MECHANICAL ENGINEERING
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Unified Control Framework of Transfemoral Prosthesis for Inclined Walking using Bezier Polynomials based Optimization

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RESEARCH HIGHLIGHT

- Achieving the inclined walking for powered transfemoral prosthesis with an unified controller
- Avoiding heavy optimization for real-time performance
- Smooth transitions for any inclined surfaces

PREVIOUS RESEARCH

Stable level walking gait [1]

- Human inspired optimization generates a set of outputs called canonical walking functions. By tracking them, a biped model yields stable human-like walking.

$$y(\theta,\dot{\theta},\alpha)=\begin{bmatrix}y_1(\theta,\dot{\theta},\alpha)\\ y_2(\theta,\alpha)\end{bmatrix}=\begin{bmatrix}y_1^a(\theta,\dot{\theta})-v_{hip}\\ y_2^a(\theta)-y_2^d(\rho(\theta),\alpha)\end{bmatrix}$$

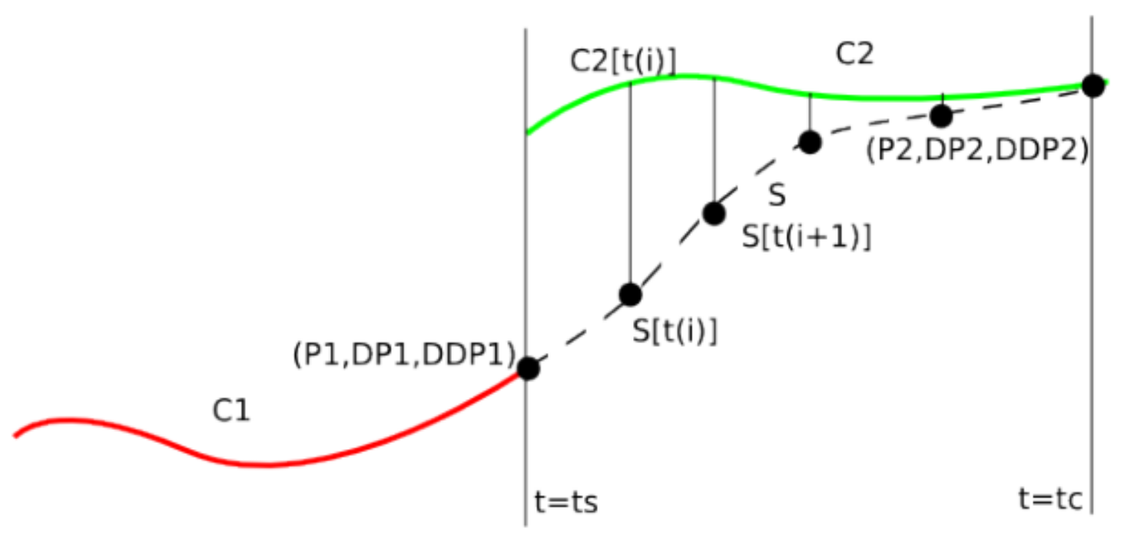
- The condition to ensure stability is based on the invariance of the Partial Hybrid Zero Dynamics (PHZD) set under impacts.

$$PZ_\alpha=\{(\theta,\dot{\theta})\in TQ_R : y_2(\theta,\alpha)=0, L_f y_2(\theta,\alpha)=0\}$$

$$\Delta_R(S_R\cap PZ_\alpha)=PZ_\alpha$$

Spline generation for upslope walking [2]

- Make the upslope walking trajectories converge into a stable level walking trajectory using cubic splines.
- A set of splines with smoothness conditions on position, velocity and acceleration are considered.
- In particular, the optimization turns out to be a linear square minimization problem, and its solution provides all the cubic splines coefficients.



$$\begin{aligned}&min\|P\lambda-Y\|\\ s.t\quad &C\lambda=d\end{aligned}$$

Fig. 1 Spline based trajectory

Limitation

- Requires demanding optimization (solved in off-line)
- Limited to the upslope walking only

BEZIER POLYNOMIALS OPTIMIZATION

- Cubic Bezier polynomials generates the desired walking trajectories for the swing phase.
- The generic cubic Bezier polynomials are described as below where t ∈ [0,1]:

$$Z(t)=(1-t)^3P_0+3t(1-t)^2P_1+3t^2(1-t)P_2+t^3P_3$$

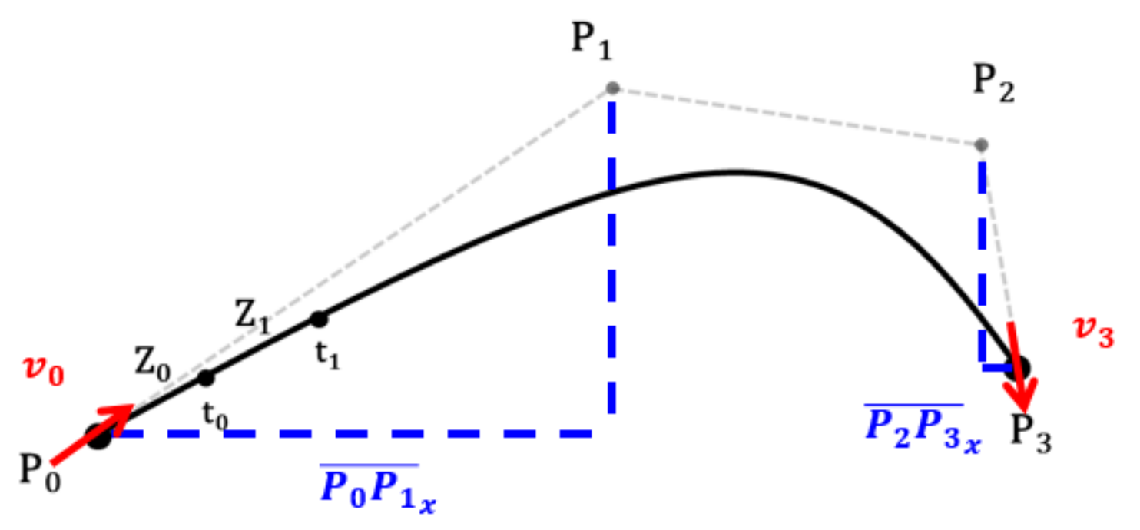
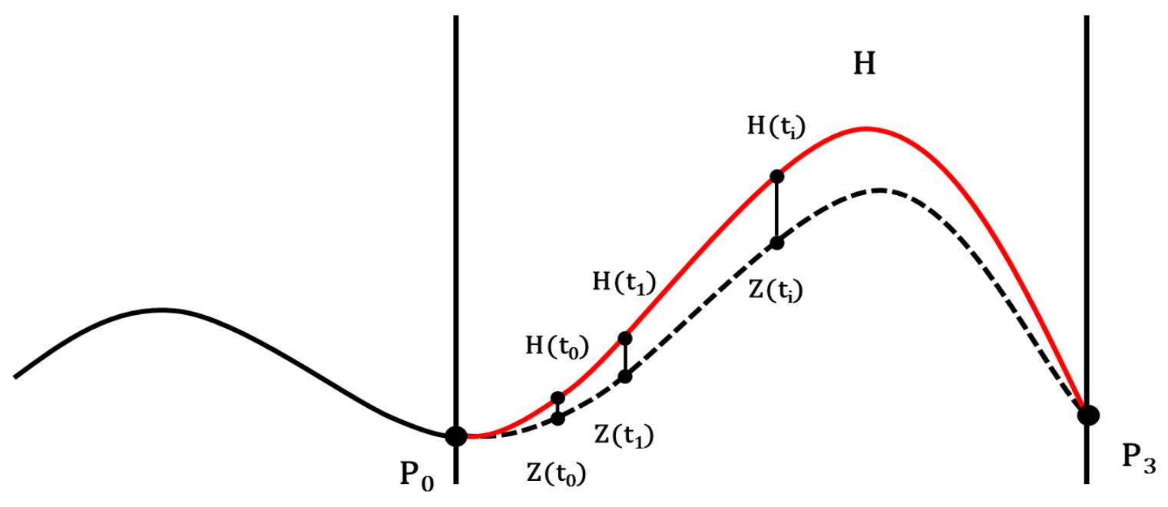


Fig. 3 The relationship between (P_1,P_2) and (P_0,P_3)

- By controlling P_1 & P_2, any different inclined walking curves can be generated.



$$\min \sum_{i=1}^{7} \| Zi(t) - Hi \|$$

$$s.t.\quad \begin{aligned}Z_i(0)&=P_{0,i}\\ Z_i(1)&=P_{3,i}\\ \dot{Z}_i(0)&=\dot{H}_i(P_{0,i})\\ \dot{Z}_i(1)&=\dot{H}_i(P_{3,i})\end{aligned}$$

Fig. 4 H_i indicates a human walking trajectory of the ith slope condition, where i = {1,2,3,4,5,6,7} ≡ {-15°,-10°,-5°,0°,5°,10°,15°} inclination. P_0, P_3 refer to the joint angle at 60%, 85% of a gait cycle, respectively.

- The optimization problem is solved to minimize the sum of error between the Bezier curves and corresponding human trajectories.
- P_0 is updated in every single gait cycle and P_3 is fixed point since all trajectories are merging at this point. $\overline{P_0P_1}_x$, $\overline{P_2P_3}_x$ are free variables to determine the control points P_1, P_2.
- Using Bezier polynomials based optimization, any inclined walking trajectories can be generated analytically.

