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Title
A toolbox for bi-directional conversions between 3D prosthetic socket stress measurements and its representations in 2D.

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Summary
A method to accurately present intra-socket stress distributions on a 2D map of individual amputees' residual limbs. The process was completed for a transfemoral amputee and verified through experimental pressure recordings, which were visualised on a specially developed desktop application.

Introduction/ basics
The powerful potential of intra-socket shear and pressure measurements of lower limb prosthetic sockets has been highly reported in the literature [1, 2, 3]. The value of this information to clinicians is highly dependent on the ability to relate the measurements to the residual limb anatomy [4, 5, 6]. For example, identification of high-pressure regions in the socket can aid prosthetists in efficient socket design modifications [7]. Most publications present the pressure recordings graphically [8, 9, 10], however, this may lead to an overwhelming number of graphs that are disjointed from the residual limb or socket anatomy. Neumann et al. [5], presented coloured pressure contours alongside anatomical compartments of the residual limb, such as Scarpa's Triangle, and femoral relief. This is an alternative method to coherently display intra-socket pressure.
A universal and repeatable process was developed to mimic this data visualisation style using accessible tools.

Material method; implementation/ process
To display anatomically accurate intra-socket pressure distributions in 2D and for convenient and precise sensor integration with the physical prosthetic socket, the following method is suggested:

1. Scan the residual limb or intra-socket surface with a 3D scanner;

2. Align the scan according to a defined coordinate frame – using computer aided design (CAD) software;

3. Discretise the digital model and physical socket –

a) Radially at 30 degree increments, starting at the greater trochanter (GT), and

b) Along the longitudinal axis at 50mm increments starting from the distal end;

4.Convert the 3D digital model into a flattened 2D map using CAD software;

5. Label the map with anatomical regions, e.g. Scarpa's Triangle and the femoral relief;

6. Position the sensors on the map – this may be based on specific requirements, e.g. at scar tissue sites or highly sensitive regions;

7. Integrate the sensors with the physical socket, using the map for guidance.

Results

A 3D scan of a test subject's residual limb was captured and pre-processed (cleaned and smoothed) in Meshmixer [11] (Figure 1A). A Solidworks [12] macro was developed to: 1) orient the scan by vertically aligning the axis connecting the midpoint between the highest point on the lateral edge (above the GT) and the lowest point on the medial edge (near Scarpa's Triangle), and the distal end (Figure 1B) and 2) discretise and convert the scans to 2D. The 2D map was then labelled with the anatomical compartments of the subject's residual limb in Inkscape [13] (Figure 2). The compartments were chosen based on Figure 2 in the paper by Neumann et al. [5].

Renderings of five sensor strips were overlaid on the subject's own residual limb map – to cover as much of the socket surface as possible, while ensuring individual sensels were located at sites of interest, e.g. ischium and femoral relief (Figure 2). A PETG copy of the subject's socket was similarly discretised using a purpose-built rig (Figure 3), and the sensors integrated in line with the map (Figure 4).

A gait monitor was connected to the subject's prosthetic leg to identify the four phases of gait such that the pressure recordings can be related accordingly. A desktop application was developed to visualise pressure distributions on the subject's own residual limb map. The data are presented as a function of the gait cycle as well as the average pressure profiles of individual sensels over the entire gait cycle (Figure 5).

Discussion/ conclusion; conclusion for the practice

The direct correlation between the physical socket and its 2D representation allows for easy and precise sensor integration with the socket. Furthermore, displaying data in the form of personalised 2D pressure maps is arguably more comprehensive than 1D pressure profiles of individual sensels.

Although this case study exploits the transparency of the PETG socket, the discretisation rig can be used in conjunction with a spreading calliper during sensor integration with opaque sockets. Alternatively, simple tools, such as a protractor (with zero degrees aligned with the GT) and a measuring tape can be used instead of the rig. Even if some precision is lost, the convenience of these tools is advantageous, and moreover would not require disassembling the prosthetic leg from the socket.

