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Title
Simultaneous intra-socket shear and pressure measurements of a transfemoral amputee during dynamic and static activities: a feasibility study

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Summary
Specially designed printed low-cost and lightweight shear and pressure sensors were successfully integrated in a transfemoral amputee's prosthetic socket. Shear and pressure were measured simultaneously during dynamic and static activities. Repeated stress patterns were evident during walking.

Introduction/ basics
The residual limb in lower limb amputees is prone to skin problems due to the unnatural environment to which it is exposed during prosthesis use. This includes shear and normal stresses, and increased humidity at the interface between the residual limb and the prosthetic liner or socket. Shear stress can cause blistering, cysts and ulcerations of the residual limb [1], [2]. Sensing technology inside the prosthetic socket, such as shear sensors, can be used to provide early identification of high shear stresses of the residual limb, thus minimising risk of cysts, ulcerations, and skin breakdown [3], [4]. Most research has focused on pressure sensor development for transtibial prosthetic sockets [5]; while very few attempts have been made to measure intra-socket shear, and even fewer attempts to measure that in transfemoral sockets [3], [6], [7]. In this study, two shear and two pressure sensors that were specially designed were tested by a transfemoral amputee

Material method; implementation/ process
A single-subject (80kg, male, transfemoral amputation, K-level 4) performed static and dynamic activities with two shear sensors and two pressure sensing strips (with 12 sensels in total) integrated inside a PETG replica of his own direct socket [8], using double-sided adhesive. Figure 1 shows the positions of the sensors relative to the subject's residual limb anatomy. A

gait monitor was used to detect the four phases of gait. The sensors were specially designed and manufactured from low-cost environmentally friendly QTSSTM conductive ink screen-printed onto a flexible PET substrate (total ~0.14mm thickness). The shear sensors have a rubber and PET puck (~2mm thickness) adhered on top and are capable of measuring in four orthogonal directions (Figure 1B, C). The pressure sensing strips have been tested and verified and were calibrated prior to the test. All sensors were connected to electronic interfaces on the socket exterior. See [9] for full sensor design and preparation details.

Results

With the sensing system integrated in his replica socket, the subject performed the following tasks three times: donning, doffing, static standing, and level-ground walking at self-selected walking speed. The results confirm the ability to simultaneously measure shear and normal stress changes inside transfemoral prosthetic sockets during dynamic and static activities, with low-cost, retrofittable printed sensors.

Measurements with the gait monitor enabled identification of repeated pressure and shear patterns with respect to the gait cycle (Figure 2). The measured resistance decreases as stress increases. The recorded resistance patterns are as expected – the resistance drops at heel strike (indicating an increase in stress) and continues to fall to a minimum during stance phase and increases again from toe-off and throughout swing phase (indicating a decrease in stress). Similarly, as expected, the stresses at the distal end are higher than at the proximal posterior region, which is indicated by the lower resistances that were measured at the distal lateral region. Furthermore, different shear magnitudes are discernible for different directions (Figure 3).

The sensors were easy to integrate into the socket and remained secured in place throughout the test session (Figure 4). The subject did not feel any pain or tightness in the socket at any point during the trial, however, red marks were visible on the skin at sites of the shear sensor pucks at the end of the test session.

Discussion/ conclusion; conclusion for the practice

This feasibility study proved the printed shear and pressure sensors can be used alongside each other to simultaneously measure stress in five orthogonal directions. It was also shown these low-cost environmentally friendly sensors are retrofittable inside an amputee's existing socket, with little or no contraindications.

Characterisation of actual shear stress values (i.e. in kPa) is not as simple as that for normal pressure – due to the sensitivity of the shear sensor to both normal and shear stresses. In many cases, it may be sufficient to evaluate stress changes (throughout the day or over weeks/ months) to detect unusually high stresses in the socket that could result in skin damage or atypically low values that could cause instability during locomotion, for example. Providing such measurements during socket fitting procedures can also help clinicians identify sites of high stress and regions where these stresses could be redistributed through socket design modifications. The combination of these sensors with the gait monitor (or other inertial measurement systems) is valuable for relating the intra-socket stress distributions with activities of daily living.