IMPEDANCE CONTROL

- During the stance phase, impedance control is used to adopt to different terrain conditions.
- The torque at each joints can be described in series of passive impedance parameters which are the function of the phase variable.

$$\tau = k(\theta - \theta^e) + b\dot{\theta}$$

- The optimal stiffness, damping, and equilibrium were chosen from the previous studies [3-5].

EXPERIMENTAL SETUP

Powered Transfemoral Prosthesis

- AMPRO II, the 2nd generation of A&M powered transfemoral prosthesis, has two actuations at ankle and knee.
- AMPRO II detects a contact with the ground based on 5 FlexiForce sensors located on its foot.

IMU Setting

- An IMU placed on the prosthesis detects the thigh angle, which is used as the phase variable to synchronize with the user's walking progression.

Test Environment

- On a treadmill with 3 different slopes (-5°,0°, and 5°)
- User comfort speed (1.71 km/h)

CONCLUSIONS

The Proposed Method …

- Allows the prosthesis to achieve the inclined walking in real-time.
- Generates any inclined walking trajectories regardless of inclination using Bezier polynomials based optimization.
- Achieves the user comfort at stance phase using impedance control.

CONTROL FRAMEWORK

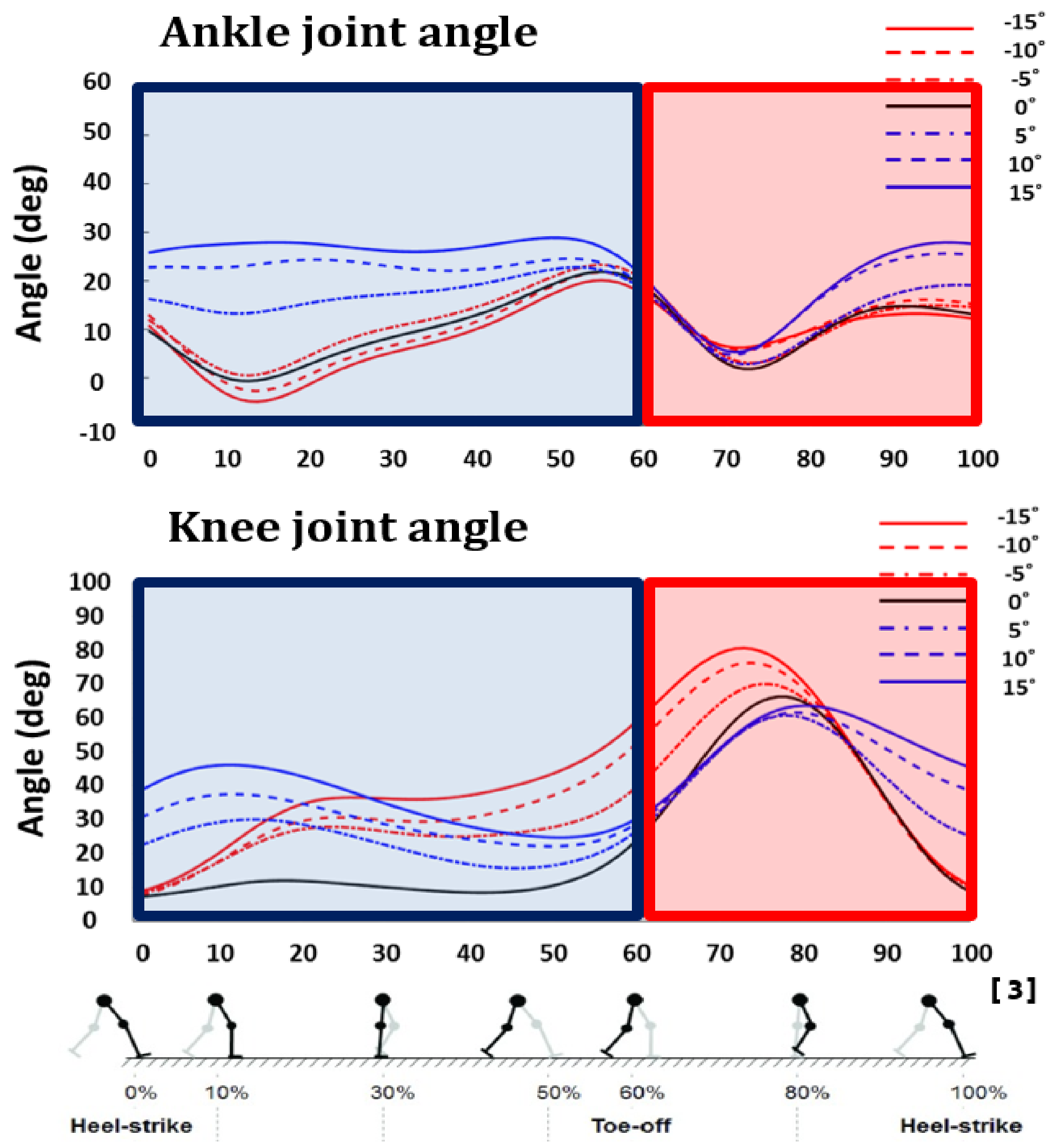


Fig. 2 Ankle/Knee joint angle trajectories for 7 different slopes.