Use of only open-source software provides wider accessibility to clinicians. The only licensed software used in this method is Solidworks, which could be replaced by free suites, such as, Blender [14]. Alternatively, a stand-alone software that automatically processes the 3D residual limb scan and outputs a fully discretised and labelled 2D map with the sensors pre-positioned would significantly decrease manual labour costs. Finally, placing identifiable markers on the residual limb during scanning (e.g. on the GT, in the middle of Scarpa’s Triangle, and at the distal end) would result in improved and more consistent digital model alignment, regardless of whether the process is automated or manual.

References

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[13] Inkscape, https://inkscape.org/, 2020.

[14] Blender, https://www.blender.org/, 2021.

Image: Figure1_175.png

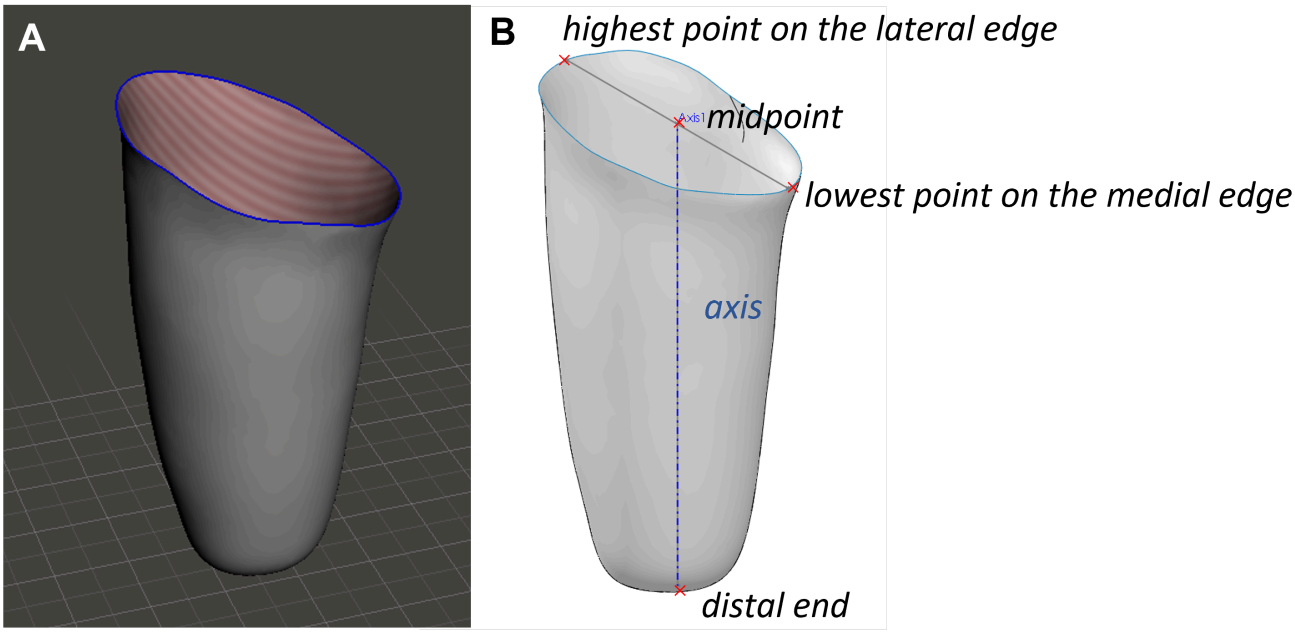

Figure 1 3D scan of test subject's residual limb A: after cleaning and smoothing in Meshmixer; B: aligned in 3D space in Solidworks

Image: Figure2_176.png

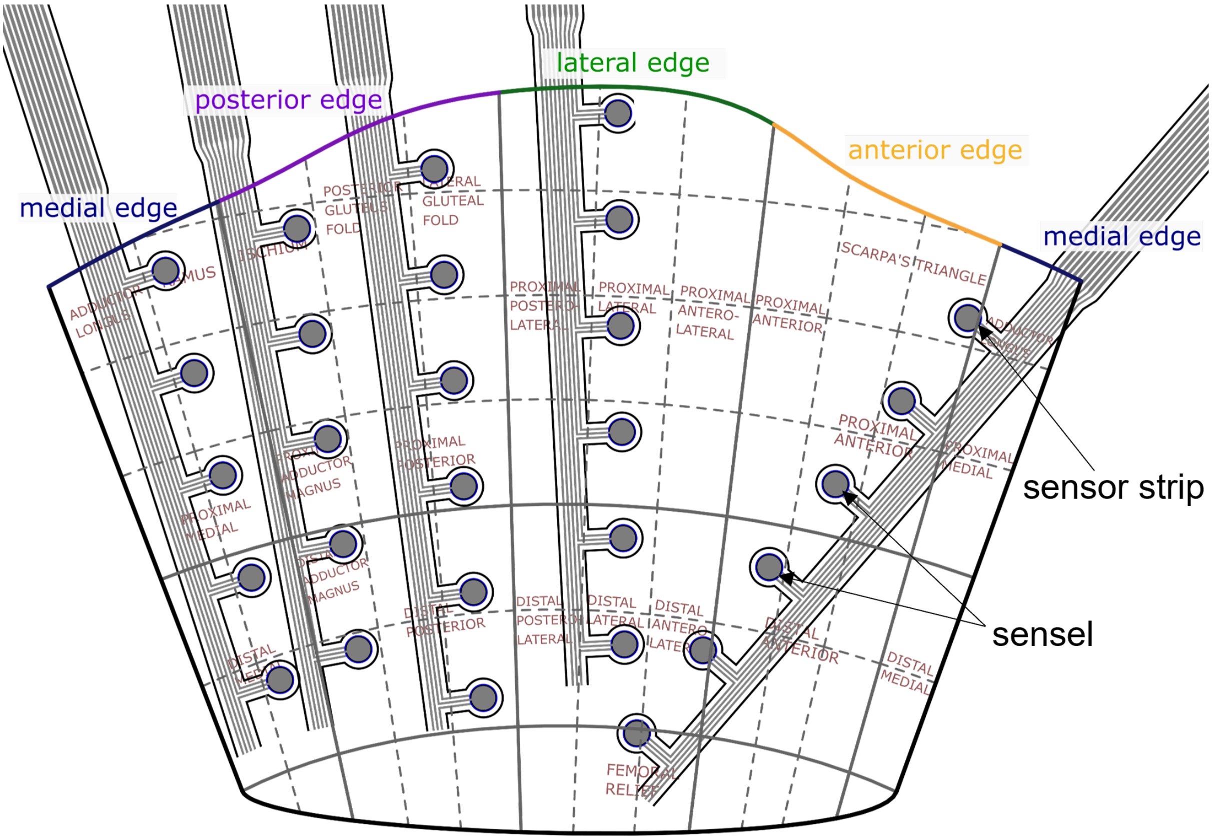

Figure 2 2D map of subject's residual limb with anatomical compartments labelled and sensor strips overlaid in specified positions