Future developments should address characterisation of shear stress values and how best to present the data to the clinicians for fast and easy usability. Further patient testing is required to evaluate the efficacy of such a system to improve socket fitting outcomes and to assist with prosthesis alignment.

References

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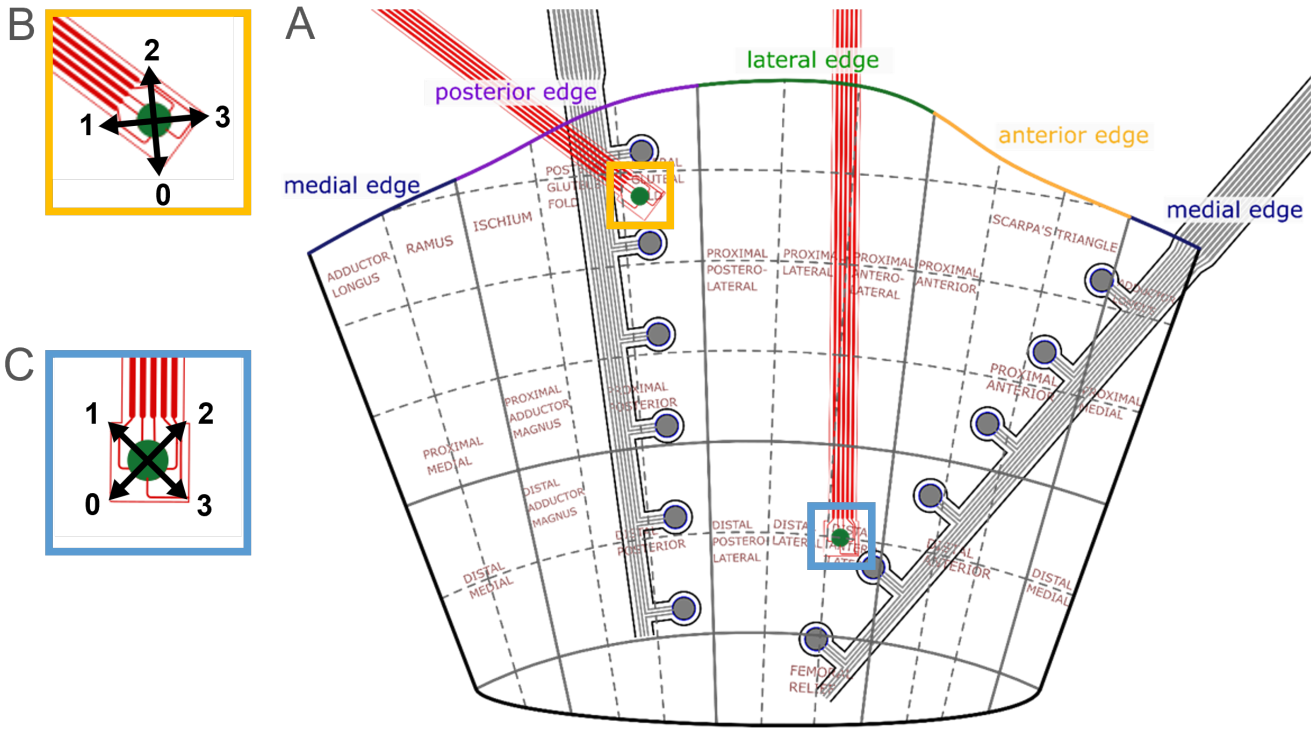

Figure 1 (A): Shear and pressure sensor positions on a 2D representation of the test subject’s residual limb. Shear sensor measurement directions at proximal posterior (B), and distal lateral (C).

