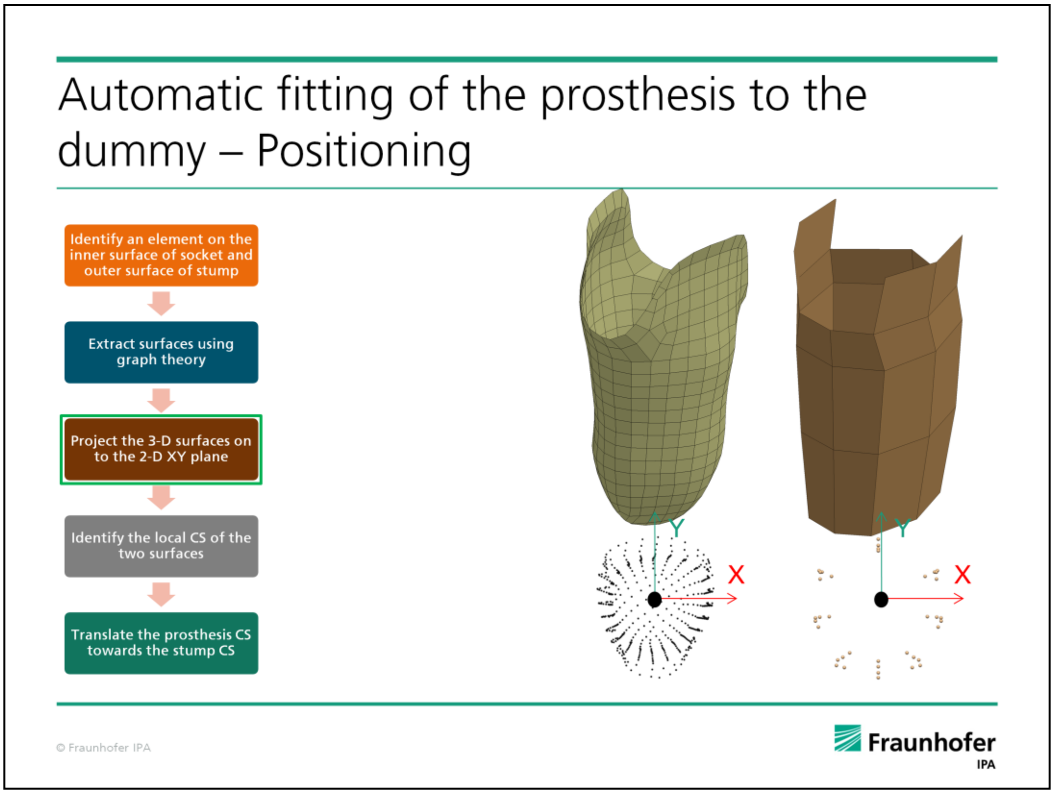
The arrows indicate the element nodes that were chosen for extracting the surface. The solid and extracted surface mesh of the socket and the residual limb of the dummy are shown side-by-side.



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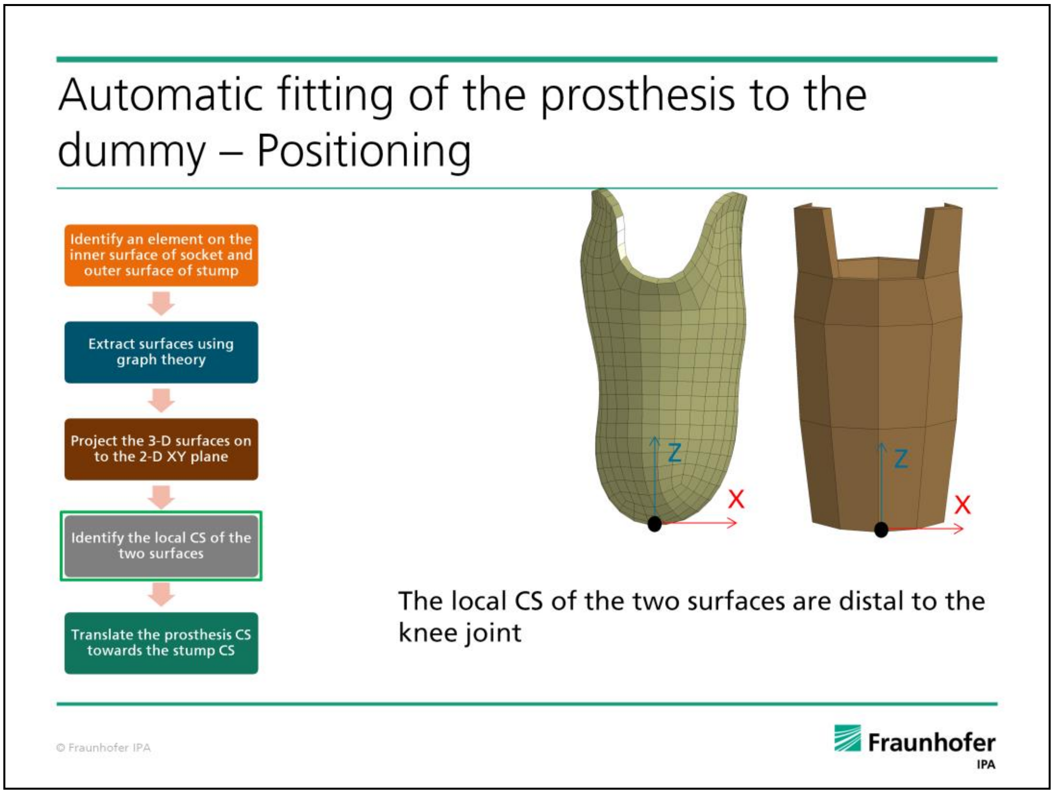
A projection of the nodes of the socket and residual limb on the XY plane is performed. The origin of the local coordinate system of the socket and the residual limb are defined as the mean of the nodal coordinates of the projected nodes.