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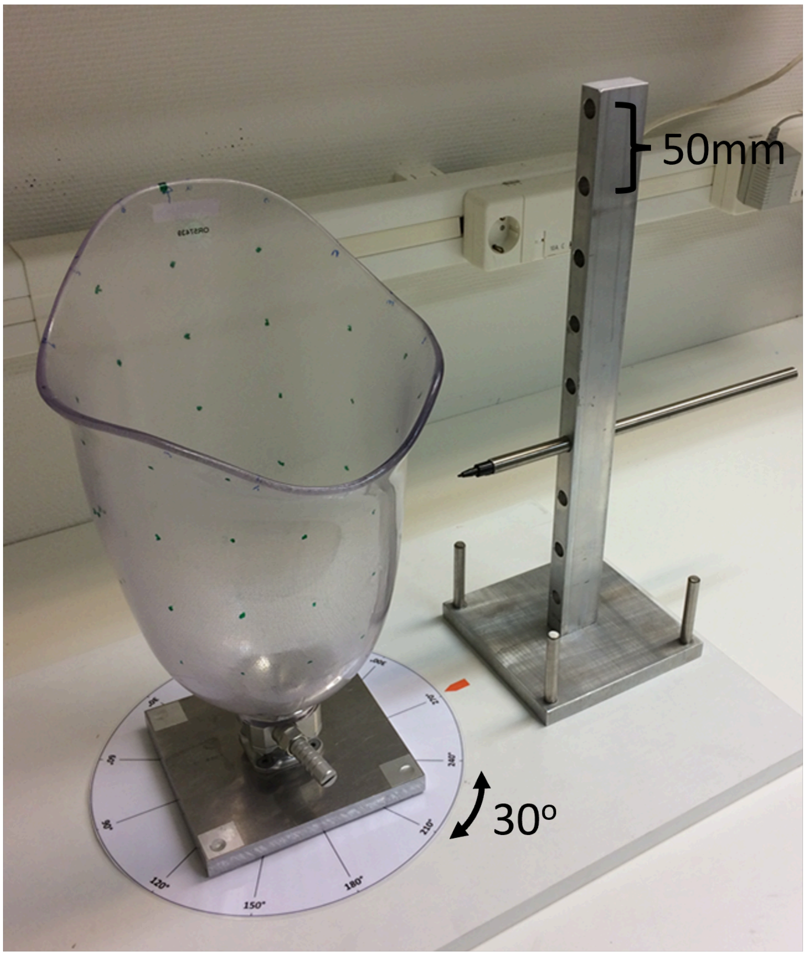

Figure 3 Purpose-built discretisation rig with an example socket

Image: Figure4_178.png

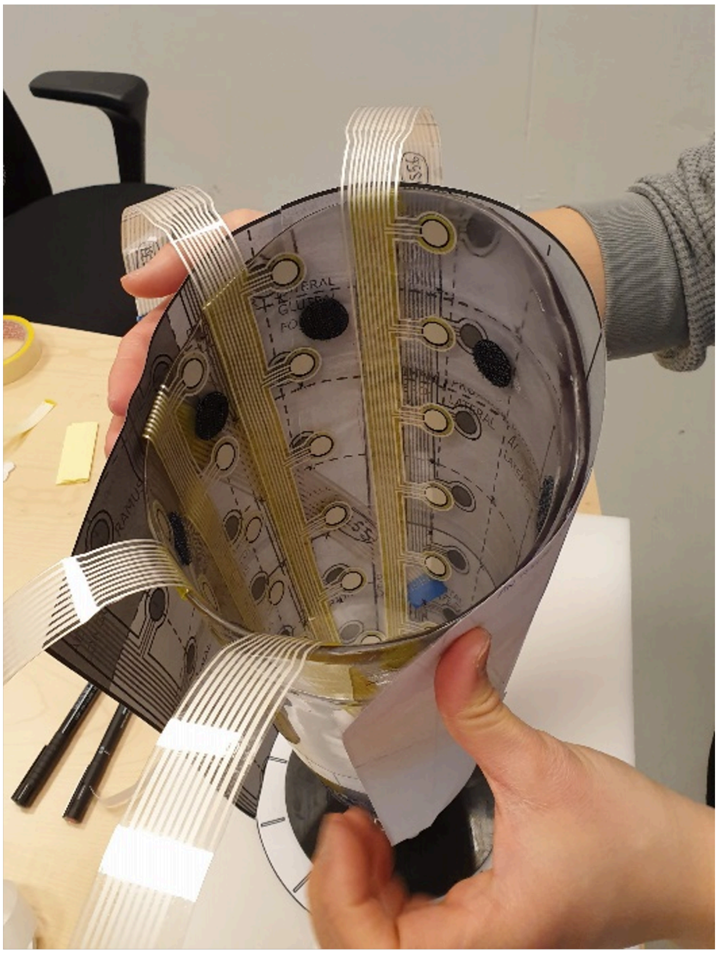

Figure 4 Sensors integrated with test subject's discretised PETG socket, using the 2D map for guidance