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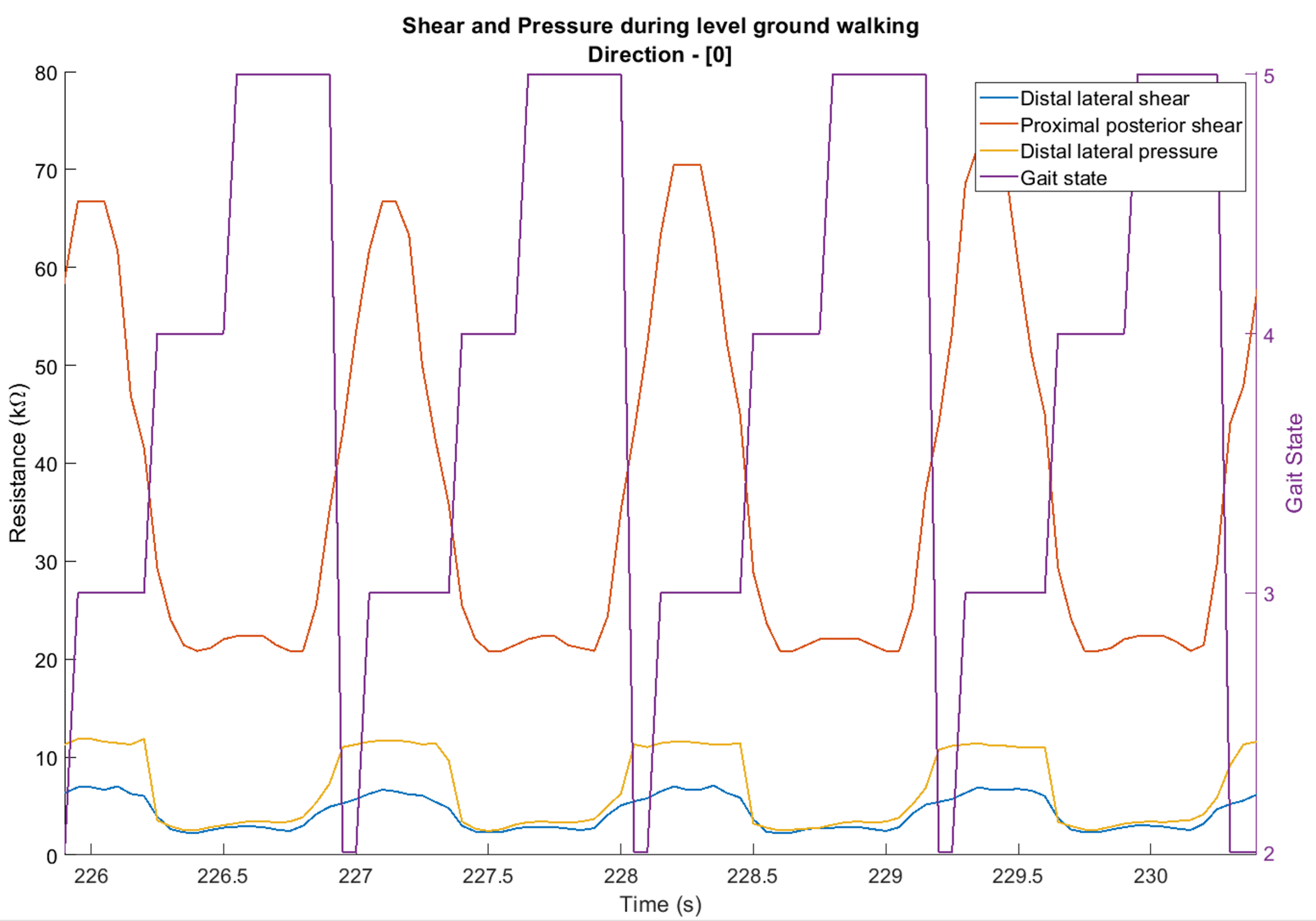

Figure 2: Shear and pressure measurements during level ground walking at self-selected walking speed.
Gait states: 2 = toe-off; 3 = swing phase; 4 = heel strike; 5 = stance phase.

