MECHANICAL ENGINEERING
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Consolidated control framework to control a powered transfemoral prosthesis over inclined terrain conditions

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RESEARCH HIGHLIGHT

- Achieving the slope walking for a powered transfemoral prosthesis with a unified control framework
- Avoiding heavy optimization for real-time performance
- Smooth transitions for any sloped surfaces without prior knowledge of slope

INTRODUCTION

Background

- Transfemoral amputees have faced more difficulties compared to healthy individuals and transtibial amputees.
- Especially, a slope walking is one of the most challenging daily task for transfemoral amputees [1].

Previous studies

- There have been several studies on a powered prosthesis to tackle this problem.
- Impedance control using sets of impedance parameters (i.e., k, b, θ^{eq}) could handle this problem, but it requires heavy tuning process to decide the parameters from the finite walking phases [2].
- The other study tackles the prosthetic slope walking using human-inspired constraint to track the given trajectories. It reduced a tuning process a lot, but this requires a prior kno wledge for the slope and for the downslope walking, they only tried on a small gradient [3].

BACKGROUND KNOWLEDGE

Human walking phases

- Human walking consists of several events: heel-strike (HS), foot-drop (FD), heel-off (HO), push-off (PO), and toe-off (TO) [4]. Considering these events, human gait can be discretized into finite phases.
- In this study, a human gait is considered to consist of two walking phases:
  i) stance phase (HS to PO): 0 – 60% of the gait cycle
  ii) swing phase (PO to HS): 60 – 100% of the gait cycle

Human gait synchronization

- To synchronize the human walking and prosthetic walking and provide the appropriate control over the prosthesis, a human walking detection is required [3].
- By using a phase variable (calculated from θ_{thigh}) and force sensors under the foot (toe, mid-foot, heel), human walking phase and events can be detected.

Human kinematics on the sloped surfaces

- Depending on the slope, human joint kinematics (ankle and knee) are varying [5].
- Providing the appropriate joint control to the prosthesis is required to the powered prosthesis for avoiding a conflict with the slope.

