Connecting Mechanical Properties to Biomechanical Performance of Prosthetic Feet via Fundamental Principles to Design Customized, Passive Devices

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This talk will present a method for quantitatively connecting the mechanical design of prosthetic feet to the biomechanical performance they induce, in order to optimize passive, compliant feet that can enable physiological kinematics and kinetics. Our optimization metric, called Lower Leg Trajectory Error (LLTE), compares motion of the prosthetic shank to able-bodied lower leg kinematics while the foot is loaded with physiological ground reaction forces (GRFs). The LLTE method enables the foot to be viewed as a "black box" that does not necessarily have to behave like a physiological foot; our hypothesis is that as long the shank – the last part of the prosthesis connected to the patient's natural body - experiences the correct loading and motions of an able-bodied lower leg, the user will feel as if they are walking normally. The theory behind LLTE, foot prototypes optimized using the metric, and experimental results will be presented.

The gait of individuals with below-knee amputation is inferior to that of able-bodied individuals in terms of mechanical and metabolic efficiency, primarily due to the limitations of commonly prescribed prostheses that promote compensatory mechanisms at the sound limb, hips, and trunk to maintain forward ambulation [1]–[15]. There is substantial evidence to suggest that the mechanical function of a passive below-knee prostheses affects walking mechanics and efficiency of users [1]–[5], [11]–[13]. However, *how* the mechanical features of a passive prosthesis affects walking functionality is not fully understood [9]. There is currently a knowledge gap about the relationship between a foot's stiffness and geometry, it's interaction with the ground and momentum transfer, and lower leg kinematics [7], [16], [17].

Our novel optimization metric, LLTE [18], provides a quantitative connection between the stiffness and geometry of a prosthetic foot and its biomechanical performance. LLTE is calculated by applying GRFs between an able-bodied foot and the ground to a model of a prosthetic foot through the stance phase of gait. The resulting prosthetic foot deflection, and thus the temporal position of the lower leg segment (shank), is computed during a step. The error between these data and the horizontal and vertical position of the knee, as well as the orientation of the lower leg segment relative to vertical of the able-bodied leg progressing through a step under the same loads, is then evaluated using a root mean squared error (RMSE) function to produce the LLTE. A foot that yields LLTE ≈ 0 is desired, as it means the prosthetic leg will follow an able-bodied kinematic trajectory under able-bodied loading. The LLTE-based design optimization process creates a parametric relationship between the stiffness and geometry of the prosthetic foot, and the resulting leg motion to replicate normative kinematics.

Our LLTE metric far exceeds the capabilities of "roll-over geometry" – a commonly used design objective and evaluation metric for passive prosthetic feet – which only accounts for x-y position of the center of pressure (CoP) with no relation to the lower leg orientation in the laboratory reference frame [19]. Roll-over geometry also does not provide any temporal information on CoP progression from initial-contact to toe-off. LLTE enables the prediction of both the spatial and temporal position of the entire lower leg through a step.

A proof-of-concept prosthesis prototype – consisting of a rotational pin joint at the ankle with interchangeable springs to vary ankle stiffness, and a flexible cantilever beam forefoot – was tested with two different ankle stiffness conditions near the optimal predicted by our LLTE-based optimization. The test subject with a unilateral transtibial amputation was approximately the same size and weight as the able-bodied subject from whom physiological data were used in our LLTE-based design optimization of the prototypes. The experimental data showed that measured ground reaction forces, center of pressure position, and lower leg trajectory were all very close to the able-bodied data that the foot was designed to replicate (Fig. 1).