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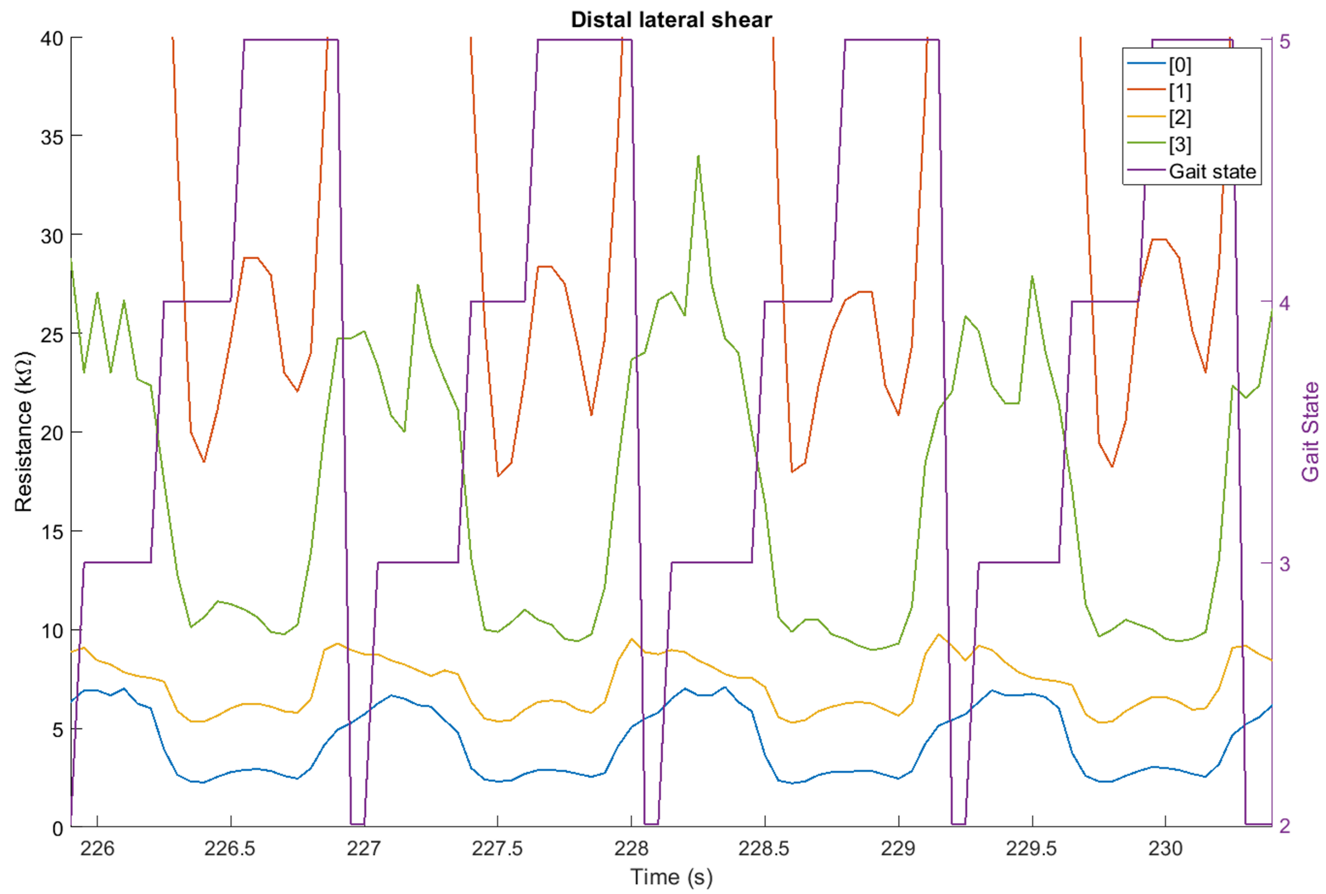

Figure 3: Four directions (0-3) of distal lateral shear stress during level ground walking at self-selected walking speed. Gait states: 2 = toe-off; 3 = swing phase; 4 = heel strike; 5 = stance phase.

