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Title
A Novel Simulation-Based Workflow for the Planning of CFRP Layup in Prosthetic Sockets for the Lower Extremity

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Summary
The present study aims to define a virtual workflow that can be used for the mechanical evaluation, failure analysis and the planning of carbon fiber layup of CFRP prosthetic lower limb sockets to improve structural integrity and reduce material usage.

Introduction/ basics
Carbon fiber-reinforced polymer (CFRP) composites are utilized in the manufacturing of prosthetic limb sockets due to their desirable mechanical properties such as, flexibility, high strength and lightweight. The design of such prosthetic sockets however, traditionally rely on the experience of the prosthetists and the feedback from the amputated patients. Moreover, there is a general lack of mechanical understanding of load bearing capacities of prosthetic components in everyday use. This often leads to overestimation of socket geometry, suboptimal utilization of the CFRP’s mechanical properties and thus, excessive material usage and higher production costs. In the following study, we aim to address these issues by defining a simulation-driven, virtual workflow that can be employed to analyse the failure mechanisms and assist prosthesists to determine the optimum fibre layup of CFRP prosthetic sockets for the lower extremity.

Material method; implementation/ process
The Finite-Element (FE) analyses of the prosthetic socket are conducted using LS-DYNA. The estimation of maximum load-bearing capacity of the socket requires an accurate representation of socket geometry and material failure. The interaction with a residual limb during loading is critical for prediction of failure zones. Such an artificial residual limb is designed using available socket geometry and common polymers, modelled as hyperelastic and linear elastic materials

(Fig 1). The simulations involve loading of the socket until it loses its structural integrity (Fig 2) and are based on the critical loading scenarios that take place during gait, namely, mid-stance, heel-strike and toe-off. The socket is assigned with orthotropic, linear-elastic material properties and failure criteria based on individual matrix and fiber strength. The optimal composite layup is then determined by quantitatively mapping the principal stress directions occurring on the mentioned loading cases (Fig 3).

Results

The FE simulations of socket failure predict deformation and structurally weak zones under static and dynamic loading, including the influence of varying socket-limb orientations occurring during gait. As a basis for planning CFRP sockets, the failure analysis was first carried out using epoxide resin DT121R as the socket material. Due to the brittle nature of the resin, the socket has shown tensile dominated failure originating firstly at the distal-end for all the three load cases (Fig 2). Toe-off loading scenario has shown relatively higher load-bearing capacity compared to the mid-stance and heel strike variants. Subsequently, the first principal stress trajectories of the resulting simulations have been extracted from the results and used in the quantitative mapping of unidirectional carbon fibres over the epoxide resin. The determined prepreg configuration was re-analysed with the composite material model and led to delayed crack initiation and higher failure loads. In order to observe the benefits of determined carbon fiber layout, another CFRP socket variant, employing fiber orientations 45° to the craniocaudal axis, has been simulated. The results show that, the optimal CFRP layup obtained from the workflow, exhibits higher load-bearing capacity and delayed crack initiation compared to all previous variants in all load cases (Fig 4).

Discussion/ conclusion; conclusion for the practice

We have introduced physics-based simulation workflow for the structural evaluation and fiber planning of CFRP prosthetic sockets. The attention has been paid to form a simulation environment that can be actualized in real world. Using 3-D printable materials and simplified geometrical estimations, the suggested simulation workflow is a potential precursor to experimental determination and validation of the structural integrity of CFRP socket and the planning of the composite layup. Identification of potentially weak zones and load-bearing capacities would significantly improve the structural behaviour of the CFRP-based sockets and can limit the need for physical testing of prototypes. This would allow prosthetists and orthotists to evaluate design variants virtually and reduce the overall lead-time for manufacturing. The fiber orientations determined via the workflow yields an optimal CFRP layup and enables the design of structurally adequate sockets using lesser material. The workflow also lays the groundwork for potential definition of standards related to safety of CFRP prosthetic socket usage under varying operational conditions.