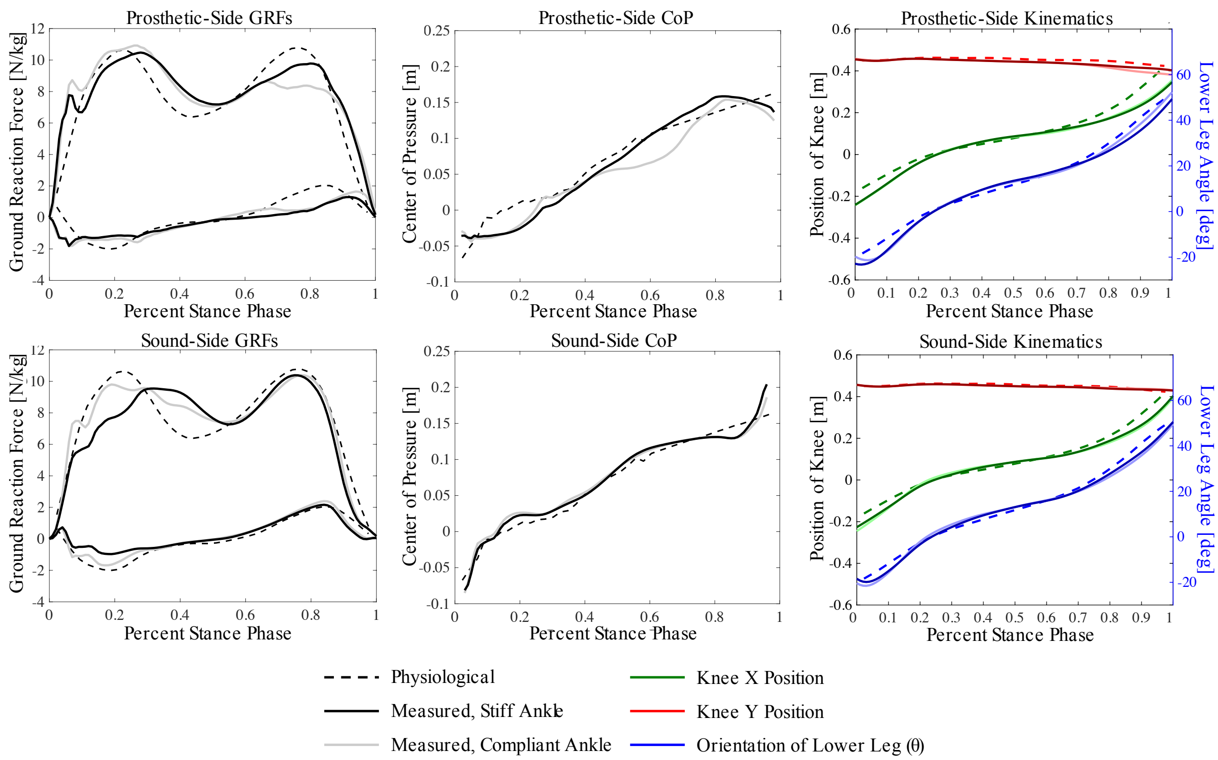

Figure 1 Measured (solid lines) ground reaction forces, center of pressure, and lower leg position throughout stance phase for both compliant and stiff experimental prototype feet compared to physiological data. The physiological data were used as inputs in the LLTE-based design optimization.

The data in Fig. 1 make us confident that able-bodied GRFs and CoP positions can be used as inputs to the LLTE model rather than amputee-specific data, given the accuracy with which the prototype feet were able to replicate physiological profiles and retain bilateral loading symmetry. We expect that future, further optimized feet that approach an LLTE-optimal design (of LLTE $\approx$ 0), will have measured GRFs and CoP progression that are even closer to able-bodied values. When the GRFs and CoP positions measured while testing the two foot prototypes are used as inputs to our model of foot deflection, rather than previously published physiological data, our model is able to predict prosthetic-side knee position to within a maximum error of 1.2 cm and the lower leg segment orientation to within 1.6 deg. These results demonstrate that our LLTE-based design optimization method provides a fully analytical constitutive relationship between the loading inputs and kinematic outputs of the lower leg, enabling us to quantitatively describe the relationship between the mechanical design of the foot and its biomechanical performance when used by an amputee.

References

[1] H. Houdijk, E. Pollmann, M. Groenewold, H. Wiggerts, and W. Polomski, "The energy cost for the step-to-step transition in amputee walking," *Gait Posture*, vol. 30, no. 1, pp. 35–40, 2009.

[2] P. G. Adamczyk and A. D. Kuo, "Mechanisms of gait asymmetry due to push-off deficiency in unilateral amputees," *Neural Syst. Rehabil. Eng. IEEE Trans.*, vol. 23, no. 5, pp. 776–785, 2015.

[3] K. E. Zelik, S. H. Collins, P. G. Adamczyk, A. D. Segal, G. K. Klute, D. C. Morgenroth, M. E. Hahn, M. S. Orendurff, J. M. Czerniecki, and A. D. Kuo, "Systematic variation of prosthetic foot spring affects center-of-mass mechanics and metabolic cost during walking," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 19, no. 4, pp. 411–419, 2011.