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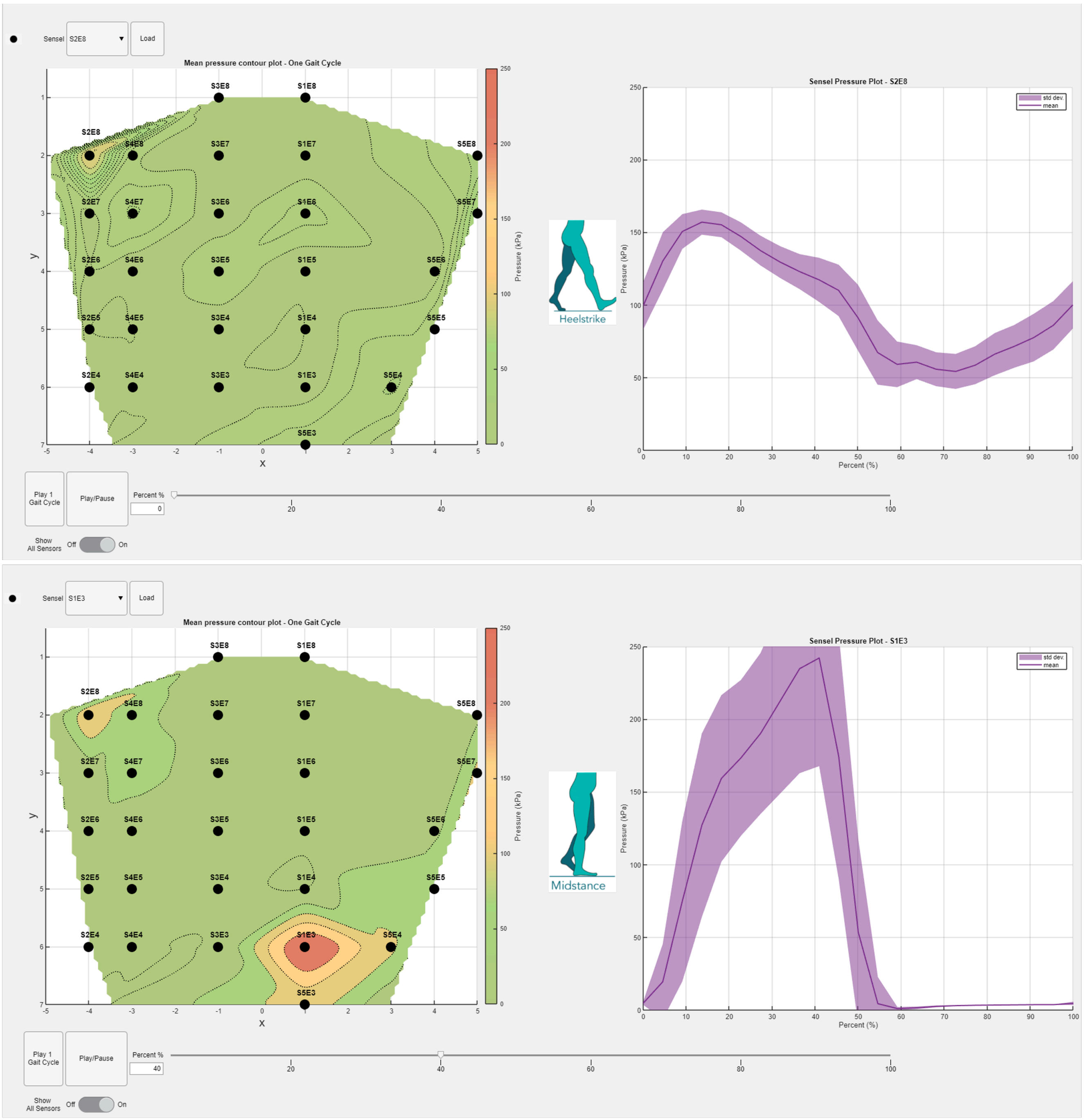

Figure 5 Desktop application presenting recorded pressures during level ground walking on a 2D map of the residual limb (left), and the pressure profile of a single sensel (right). Black dots represent sensel locations. Top: pressure distribution at heel strike, profile of proximal medial sensel. Bottom: pressure distribution at midstance, profile of distal lateral sensel.