References

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Image: Fig1_Simulation_Model_191.png

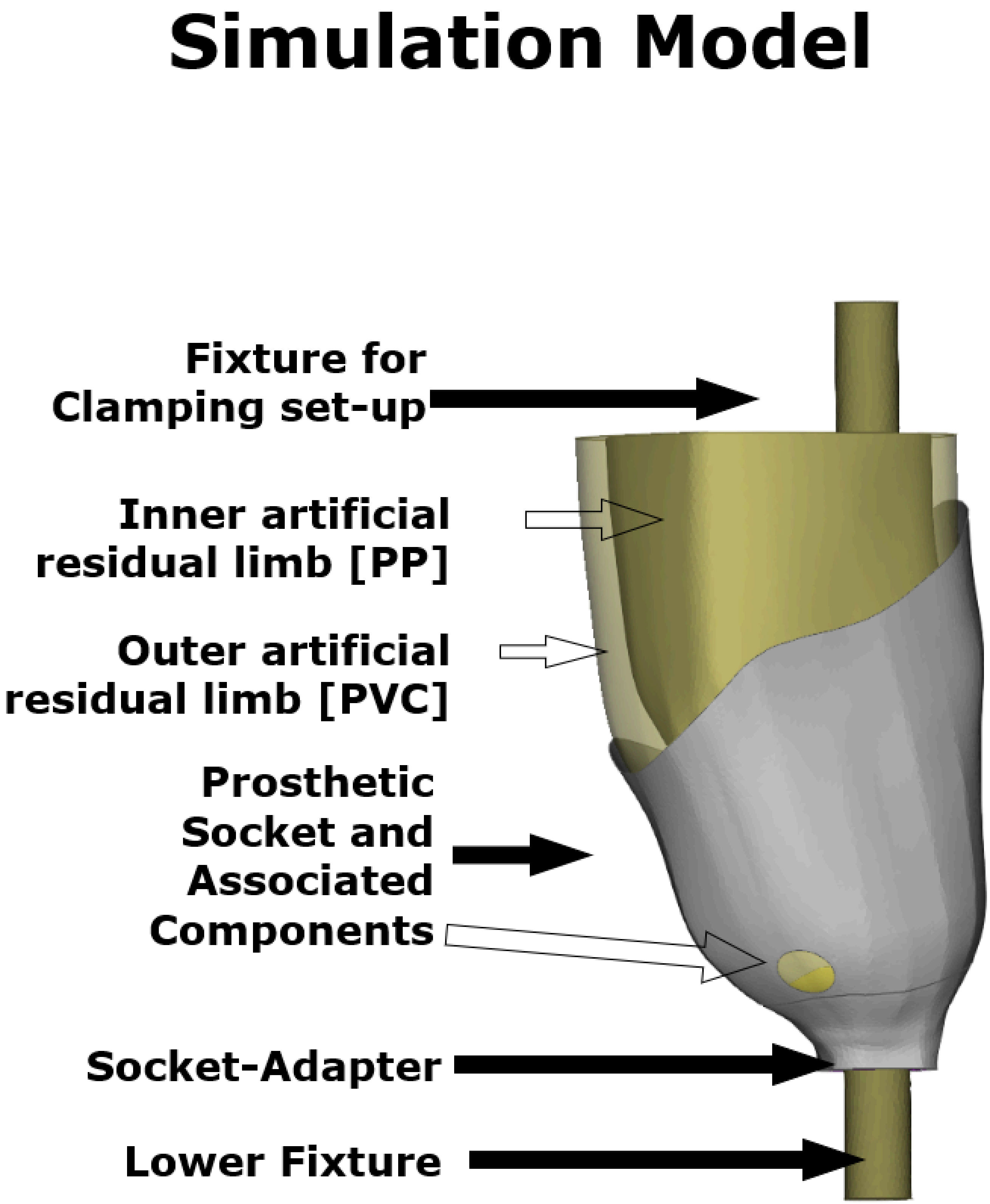

