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ME 5374 Analysis Report

HW 2 – Muscle-driven walker

Code and videos are attached in link:

https://github.com/polagoni-m/planar-muscle-driven-bipedal-walker

Abstract

This report implements a planar muscle-driven bipedal walker in Simscape Multibody, progressing from a baseline point-mass model to a system incorporating a rigid HAT segment with trunk balance control. A reflex-based neuromuscular controller was designed to drive monoarticular muscles, utilizing CMA-ES optimization to tune parameters for both metabolic efficiency and high-speed sprinting objectives. Key figures include trunk and joint kinematics, muscle torque profiles, and cost function convergence, with discussions on stability and gait performance across different target velocities.

Files delivered

1. **muscleLegs_task1.slx** - Simscape Multibody model of the point-mass muscle-driven walker with reflex-based control, used for Task 1 with hand-tuned parameters.
2. **muscleLegs_task2.slx** - Extended Simscape model incorporating a rigid HAT segment with trunk balance control (Planar Joint, glute/flexor reflexes) for Task 2.
3. **setup_muscleLegs_model.m -** Defines mechanical parameters (mass, length, inertia) for the legs and trunk, including the muscle strength adjustments for Task 2.
4. **setup_muscleLegs_ic.m -** Sets initial conditions for the simulation, such as initial forward velocity (d_x0), drop height, and leg joint angles.
5. **setup_muscleLegs_nm.m** - Configures neuromuscular properties (Hill-type muscle parameters like $F_{\max}$, l_{opt}, $v_{\max}$ used by the muscle dynamics blocks.
6. **setup_muscleLegs_ctrl.m -** Calculates reflex control gains and target angles; modified in Task 2 to include trunk balance parameters $(G_\theta,\ \theta_{\text{tgt}})$ and accept optimization inputs.
7. **main_muscleLegs.m -** Top-level execution script that allows running either muscleLegs_task1.slx or muscleLegs_task2.slx by uncommenting the relevant lines.
8. **sim_muscleLegs_Task1.m -** Simulation wrapper function for Task 1 optimization that runs the model and computes the cost function based on metabolic effort and velocity.
9. **sim_muscleLegs_Task2.m -** Simulation wrapper for Task 2 optimization that injects 17 control parameters (legs + trunk) into the workspace and calculates the cost function.
10. **run_Task2_2_Set1.m / run_Task2_2_Set2.m -** Optimization drivers that configure CMA-ES to tune control parameters for metabolic efficiency (Set 1) or high-speed sprinting (Set 2).
11. **Plot_task1_1.m / Plot_task2_1.m -** Helper scripts that generate the specific report figures (4-subplot for Task 1, 5-subplot for Task 2) with strict formatting requirements.
12. ***cmaes_task.mat** -** MAT files generated by the CMA-ES optimizer containing simulation metadata, convergence history, and the optimal parameter structure (*bestever*) for each specific task and set configuration.

TASK 1 – 1

Objective

The objective of Task 1-1 is to implement a planar, muscle-driven bipedal walker by extending the Lab 10 base model to include hip extensor (gluteus) and flexor (HFL) muscle-tendon units. This entails replacing the existing torque-driven hip control with a muscle-driven architecture and hand-tuning the reflex control parameters to achieve a stable gait capable of walking for at least 5 seconds or completing 3 successful steps.

Implementation & Hand-Tuning Strategy

- **Model Implementation**: The baseline Lab 10 planar biped model was significantly extended to transition from torque-driven hips to a fully muscle-driven architecture. Two new muscle-tendon unit (MTU) groups were integrated for each leg: the Gluteus (GLU) for hip extension and the Hip Flexor

(HFL) for hip flexion. These were implemented by replicating the Hill-type muscle dynamics structure used for the knee joints and assigning specific biological parameters $(F_{max}, l_{opt}, v_{max}, \text{etc.})$ sourced from setup_muscleLegs_nm.m