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The local CS of the two surfaces are distal to the knee joint

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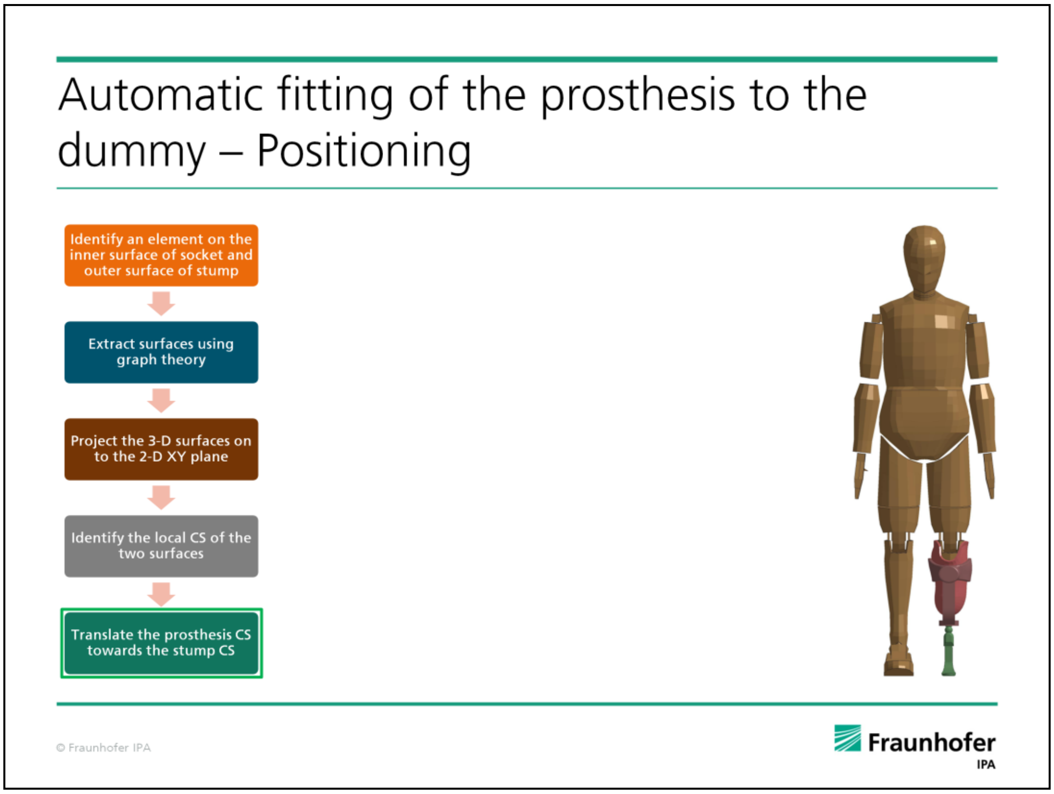
The local CS is positioned at the distal end of the socket and the residual limb. When the origin of the socket CS coincides with the origin of the residual limb CS, we have successfully positioned the socket over the residual limb.