[4] E. Klodd, A. Hansen, S. Fatone, B. P. O. Hons, and M. Edwards, "Effects of prosthetic foot forefoot flexibility on gait of unilateral transtibial prosthesis users," *J. Rehabil. Res. Dev.*, vol. 47, no. 9, pp. 899–910, 2010.

[5] E. Klodd, A. Hansen, S. Fatone, and M. Edwards, "Effects of prosthetic foot forefoot flexibility on oxygen cost and subjective preference rankings of unilateral transtibial prosthesis users," *J. Rehabil. Res. Dev.*, vol. 47, no. 6, pp. 543–552, 2010.

[6] K. Postema, H. J. Hermens, J. De Vries, H. F. J. M. Koopman, and W. H. Eisma, "Energy storage and release of prosthetic feet Part 1: biomechanical analysis related to user benefits," *Prosthet. Orthot. Int.*, vol. 21, pp. 17–27, 1997.

[7] C. Hofstad, H. Van Der Linde, J. Van Limbeek, and K. Postema, "Prescription of prosthetic ankle-foot mechanisms after lower limb amputation (Review)," *Cochrane Libr.*, no. 1, 2009.

[8] M. J. Major, M. Twiste, L. P. J. Kenney, and D. Howard, "The effects of prosthetic ankle stiffness on ankle and knee kinematics, prosthetic limb loading, and net metabolic cost of trans-tibial amputee gait," *Clin. Biomech.*, vol. 29, no. 1, pp. 98–104, 2014.

[9] N. P. Fey, G. K. Klute, and R. R. Neptune, "The influence of energy storage and return foot stiffness on walking mechanics and muscle activity in below-knee amputees," *Clin. Biomech.*, vol. 26, pp. 1025–1032, 2011.

[10] R. L. Waters, "The Energy Expenditure of Amputee Gait," pp. 1–9.

[11] X. Bonnet, C. Villa, P. Fode, F. Lavaste, and H. Pillet, "Mechanical work performed by individual limbs of transfemoral amputees during step-to-step transitions: Effect of walking velocity," *Proc. Inst. Mech. Eng. H.*, vol. 228, no. 1, pp. 60–66, 2014.

[12] M. J. Nederhand, E. H. Van Asseldonk, H. van der Kooij, and H. S. Rietman, "Dynamic Balance Control (DBC) in lower leg amputee subjects; contribution of the regulatory activity of the prosthesis side," *Clin. Biomech.*, vol. 27, no. 1, pp. 40–45, 2012.

[13] M. J. Major, L. P. Kenney, M. Twiste, and D. Howard, "Stance phase mechanical characterization of transtibial prostheses distal to the socket: a review," *J. Rehabil. Res. Dev.*, vol. 49, no. 6, pp. 815–829, 2012.

[14] J. Perry and J. Burnfield, *Gait Analysis: Normal and Pathological Function*, 2nd ed. Thorofare, NJ: Slack Incorporated, 2010.

[15] M. J. Major, R. L. Stine, and S. A. Gard, "The effects of walking speed and prosthetic ankle adapters on upper extremity dynamics and stability-related parameters in bilateral transtibial amputee gait," *Gait Posture*, vol. 38, no. 4, pp. 858–863, 2013.

[16] B. J. Hafner, "Clinical Prescription and Use of Prosthtic Foot and Ankle Mechanisms: A Review of the Literature," *J. Prosthetics Orthot.*, vol. 17, no. 4, pp. S5–S11, 2005.
[17] V. Der Linde, J. Cheriel, and C. H. Alexander, "A systematic literature review of the effect of different prosthetic components on human functioning with a lower-limb prosthesis," *J. Rehabil. Res. Dev.*, vol. 41, no. 4, pp. 555–570, 2004.
[18] K. M. Olesnavage and A. G. Winter, "Correlating mechanical design of passive prosthetic feet to gait kinematics using a novel optimization parameter: lower leg trajectory error." In Revision.
[19] a. H. Hansen, D. S. Childress, and E. H. Knox, "Prosthetic foot roll-over shapes with implications for alignment of trans-tibial prostheses," *Prosthet. Orthot. Int.*, vol. 24, no. 3, pp. 205–215, Jan. 2000.