CONTROL FRAMEWORK

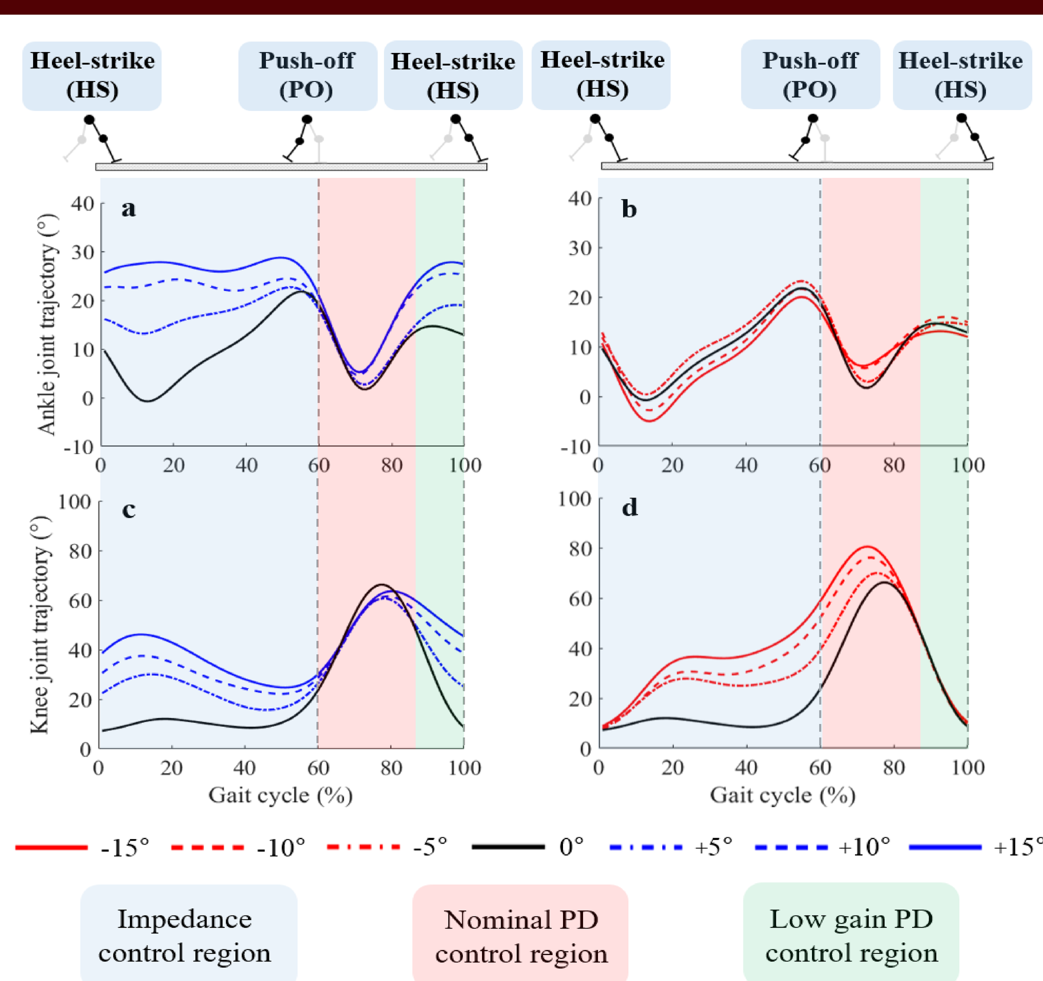


Fig. 2 Human joint angle on 7 sloped surfaces: ankle (top), knee (bottom) Different controllers are represented in different color.

Stance phase: Impedance control

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

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

- The optimal stiffness, damping, and equilibrium were chosen from the previous studies [7-10].

Swing phase: Trajectory tracking

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

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

- In Fig. 3, by controlling P_1 & P_2, any different slope walking curves can be generated.

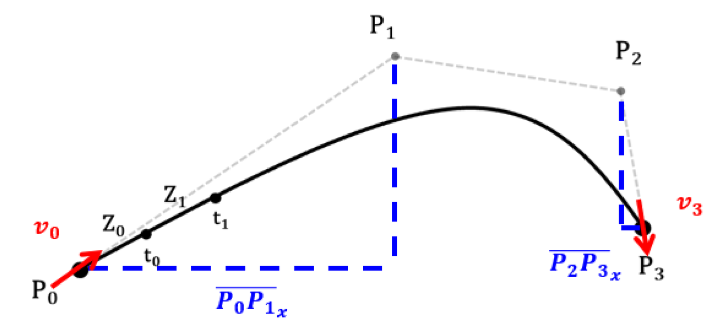


Fig. 3 The relationship between (P_1,P_2) and (P_0,P_3)

- 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.

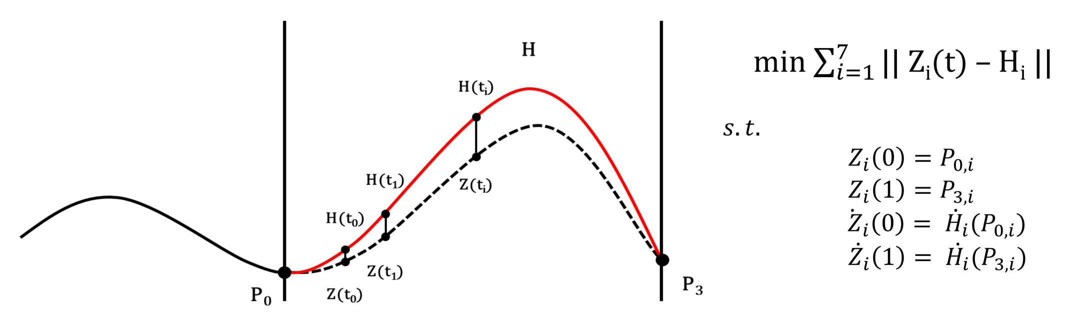


Fig. 4 H_i indicates a human walking trajectory of the i[th] slope condition, where i = {1,2,3,4,5,6,7} ≡ {-15°,-10°,-5°,0°,5°,10°,15°} inclination. P_0, P_3 refer to the joint position at 60%, 85% of a gait cycle, respectively.

- The optimization problem is solved to minimize the sum of error between the Bezier curves and corresponding human trajectories (Fig. 3).