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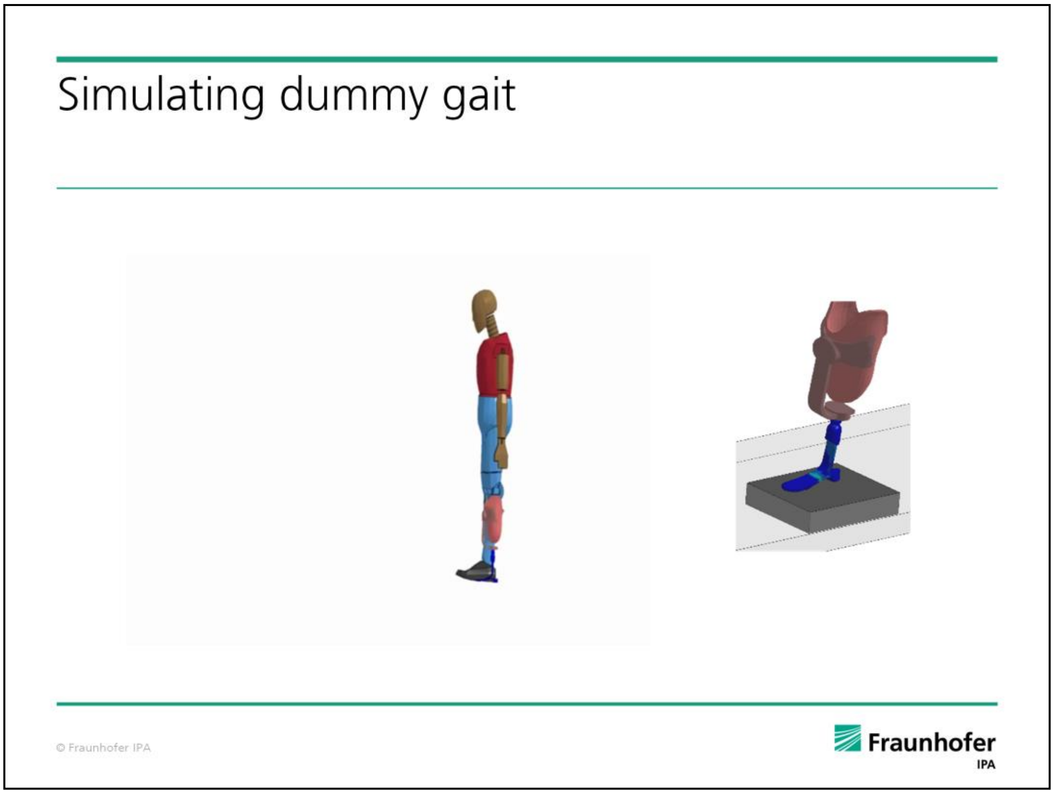
A manual check might also be necessary here to check for penetrations between the mesh of the prosthetic limb and the residual limb. This is necessary when the prosthetic limb does not match the dummy’s residual limb.

The dummy’s residual limb is rigidly coupled to the socket of the prosthetic limb. As we are only interested in the dynamic loads transferred by the dummy onto the prosthetic limb, the residual limb-socket interface is of least interest here.



Simulating dummy gait

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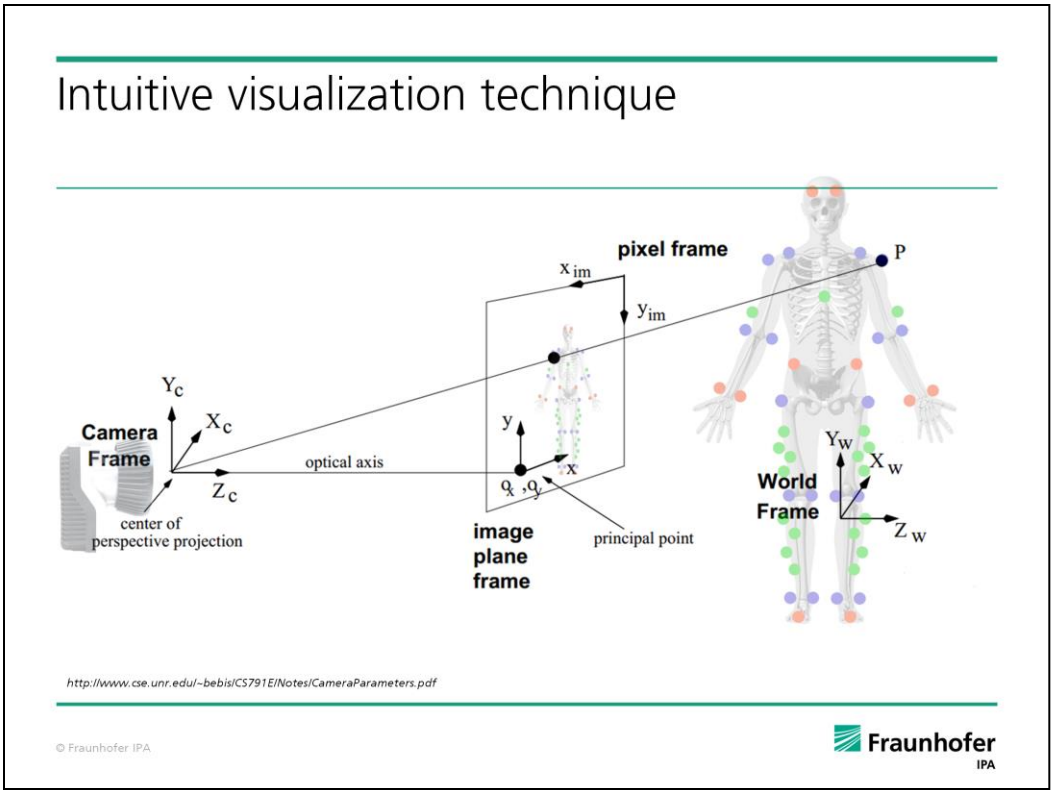
An explicit dynamics FE analysis was performed. The stress on the prosthetic limb is shown on the right.