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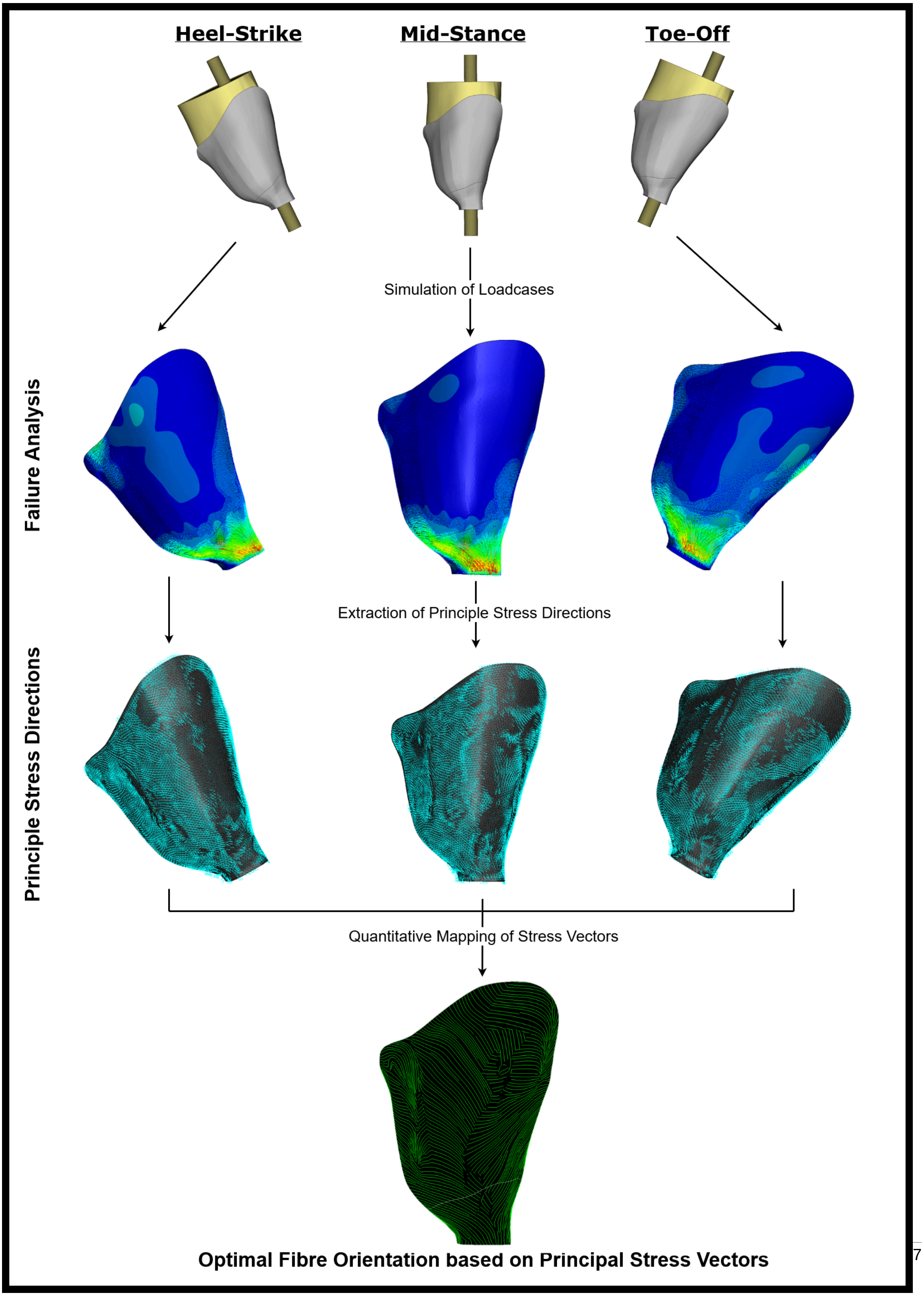
Image: Fig3_Socket_Workflow_193.png



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