Author
Tryggvason, Heimir (Reykjavík IS)
University of Iceland - Faculty of Industrial Engineering, Mechanical Engineering and Computer Science

Title
Enhancement of prosthetic foot design – Linking mechanical gait test method and FE model for simulation of stiffness response

Coauthors
Starker F, Jónsdóttir F, Lecomte C

Summary
The research is based on a finite element (FE) model of a known prosthetic foot design, which is validated by mechanical testing of the actual product. The model is used to define the stiffness characteristics of the foot and further enhanced to simulate a controllable stiffness element in the foot.

Introduction
Adaptive prosthetics that suit a range of activities will improve the quality of life for the user. The human ankle and limb adapts dynamically to terrain and variations in pace [1, 2] and imitating this function calls for prosthetic feet that have real-time variable stiffness.
The goal with this research is to use modelling to develop an actively controlled prosthetic that adapts dynamically to the users' needs. Determining the optimal stiffness of prosthetic feet is still a process of repetitive prototyping and user testing, relying highly on users' feedback. Standardized mechanical testing and FE analysis as methods to optimize the stiffness characteristics of a prosthetic foot will partly remove uncertainties associated with subjective testing. The standardized testing can be viewed as a step between simulations and patient based user tests that provides consistent results and a less complex way of understanding and improving the stiffness of prosthetic feet.

Methods
The approach for this study is to use a combination of mechanical testing and finite element analysis. A new ESAR foot was selected as a subject for the analysis as an example of a passive prosthetic foot design. The mechanical characteristics were determined using a

dynamic test machine. The overall quasi stiffness was measured according to a standard for structural testing of lower-limb prostheses (ISO10328). Secondly, dynamic tests are made according to standard (ISO/TS 16955) assessing performance indicators of prosthetic foot devices.

A FE model (ANSYS) was constructed with the purpose to serve as a framework for experimenting with varying function, as well as additional elements, to improve the characteristics of the prosthetic design (see attached image of simulation). Both static and dynamic simulations were carried out. The simulation results were validated by comparison with the results from the mechanical testing.

Results

Mechanical tests and simulation showed comparable results for a full roll-over test of the subject. For the initial set parameters of the load vs. rotation profile in dynamic testing, an accuracy of better than +/- 1 % of the maximum force value was achieved. The overall correlation between measurements and simulation are within required parameters for a valid comparison and evaluation of shifts in the curves as design alterations are modelled.

Model modifications focus on introducing an additional spring and dampening element in the foot design allowing for a greater range of motion. Initial parameters for spring stiffness and damping for the new joint is chosen as a moderate change for controlled adjustment steps towards a modified function i.e. a relatively high spring constant and low damping coefficient. The quasi stiffness curve shows similar characteristics with a reduced peak stiffness at heel strike and a softer late stance, due to the higher range of motion in the pivot within the prosthetic foot model and a deflection of the spring and damper element.

Comparing all data shows that the modified prosthetic foot does not evenly change its stiffness as it would by using softer carbon fiber spring blades. The spring-damper system in combination with the carbon fiber springs alters the overall transition and mechanical behavior of the foot.

Conclusion

The study has shown that the standardized test procedure can be simulated and modifications to the model show anticipated shifts in function. The proposed method will increase the potential of FE modeling in the prosthetic design process. Further work is aimed at modeling the desired shift in function of the modified foot for different displacement rates and parameters for the spring/damper element.

Ongoing research has to prove the links between these mechanical characteristics and different groups or the individual amputees. Nevertheless, the FE simulation model showed high correlation with the machine test results. Some differences can be explained by the use of a cosmetic cover within the machine test to allow for a defined friction. The FE model seems highly capable to optimize the application of new non-linear function in the foot.

Comparison and interpretation of simulation results against standardized test machines is more practical than to traditional gait data. Further studies have to connect prototypes to the user experience and close the methodological development loop. Subsequently, this will also provide a link back from the user data directly to mechanical characteristics of prosthetic feet for further benefit for patient as specific preferences for prosthetic response can be modeled for validity before implementing.

References

[1] Jin, L., Adamczyk, P. G., Roland, M., & Hahn, M. E., 2016, “The effect of high- and low-damping prosthetic foot structures on knee loading in the uninvolved limb across different walking speeds”, Journal of Applied Biomechanics, 32(3), pp. 233–240.

[2] Hunter, L. C., Hendrix, E. C., & Dean, J. C., 2010, “The cost of walking downhill: Is the preferred gait energetically optimal” Journal of Biomechanics, 43(10), pp.1910-1915.

Image: ESAR Simulation_2108.jpg