Intuitive visualization technique

http://www.cse.unr.edu/~bebis/CS791E/Notes/CameraParameters.pdf

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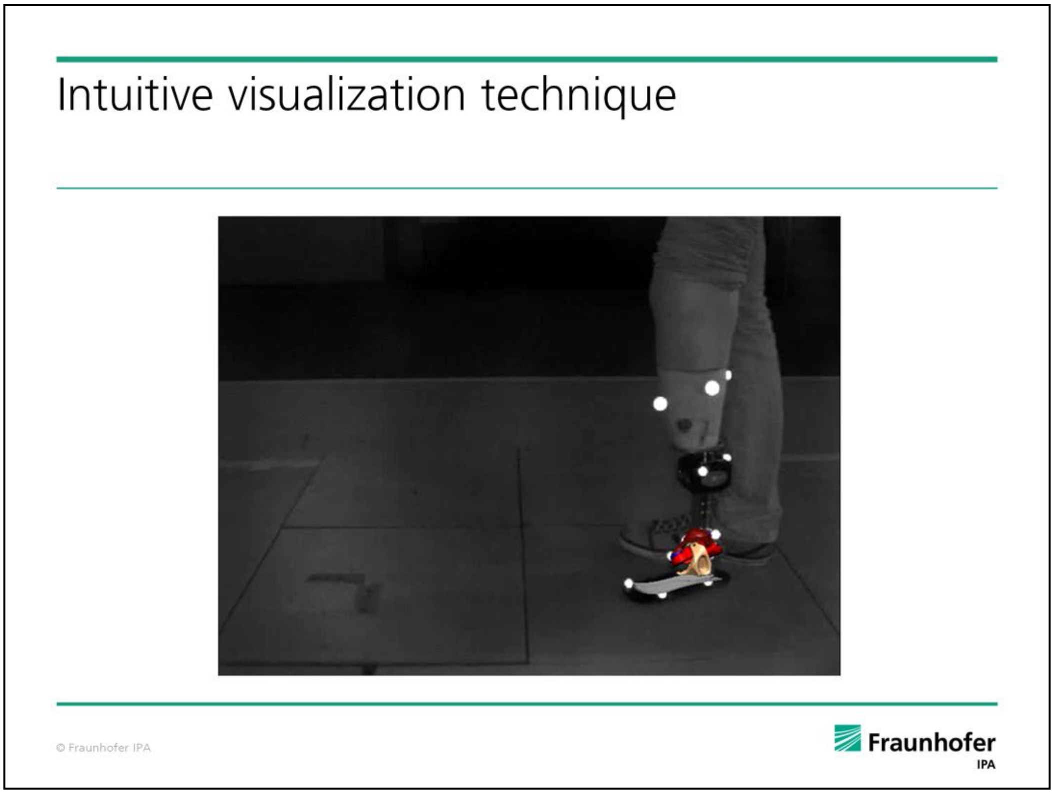
For prosthetic technicians, the information on stresses might not be very informative. Also, the visualization of the stresses, in some cases, could be counter-intuitive. So, we have developed a visualization technique that projects the simulated results upon the gait video of the subject.

The Qualisys motion capture cameras have information on their own position and orientation in the global coordinate system. Using this information, we can project the video on an image plane in the lab coordinate system for a graphical overlay of video and simulated data.



Intuitive visualization technique

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The prosthesis can be seen overlaid on the video.

Thank you

Ellankavi Ramasamy
Ellankavi.ramasamy@ipa.fraunhofer.de

Biomechatronische Systeme
Virtual Orthopedic Lab

Fraunhofer Institute for Manufacturing
Engineering and Automation (IPA)
Nobelstr. 12
70569 Stuttgart, Germany