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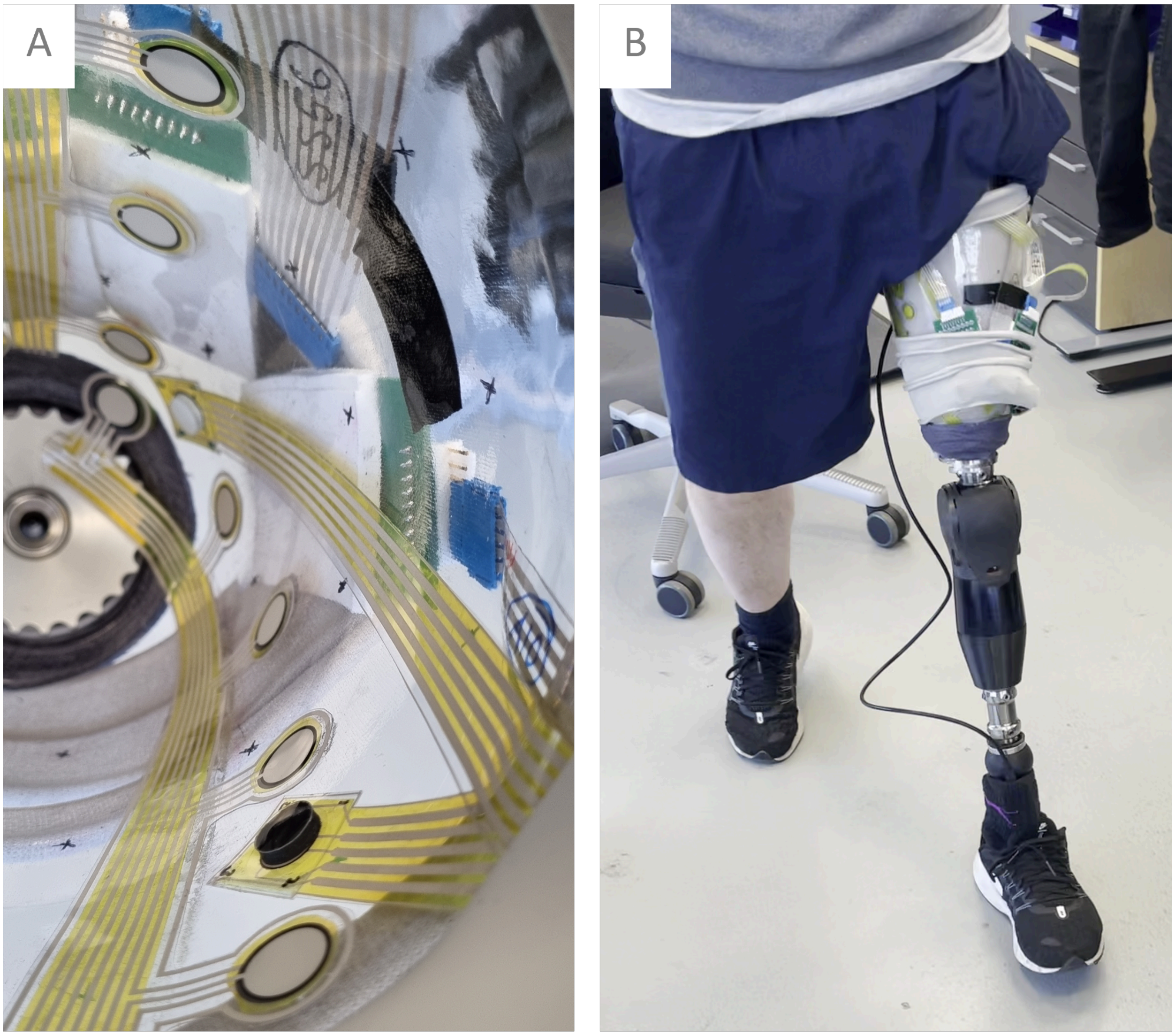

Figure 4 (A): Printed shear and pressure sensors integrated inside socket. (B): Test subject wearing prosthesis with sensors integrated in a transparent replica socket.