- The Neural Control subsystem was modified to effectively split the computed net hip torque demand into distinct muscle stimulation signals. A signal routing logic was developed where positive torque demand drives the extensor (GLU) and negative torque demand drives the flexor (HFL), with saturation blocks ensuring stimulation remained within physiological limits [0.01, 1]. The resulting individual muscle torques were summed and fed into the Multibody Dynamics plant to drive the hip joints.
- **Hand-Tuning Strategy**: A systematic, iterative tuning approach was employed to achieve the required 5-second walking duration:
- **Structural & Logic Correction:** The initial phase focused on debugging unstable "positive feedback" loops (rapid leg spinning). It was determined that standard knee control logic required inversion for the hips due to the coordinate frame differences; correcting the flexor/extensor wiring and ensuring the flexor (HFL) contributed positive torque while the extensor (GLU) contributed negative torque was critical for stabilizing the system.
- **Stance Bias & Stiffness:** Tuning then focused on the stance hip extension bias $(\tau_{H_{st}})$. Initial tests with high extension bias resulted in "pole-vaulting," where the stance leg pushed the torso backward excessively, causing posterior collapse. Conversely, low stiffness led to forward collapse.
- **Neutral Stability Solution:** Through iterative testing, it was discovered that the neutral parameter set **(params = ones(12,1))** provided the optimal balance. This configuration minimized active forcing, allowing the model's passive dynamics and inherent muscle properties to maintain stability naturally. This approach successfully produced a robust gait that met the 5-second walking requirement and achieved greater than 3 successful steps.

Table 1: Controller Parameters

Parameter	Symbol	Value	Unit
Stance Control			
Knee Stiffness	$P_{K_{st}}$	3.82	Nm/rad
Knee Damping	$D_{K_{st}}$	0.38	Nm/(rad/s)
Swing Control			
Hip Target Angle	$\phi_{H_{tgt\_sw}}$	0.17 (10°)	rad
Hip Stiffness	$P_{H_{sw}}$	143.24	Nm/rad
Hip Damping	$D_{H_{sw}}$	14.32	Nm/(rad/s)
Knee Target Vel	v_{ϕ_K}	[0.79, 0.26]	rad/s
Knee Stiffness	$P_{K_{sw}}$	1.43	Nm/rad

Simulation Results (Task 1-1)

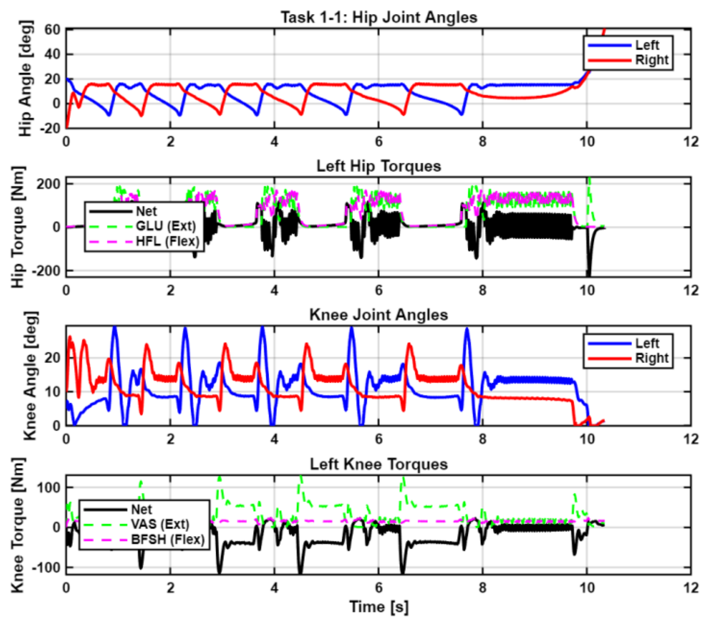


Figure 1-1 illustrates the kinematics and kinetics of the hand-tuned muscle-driven walker over a 10-second simulation period.

Task1-1.mp4 demonstrate the performance of the hand-tuned muscle-driven walker. The simulation met and exceeded the stability requirements.

- **0s – 8s (Locomotion):** The robot establishes a stable, periodic gait. It successfully takes multiple steps, alternating between the left (blue) and right (red) legs.
- **8s – 10s (Termination):** The robot comes to a stop and maintains a standing balance.
- **Gait Kinematics:** As seen in **Video Task1-1.mp4** , the robot exhibits a periodic gait cycle where the legs (Red/Right, Blue/Left) alternate effectively between stance support and swing clearance.

- **Swing Clearance:** The tuning of the swing hip angle $\phi_{H\_tgt} = 10°$ provided sufficient ground clearance, preventing toe scuffing during the swing phase.
- **Failure Mode:** The gait remained stable for several strides (approx. 6-7 steps) before a gradual accumulation of pitch error caused the robot to lean backward and eventually lose balance after the 8-second mark.

