Doctoral Dissertation
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Modelling the Physical Human-Exoskeleton Interface

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Summary

Development of exoskeletons has seen a boom in the last few years, and they are seeing increasing adoption in industrial and medical/rehabilitative fields. The design and assessment of exoskeletons have benefitted through virtual multibody models. The use of musculoskeletal models to evaluate the combined human-exoskeleton system allows estimating the effect of the exoskeleton on the user. However, models to investigate the physical human-exoskeleton interface are lacking. The use of contact models to investigate the interface properties is almost non-existent, even though they are used extensively in other applications in musculoskeletal models, e.g., ground reaction force prediction. The human-exoskeleton interface is generally simulated through reaction forces associated with kinematic joints that are used to constrain the exoskeleton to the user. The reaction forces can only provide limited information about the interface forces. However, the interface forces are of interest as they affect the overall comfort of the user and are being investigated to establish thresholds for discomfort.

Thus, the aim of this dissertation is to use a contact model, validated extensively in ground reaction force prediction, to simulate the forces at the human-exoskeleton interface. The contact model estimates the contact forces through contact elements that are configured to estimate the normal and frictional forces. The contact model is characterized by a coefficient of static friction and a maximum force-generating capacity of the contact elements (or the strength of the elements). The contact forces are estimated as the solution of an optimization problem that aims to minimize the activation of the contact elements and the muscles of the human model. The contact model could provide additional information about the interface forces that could be used to optimize the interface design. This thesis describes the application of the contact model in the context of the human-exoskeleton interface. Furthermore, the results of the contact model are

compared to those from the conventional model of simulating the human-exoskeleton interface forces through the kinematic joints.

The thesis was developed over three studies that progressed in complexity from the simulation of a single interface as a planar surface, then as a curved surface, and finally the simulation of multiple curved interfaces. In the first study, the existing contact model was applied as it is to simulate the interface of a lower limb exoskeleton, the Chairless Chair. The exoskeleton has a simple interface that offered similar conditions to the existing use case of the contact model. In this study, the exoskeleton was trialled by a subject simulating three different postures and body weight distribution between the user and the exoskeleton was used as a reference for the interface forces from the contact and conventional models. Both the contact and conventional model were able to capture the change in the body weight distribution with the change in posture. However, the conventional model showed an unreasonable reduction in the knee extension moment in more challenging postures, where a greater knee extension moment was expected. Further, parameters of the contact model, such as the coefficient of friction and the angle of contact, were investigated. The support from the exoskeleton dropped sharply for friction coefficients lower than 0.4 at the interface. The contact model also showed the dependence of the effectiveness of the exoskeleton on the angle of contact such that a more horizontal angle of contact required a lower friction coefficient for the exoskeleton model to support the user.

The second study aimed to simulate the seat of the Chairless Chair as a generalized curved surface since the angle of contact influenced the model results. This was done by simulating the surface of the seat through multiple planar surfaces distributed over the seat, each with its unique orientation. The discretization resulted in unrealistic solutions that required the optimization of the strength of the contact elements. The strength of the contact elements was optimized by considering only the virtual centre of pressure and predicted body weight distribution. The results of the contact model were compared with the results obtained from a pressure mat placed at the interface and the body weight distribution in three different use cases of the exoskeleton. The centre of pressure and the body weight distribution from the optimized contact model showed good agreement with the empirical measures.

The necessity to optimize the contact model in the second study motivated the third study where the contact model was implemented on another exoskeleton. The second exoskeleton is an active exoskeleton for the lower limb and consists of three interfaces that provided a 360° contact with the thigh, shank, and foot. Mocap data from eight trials were used as an input in the model. The contact model at multiple interfaces exploited the misalignments in the human and exoskeleton joints to unload the physiological muscles. A method is presented to ensure kinetic alignment between the human and exoskeleton, which prevents the contact elements from unloading the physiological muscles. The results of the contact and conventional model were compared to a reference model where the exoskeleton assistance was applied directly to the human model. The biomechanical outputs, such as the moments or the compression force at the knee and ankle joints, showed good agreement between the contact and reference model. In general, the contact model showed more consistent results than the conventional model and provided more information about the interface forces than the conventional model, which was limited to only eight reaction forces.

In conclusion, the contact model was applied to two different exoskeletons that could be representative of the interface conditions of several exoskeletons. The thesis provides methods to successfully apply the contact model in different interface conditions. However, the contact model is limited as it simulates contact between rigid bodies and cannot account for compliance at the human-exoskeleton interface. Open issues concerning the validity of the contact forces and the ability to account for the undesired interface forces due to the misalignments between the human and exoskeleton in the contact model still remain. These topics could be of interest for future studies.