Stance Phase (blue region)

- Prosthesis is controlled using impedance parameters of human subject.

Swing Phase (red region)

- Trajectory tracking method is used in Swing Phase.
- The desired trajectory is generated using the optimized cubic Bezier polynomials with human walking trajectory.

RESULTS

- The prosthetic data was captured from 2 encoders on the prosthesis for each joint.
- It is shown that the actual data follow the desired trajectories in the shaded region for each terrain condition.
- Because of the physical constraints (the frame of the prosthesis), the knee flexion cannot exceed 63°.

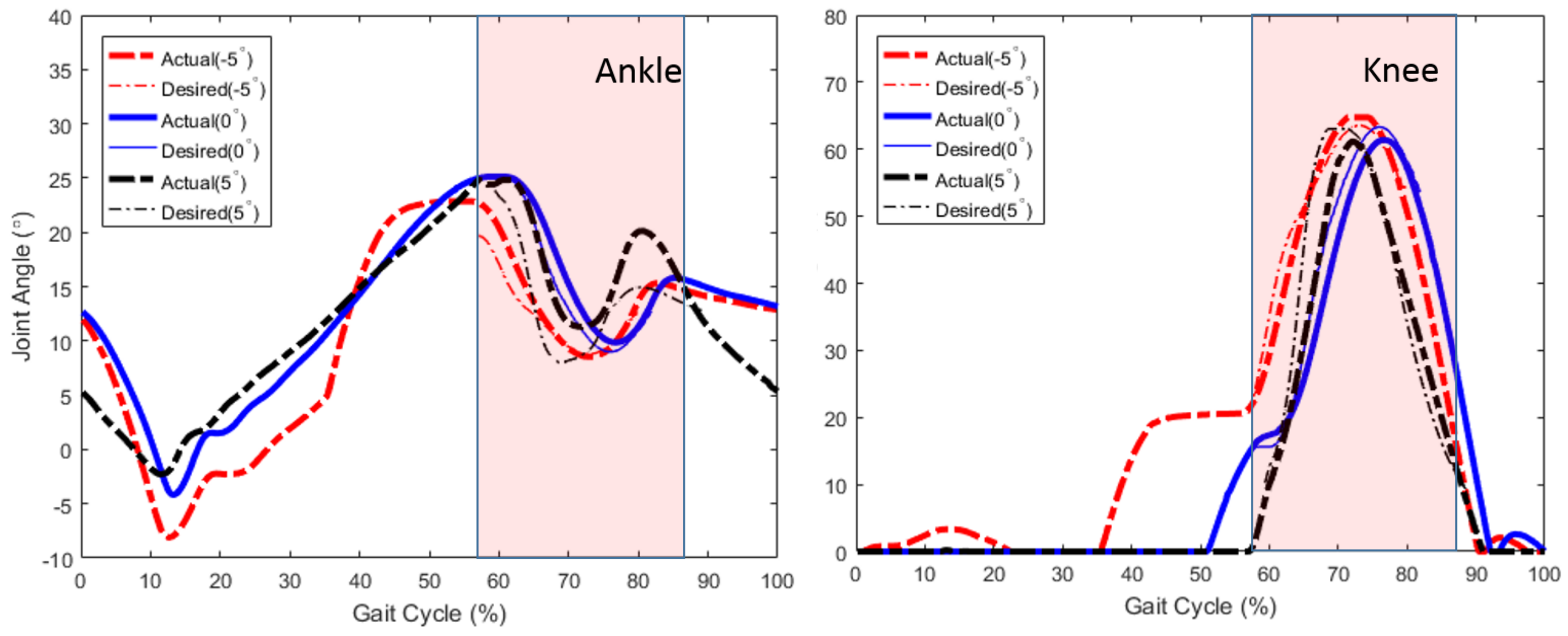


Fig. 5 Ankle and knee trajectories for 5 different slopes. The red region indicates the area of trajectory tracking to follow the desired trajectories based on Bezier curve.

Fig. 6 Prosthesis walking on upslope (10°) and downslope (-10°) surfaces

References

[1] A. D. Ames. *Robot Motion and Control*, 2012.
[2] V. Paredes, et al., *IROS, 2016.*
[3] H. Lee, et al., *Transactional Engineering in Health and Medicine*, 2016.
[4] E. J. Rouse, et al., *Neural Systems and Rehabilitation Engineering*, 2014.
[5] F. Sup, et al., *Neural Systems and Rehabilitation Engineering*, 2011.