Template-based control of prosthetic feet

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***Abstract*— In this paper, we present a novel template model-based control approach for control of ankle prosthesis. This method which is called FMCA (force modulated compliant ankle) employs ground reaction force to modulate ankle joint impedance. Inspired by our previous studies and also findings in human gaits, we know that leg force could play an important role in legged locomotion control. Here, we employed this method first on a simulation model using a neuromuscular model of human walking and then on a prosthetic foot. We showed that the same controller can assist subjects to generate normal gait patterns in walking at different speeds. Using template models which are resulted from an abstraction of complex biological models provide one simple controller which be used at different walking conditions.**

I. Motivation and Problem Definition

Generating a universal bioinspired control approach to assist healthy or impaired people in different gait conditions (e.g., speed) is challenging in gait assistance. In contrary to trajectory-based approaches [1], model-based methods [2] could potentially address the applicability of the controller in different situations. Among them, neuromuscular models [3] are useful tools for approximating human behavior to provide the required torque in assistive devices. The main barrier in using such models is their complexity which hinders researchers to apply them on systems with few degrees of freedom such as ankle prostheses. To resolve this issue, in this paper, we introduce FMCA (force modulated compliant ankle) as a template based control method to control ankle prosthesis. The simulation and (pilot) experimental results support the functionality and generalization property of this approach. Here, we considered three different motion speeds which can be controlled by a unique controller.

II. Related Work

Regarding higher energy consumption and slower self-selected speeds reported by transtibial amputees using passive Ankle devices, scholars realized that an active prosthesis needs to generate positive net work over a gait cycle. Thus, several control structures produced for these type of prosthesis like a quasi-stiffness control [4] and minimum jerk swing control [5]. An Impedance control which uses piecewise impedance function to mimic normal gait pattern is one of the most common control schemes in powered prosthesis [6], [2]. The impedance function needs to alter to adapt to the environment (e.g., terrains), to cope with undesired disturbances or to change gait condition (e.g., speed). One bioinspired approach is using neuromuscular reflex control [2] for predicting the dynamics of human gait to adapt the prosthesis controller accordingly. In such model-based control methods, human musculoskeletal model and the neural (reflex based) control [2] can be used instead of following predefined joints torques (or positions). Although the ability to predict human reaction enables this controller to be adaptive while needed, the proposed model is too complex to be preferred to simple trajectory-based approaches.

From another perspective, abstraction is a useful tool in simplifying complex model (termed Anchor models) to the template level [7]. With biomechanical template models, we can describe some significant features of locomotion with simple physical systems (e.g., Spring mass system) [7]. In [8] we introduces the FMCH (force modulated compliant hip) model as a template for posture control. In this method, the leg fore is utilized to adjust hip compliance. This approach was successfully implemented on LOPES II exoskeleton resulting in metabolic cost reduction in human walking [9]. Using leg force feedback in a simple control architecture to tune the stiffness of linear spring at hip joint could be also used for controlling other joint. In this paper this sensory information is utilized to control ankle joint impedance in a prosthetic foot.

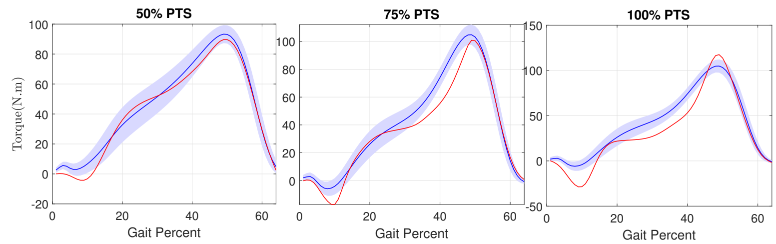

Fig. 1. Normal Torque(blue) and Estimated Torque(red) in 50,75 and 100 percent of preferred speed

III. Own Approach and Contribution

In the here presented FMCA method, the ankle torque is approximated by the ankle angle and angular velocity (as a variable impedance) which is modulated by the leg force (GRF). This model should predict required ankle torque at different speeds. The dependency of joint torques and ground reaction force at different speeds [10], [11], [12] support the idea of using GRF as a useful sensory signal which can be used to predict the required joint torques needless to