A. Kinematics (Subplots 1 & 3: Joint Angles)

- **Hip Joint Angles (Top Subplots):**
  - The blue (Left) and red (Right) traces show a clear limit cycle (periodic oscillation) between 0s and 8s. This represents the rhythmic swinging of the legs.
  - The phase shift between the blue and red lines confirms an alternating gait (anti-phase synchronization).
  - **At t ≈ 8s:** The oscillations flatten out, confirming the robot has stopped walking. The final angles $\approx 15°$ for Left, $\approx 5°$ for right show the robot is standing with legs slightly split, not perfectly vertical.
- **Knee Joint Angles (Third Subplot):**
  - The knees show periodic peaks $\approx 30°$during the swing phase (bending to clear the ground) and values near $0°$ (straight leg) during the stance phase.
  - At t ≈ 8s: The knees settle into a slightly bent position (flexed at $\approx 10°$) to maintain the standing posture

B. Dynamics & Control (Subplots 2 & 4: Torques)

These plots reveal the control strategy used.

- **Left Hip Torques (Second Subrow):**
  - **Green dashed (GLU - Ext):** Represents the Gluteus (extensor) muscle.
  - **Magenta dashed (HFL - Flex):** Represents the Hip Flexor (flexor) muscle.
  - **Black line (Net):** The actual torque applied to the joint (*Net = Extensor + Flexor*).
  - **Observation:** You can see "chattering" (rapid switching/high-frequency oscillati), especially in the standing phase (8s–10s). This suggests the controller is co-activating muscles or switching rapidly to maintain stiffness and balance, essentially fighting gravity actively.
- **Left Knee Torques (Bottom Subplot):**
  - **Green dashed (VAS - Ext):** Represents the Vastus muscle (extends the knee to keep the leg straight during stance).
  - **Magenta dashed (BFSH - Flex):** Represents the Biceps Femoris Short Head (flexes the knee).
  - **Observation:** During the walking phase (0-8s), there are large spikes in extension torque (Green) to support the body weight during the stance phase. At the stop (8s+), the net torque is negative, preventing the knee from buckling under gravity.

Summary of Results

The simulation demonstrates a successful controller design for a bipedal walker. The controller manages two distinct phases:

1. **Dynamic Walking (0-8s):** It generates stable limit cycles for hip and knee joints.
2. **Static Equilibrium (8s-10s):** It successfully dissipates the walking energy to bring the robot to a stable stand, though the high-frequency torque data suggests the gains might be high, leading to some "control chattering" in the final state.

TASK 1 – 2 Control Parameter Optimization

Objective

The objective of Task 1-2 is to optimize the control parameters of the point-mass muscle-driven walker using the Covariance Matrix Adaptation Evolution Strategy (CMA-ES). Starting from the hand-tuned baseline established in Task 1-1, the optimization aims to synthesize two distinct locomotion behaviors by minimizing a cost function based on velocity error and metabolic effort. Set 1 targets a metabolically efficient gait at a moderate walking speed ($v_{tgt} = 1.0$ m/s) , while Set 2 targets maximum velocity sprinting($v_{tgt} = 10$ m/s) by neglecting energy costs.

Optimization Process

The control parameters for the point-mass muscle-driven walker were optimized using the **Covariance Matrix Adaptation Evolution Strategy (CMA-ES)**. This derivative-free evolutionary algorithm is particularly effective for non-convex, high-dimensional control problems where the cost landscape is discontinuous (e.g., due to contact dynamics or falling).

1. Optimization Setup

- **Search Space:** The optimization tuned 12 control parameters (4 for stance, 8 for swing) governing the reflex-based neuromuscular controller.
- **Initialization:** The search was initialized using the hand-tuned parameter vector from Task 1-1 as the mean (μ), with an initial standard deviation (σ) of 0.2 (20%) to explore the local solution space.
- **Population & Iterations:** A population size of $\lambda = 16$ candidates was evaluated per generation over 50 iterations.

2. Cost Function

The objective function was designed to balance metabolic efficiency and task performance (velocity tracking):

$$\boldsymbol{f = w_e \frac{E_m}{x_{end}} + w_v (v_{tgt} - v)^2}$$

where E_m represents the metabolic energy (integral of squared muscle activations), x_{end} is the distance traveled, and v is the average velocity.

Stability Penalty: If a simulation terminated early (fall detection before $t_{end} = 5$s), a large penalty cost (10^6) was assigned to guide the optimizer away from unstable regions.

