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A mechanical-electrophysiological membrane model for axonopathy

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Electrophysiological alterations are commonly observed in mechanically induced axonal injury [1]. Recent research efforts have focussed on primary injuries by making use of numerical models aimed at simulating such functional deficits. The overwhelming majority of these primary injury models only consider axonal stretching as a loading mode, while other modes of deformation such as crushing or mixed modes—highly relevant in traumatic brain injury and spinal cord injury —are not modelled. To this end, we propose a novel 3D finite element framework coupling mechanics and electrophysiology by considering the electrophysiological Hodgkin-Huxley and Cable Theory models as surface boundary conditions introduced directly in the weak form, hence eliminating the need to geometrically account for the membrane in its electrophysiological contribution. After verification, the approach is leveraged to i) model an idealised axonal dislocation injury and ii) study the mechanical-electrophysiological coupling in voltage clamp of axonal membrane.

The results of the axonal dislocation injury model show that the sole consideration of induced longitudinal stretch following transverse loading of a node of Ranvier is not necessarily enough to capture the extent of axonal electrophysiological deficit. Additionally, the non-axisymmetric loading of the node participates to a larger extent to the subsequent damage. On the contrary, a similar transverse loading of internodal regions was not shown to significantly worsen with the additional consideration of the non-axisymmetric loading mode. The results of the voltage clamp model show that the geometrical changes caused by suction applied to the membrane (part of the experimental protocol) may offer an alternative explanation to the electrophysiological "left-shift" observed by Wang et al. [2].

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