POWERED PROSTHETIC SYSTEM

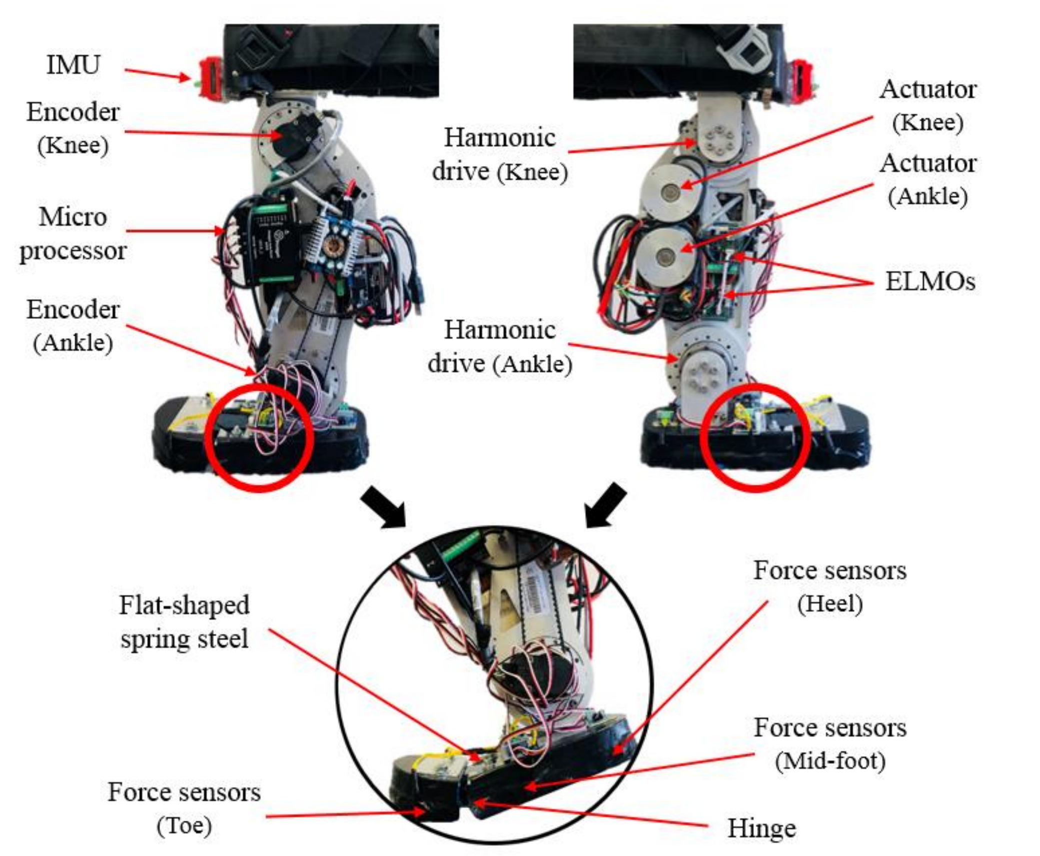


Fig. 1 The powered transfemoral prosthesis AMPRO II (top) has two actuations at ankle and knee, and its human-inherent designed foot has a toe joint with spring steel for providing required PO force (bottom).

Sensor Setting

- An IMU placed on the prosthesis detects the thigh angle for the synchronization with the user's walking progression.
- Human walking events are detected by 5 FlexiForce sensors located on its foot.

Prosthetic foot with a toe joint

- Prosthetic foot consists of the toe part and foot base.
- Two parts are connected by the hinge and the flat shaped spring steel.
- The toe length is determined based on the human factor considering where the forefoot strike occurs [6].

EXPERIMENTAL SETUP

Experiment subject

- A healthy male (29 years, height 170cm, weight 68kg)
- Using a L-shape adapter to simulate an amputee gait