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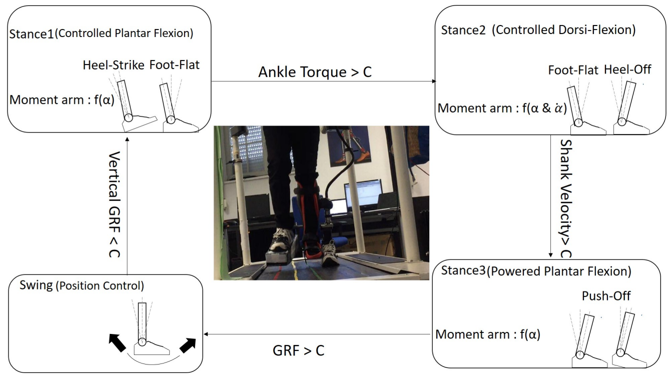

Fig. 2. FMCA Hybrid System Implemented on Spring-Active Prosthesis. The ankle angle and angular speed are shown by α and $\dot{\alpha}$, C= threshold.

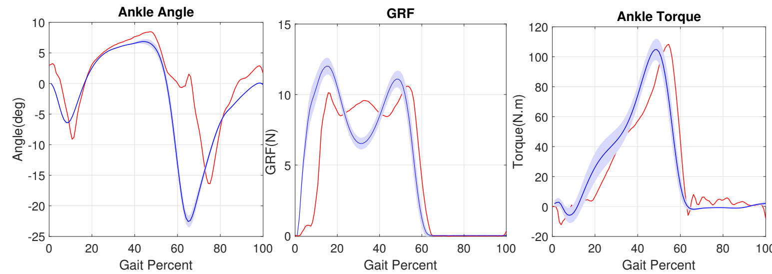

Fig. 3. Ankle Angle, GRF and Ankle Torque of Prosthetic Foot Normal (blue) , Spring-Active(red)

measure the gait speed. In this study first, we use human walking data at three different speeds from [13]. Defining PTS as the preferred transition speed between walking and running, 50%PTS, 75%PTS, and 100%PTS are utilized as a normalization tool (for comparing different human subjects) for slow, moderate and fast walking. For investigating the validity of the FMCA approach, first, we predict human ankle torque based on the measured data. By building a simple model of the foot as a spring and damper, the GRF tuned the stiffness and damping coefficients with a similar formulation for different walking speeds. For this, we estimate the moment arm at different speed by using ankle angle and angular velocity. Then by using this moment arm and multiplying to GRF, ankle torque will be achieved. Fig. 1 shows the comparison between the measured ankle torque and the approximation using FMCA.

The next step is implementing the proposed control approach on the prosthesis. We divided the stance phase into three states. Fig. 2 shows a finite state machine with a predefined threshold (C) for a transition between these three states. In each state of the stance phase, the moment arm is determined based on the ankle angle α or angular velocity $\dot{\alpha}$. The most important phase for assistance is the push-off phase which happens in the third state.

In order to implement FMCA on the prosthetic foot, we used GRF measured by an instrumented treadmill. We applied the method on the powered ankle prosthesis developed by Spring-Active. As shown in Fig. 2 the experiment was on a healthy subject while human ankle joint was bypassed and the second leg height was increased by additional foam. The experimental results are shown in Fig.3. It is observed that the ankle angle, GRF, and ankle torques are comparable with those of normal walking (from [13]).

IV. Conclusion

In this study, we showed that a template-based control can generate human-like ankle torque at a different speed. This method was successfully implemented on an ankle prosthetic foot. generating he ranges and patterns for the measured variables (GRF, ankle torque, and ankle angle) are similar to reported data for level ground walking at normal speed (75%PTS). This study is the first step in developing a template based controller for prostheses and is in line with our previous findings on exoskeletons [9]. This is a new approach in control of assistive devices which is founded on top of human-inspired control modeling.

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