Types of transducers for interface pressure and shear stress measurements within (transtibial) prosthetic sockets

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“Types of transducers used for interface pressure and shear stress measurements within below-knee (transtibial) prosthetic sockets and their relative merits and demerits”

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More details about the working principles, advantages and disadvantages of such transducers can be found in [1].

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### Table 1: Strain gauge-based transducers

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<th>Transducer Type</th>
<th>Structure and Mounting Technique</th>
<th>Parameters to Measure</th>
<th>Merits</th>
<th>Demerits</th>
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<tr>
<td><strong>Diaphragm SG</strong></td>
<td>(i) A circle-shaped sensing element with a diameter and thickness of 3.2 and 0.8 mm, respectively, and a four conductor ribbon cable of 0.5 mm thickness is attached to its bottom surface. (ii) It is a monolithic integrated circuit Wheatstone bridge formed directly on a silicone diaphragm. (iii) It could be inserted within the socket. (iv) No longer used.</td>
<td>(i) Strains (ii) Forces (iii) Direct pressures</td>
<td>(i) Simplicity, (ii) High sensitivity, (iii) Light weight</td>
<td>(i) Its stiff backing mismatches with the residual limb tissues, causing stress concentrations at the sensor edges, (ii) Loads are measured at isolated sites, (iii) When put in an array of sensing elements. It would be subjected to crosstalk due to its rigidity and the cables restrict the subject movement which alters the amputee’s normal gait.</td>
<td>[2, 3]</td>
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<td><strong>Piston-type SG</strong></td>
<td>(i) Small patches of silicone or metal, (ii) An assembly of SG sensing elements and cylindrical piston are configured in a cylinder-like housing, and (iii) Mounted onto the socket wall in locations of significance through drilled holes</td>
<td>(i) Forces (ii) Normal and shear stresses</td>
<td>(i) High sensitivity and accuracy (ii) No crosstalk and edge stress concentrations</td>
<td>(i) Holes in the socket wall alter the pressure distribution, (ii) Bulky size, (iii) The data cables increased the prosthesis weight, distorting the stress measurement. (iv) Require a relatively more power to operate.</td>
<td>[4-7]</td>
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<td>Single-point FSRs</td>
<td>(i) A sensitive element in form of an elastomer, conductive ink, conductive rubber, or carbon fiber that is sandwiched between two layers of flexible polyester films glued by an adhesive to form a piezoresistive pressure sensor. (ii) Positioned in-situ within the prosthetic socket.</td>
<td>(i) Forces, (ii) Direct contact pressures</td>
<td>(i) Thin construction, (iii) Flexibility, (iv) Good sensitivity, (v) simple structure, (vi) Ease of use, (vii) Available in various shapes and sizes</td>
<td>(i) Covers a very small sensing surface</td>
<td>[8, 9]</td>
</tr>
<tr>
<td>Array of Piezoresistive (Most commonly used within prosthetic sockets)</td>
<td>(i) Constructed of 96 individual sensing points (sensels) arranged in a matrix of 16 rows and 6 columns. (ii) Could be within prosthetic sockets.</td>
<td>(i) Direct contact pressures, (ii) Forces.</td>
<td>(i) Requires no modifications in sockets, making them superior over piston-type SGs, (ii) Provides higher spatial resolution, (iii) Satisfactory reproducibility and sensitivity, (iv) Flexibility, thin structure, and simple electronics</td>
<td>(i) Non-linearity, (ii) Needs to be equilibrated and calibrated before each use, (iii) Drift and hysteresis, (iv) Temperature sensitivity, (v) Their disability to measure shear stresses.</td>
<td>[8, 10-15]</td>
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| Capacitive (Single sensing element) | (i) A dielectric material sandwiched between two parallel conductive surfaces. (ii) Could be mounted within and/or outside below-knee sockets. | (i) Forces  
(ii) Pressures  
(iii) Displacement | (i) Flexibility  
(ii) The operational accuracy was ±20% | (i) Their use in prosthetic sockets was limited due to their rigid substrates that do not comply with the residual limb geometry.  
(ii) Their sophisticated manufacturing techniques hindered low cost fabrication of multiple sensor arrays. | [16-21] |
| “Novel” Capacitive (Array) | (i) A matrix array of 16 sensing sites (4 × 4) mounted in silicone substrate (2.5 cm × 2.5 cm) with a thickness of 0.63 mm. (ii) Could be inserted between the skin and liner or between the liner and socket. | (i) Interface pressures | (i) Showed no noticeable sensor drift occurred between pre- and post-test calibration.  
(ii) Good accuracy, and  
(iii) Superior to piezoresistive sensors | (i) Still unidirectional, measuring only direct pressures | [15, 22] |
‘Table 3, Continued’

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<td><strong>3-D printed Capacitive</strong></td>
<td>(i) A flexible frame (20 mm × 20 mm), with thickness of 4 mm. (ii) Could be within prosthetic sockets</td>
<td>(i) Interface normal and shear stresses</td>
<td>(i) Low-cost and versatile solution with capability of adopting irregular shapes. (ii) Small in size (iii) Higher sensitivity and flexibility, lower temperature dependency, more robust structure, lower power consumption, better frequency response and a larger dynamic range than piezoresistive devices.</td>
<td>(i) Their susceptibility to crosstalk noise, (ii) Require more sophisticated electronics</td>
<td>[23]</td>
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Table 4: Fibre-optic transducers

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<tr>
<td>Fibre-optics</td>
<td>(i) The optical fiber based sensors (FBG) has a longitudinal periodic variation of the refractive index ( n_{eff} ) written in the core of optical fiber for generating the required spatial pattern. When an optical fiber with an FBG is coupled to a light source and subjected to any external mechanical forces, the light passing through it will be back-reflected by the FBG itself at a Bragg wavelength, ( \lambda_B ), depending on the spacing between the periodic variations and the strain-optic effect. (ii) Could be inserted inside sockets, embedded in the socket wall, or embedded in the prosthetic silicone liners</td>
<td>(i) Strains, (ii) Forces, (iii) Normal &amp; shear stresses, (iv) Vibration, (v) Temperature, etc..</td>
<td>(i) High sensitivity, (ii) durability, (iii) immunity to electromagnetic interference (EMI), (iv) multiplexability, (v) and resistant to harsh environments</td>
<td>(i) Full operation might be hampered due to any damage to the optical fiber.</td>
<td>[24-28]</td>
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<td>Optoelectronic</td>
<td>(i) Made of an external silicone bulk structure and a printed circuit board which accommodates an array of sensitive elements (LEDs &amp; Photodiodes). (ii) Could be inserted inside sockets or embedded in the prosthetic silicone liners</td>
<td>(i) Normal and shear stresses, (ii) Displacement</td>
<td>(i) Accuracy, and (ii) Sensitivity</td>
<td>(i) Susceptible to EMIs (ii) Bulky</td>
<td>[29, 30]</td>
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References:


