Continuous Phase-Varying Impedance Control of a Knee-Ankle Prosthesis for Incline Walking

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I. Introduction

The development of intuitive, natural, and safe control strategies for robotic leg prostheses is critical to their success, but challenges in tuning these control strategies for each user and activity hinder translation. Impedance control is a promising control strategy because of its ability to replicate the natural dynamics of the healthy human body, provide compliant ground interaction, and maintain locally passive closed-loop behavior. However, manual tuning of impedance control parameters can require many hours of adjustment from experienced researchers [1] that may be infeasible for widespread use. In this work, we automated the parameter tuning process by prescribing a functional relationship between the gait cycle phase and the impedance controller parameters. An offline optimization technique was used to find impedance parameter functions that best replicated the observed kinetics given the kinematics from a dataset of able-bodied walking for various inclines. The impedance parameter functions were then tested in a preliminary level ground walking experiment and were shown to produce torque angle relationships resembling able-bodied data.

II. Methods

An impedance relationship for the joint torque τ at the knee and ankle during the stance phase was designed as

$$\tau = K_\gamma(s)(\theta_{\text{eq},\gamma}(s) - \theta) - B_\gamma(s)\dot{\theta}, \qquad (1)$$

where the joint stiffness $K_\gamma(s)$, damping $B_\gamma(s)$, and equilibrium angle $\theta_{\text{eq},\gamma}(s)$ are functions of gait cycle phase s and are unique to a specific incline γ. The impedance parameters were constrained to vary linearly with phase.

For each subject and incline combination in an able-bodied dataset [2], the impedance parameter functions for the knee and ankle were optimized such that the root mean squared error between the dataset joint torque and the corresponding joint torque calculated using (1) was minimized. Inequality constraints $K_\gamma(s) > 0, B_\gamma(s) > 0$ were enforced for stability. Variance Accounted For (VAF) was used to quantify how well the torque estimated using (1) agreed with the torque obtained from the dataset for each subject and incline pair. The inter-subject average of the optimized impedance parameter functions, with stiffness and damping normalized by subject mass, were calculated for each incline and implemented on a powered prosthesis. A single able-bodied subject then walked with the prosthesis on a level treadmill at 1.0 m/s for 69 strides.

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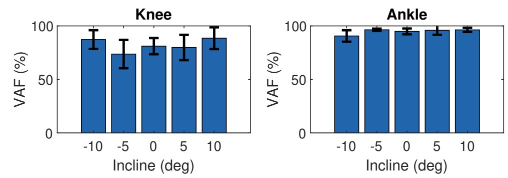

Fig. 1. The inter-subject mean Variance Accounted For (VAF) at each incline. The high VAF indicates that the forms of the impedance parameter functions capture the variability of the dataset.

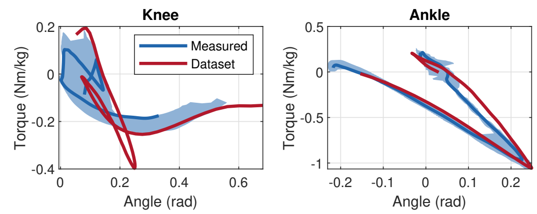

Fig. 2. The mean torque angle curves (blue) produced by the stance controller during the walking experiment. The transparent blue area shows the envelope of all observed points. The mean closely resembles the mean dataset curve (red), indicating that the control strategy is effective in reproducing biological behavior, particularly at the ankle.

III. Results & Discussion

The VAF was calculated for each subject and incline using subject specific impedance parameter functions. The high VAF (Figure 1) indicates that the impedance parameter functions agree with the joint torques and behave consistently across inclines. On average, the model accounted for 82.1% and 94.8% of torque variance at the knee and ankle, respectively. In walking trials, the controller produced biologically similar behavior, as the mean torque angle curve resembled the mean dataset curve (Figure 2). However, the variation between the knee torque angle curves suggests that nonlinear impedance parameter functions may be beneficial.

IV. Conclusion

We demonstrated a data-driven method for identifying impedance parameters and initial experimental results with an able-bodied subject. Future work will combine the incline-specific impedance parameter functions into a continuous surface parameterized by incline, walking speed, and phase.

References

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