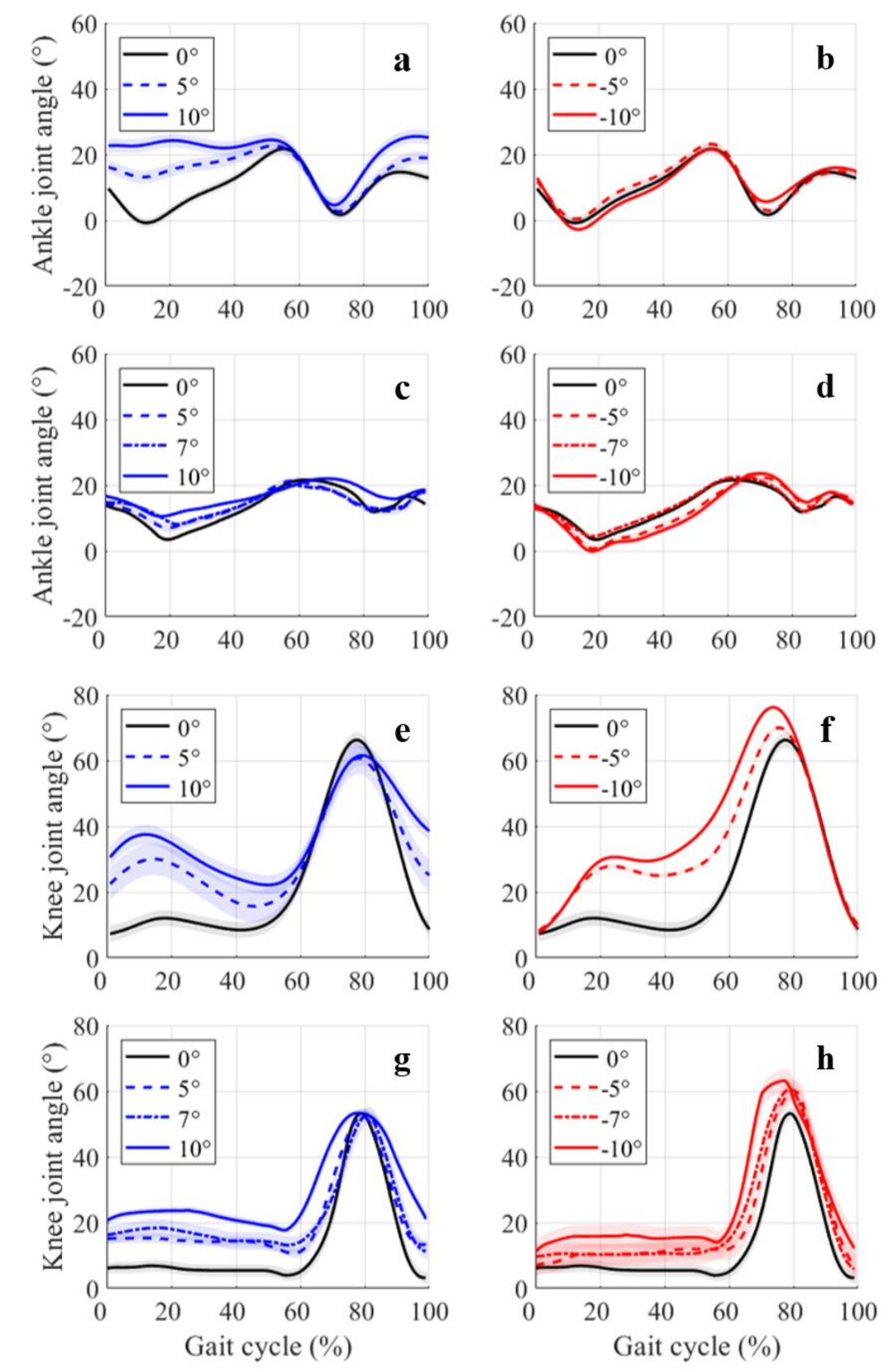
Experiment environment

- Treadmill walking on 7 different slopes: -10°,-7°,-5°,0°,5°,7°,10°.
- User comfort speed (1.71 km/h)

Experiment data recording

- The kinematic data (i.e., knee and ankle joint angles) were captured via 2 encoders on the prosthesis.

RESULTS AND DISCUSSIONS



Experimental results

- Note that since the experiment was conducted with a healthy subject using a simulator, the subject's gait itself could be affected.
- The results show that both ankle and knee joint trajectories (Fig.5. cdgh) are qualitatively similar compared to human slope walking trajectories (Fig.5. abef).
- Specifically, at the knee joint, compliant walking during the stance phase and the enlarged flexion depending on the downslope stiffness are clearly shown.
- For both upslope and downslope, PO can be observed in the prosthetic walking even though this is not as great as human walking.

Discussions

- It is shown that knee flexion on the downslopes are still small compared to human. This is mainly because of the hardware limitation; the knee flexion is restricted by 63°.
- In the results, the prosthetic walking results have quantitative differences during the stance phase, even though the trends are similar. This result can be improved by a further tuning process to provide better impedance parameters.

CONCLUSIONS

- The proposed study is having a benefit to unify the trajectory generation process for slope without prior knowledge of slope.
- This results in a fast trajectory generation with a proper foot clearance for human-like slope walking.
- By using a function of impedance parameters, a compliant interaction during the stance phase can be achieved with a simple tuning.

FUTURE WORKS

- For a better adaptation and a more powerful push-off as like human, a deeper impedance control studies will be conducted.
- Related to push-off, the deeper prosthetic foot study including the characteristic of toe joint and the foot pad are planned.
- For a solid validation, amputee walking study will be conducted with this control framework.

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