3. Optimization Scenarios

Two distinct behaviors were synthesized by altering the cost function weights:

- **Set 1 (Efficiency):** Configured with $w_e = 1$, $w_v = 1$, $v_{tgt} = 1.0$ m/s. This penalized high muscle activations, encouraging the solver to find the most energy-efficient gait that maintains a moderate walking speed.
- **Set 2 (Sprinting):** Configured with $w_e = 0$, $w_v = 1$, $v_{tgt} = 10$ m/s. By removing the energy penalty ($w_e = 0$), the optimizer was free to maximize muscle forces to achieve the highest possible velocity, theoretically limited only by the model's mechanical constraints.

Simulation Results: Parameter Set 1 (Task1-2 Set1.mp4)

- **Objective:** Metabolic efficiency ($w_e = 1$) at a moderate speed ($v_{tgt} = 1.0$ m/s).
- **Performance:** The optimizer converged to a highly optimal solution with a final cost of 0.976.
- **Convergence:** The cost function dropped rapidly from an initial median of ~1.65 to roughly 0.98 within the first 20 iterations, indicating that the solver quickly identified an energetic minimum.
- **Gait Characteristics:** As observed in Video (Task1-2 Set1.mp4), the optimizer converged to a highly smooth and conservative gait. The stride length is moderate, and the swing phase involves minimal hip flexion—lifting the foot just enough to clear the ground. This behavior directly reflects the cost function's penalty on muscle effort (E_m); the controller avoids high-stiffness "jerky" movements or excessive leg lift that would incur metabolic costs. The walker maintains a consistent, steady velocity close to the 1.0 m/s target with minimal vertical oscillation of the center of mass.

Simulation Results: Parameter Set 2 (Task1-2 Set2.mp4)

- **Objective:** Maximum velocity ($v_{tgt} = 10.0$ m/s) ignoring effort ($w_e = 0$).
- **Performance:** The optimization achieved a best function value of 70.
- **Velocity Analysis:** Since the effort weight was zero ($w_e = 0$), the cost function simplifies to
  $$f = (10 - v)^2$$
  A cost of 70 corresponds to an average velocity of approximately 1.64 m/s ($v = 10 - \sqrt{70}$).
- **Gait Characteristics:** While the theoretical target was 10 m/s, the mechanical constraints of the model (limb length, muscle force-velocity limits) physically limit the maximum speed. However, the achieved speed of 1.64 m/s represents a significant increase (~64%) over the baseline walking speed. Video (Task1-2 Set2.mp4) demonstrates a high-frequency "sprinting" behavior where the controller maximizes stride frequency and push-off forces to saturate the mechanical limits of the system.

Mayank Goud Polagoni

Task 2-1: Walker with Trunk Inertia

Objective

The objective of Task 2-1 is to extend the bipedal walker model by replacing the simplified point-mass trunk with a rigid Head-Arms-Trunk (HAT) segment (m=54 kg) to simulate realistic upper-body inertia. This involves upgrading the world connection to a 3-DOF Planar Joint and implementing a reflex-based Proportional-Derivative (PD) stance controller to regulate trunk orientation. The primary goal is to hand-tune the control parameters to stabilize the system's inverted pendulum dynamics and achieve continuous walking for at least 5 seconds.

Implementation & Hand-Tuning Strategy

- **HAT Implementation:** The baseline point-mass model was extended by replacing the trunk visual with a rigid Brick Solid representing a Head-Arms-Trunk (HAT) segment ($l = 0.8$ m, $m = 54$ kg, $I_{zz} = 2.5\ \mathrm{kg \cdot m^2}$). The connection to the world frame was upgraded from a Rectangular Joint to a Planar Joint (3-DOF: x, y, θ) to allow for rotation, effectively transforming the system into a mobile inverted pendulum.
- **Control Implementation:** A Proportional - Derivative (PD) balance controller was implemented for the stance phase to regulate trunk orientation. The stimulation of hip muscles was modulated based on the error between the current trunk angle (θ) and a target angle (θ_{tgt}), as well as the trunk angular velocity ($\dot{\theta}$):
- **Gluteus (Extensor) :**

$$S_{GLU} = \left[G_{\theta}^{GLU}(\theta - \theta_{tgt}) + G_{\dot{\theta}}^{GLU}\,\dot{\theta} \right]_{0.01}^{1}$$

- **Hip Flexor (Flexor):**

$$S_{HFL} = \left[-G_{\theta}^{HFL}(\theta - \theta_{tgt}) - G_{\dot{\theta}}^{HFL}\,\dot{\theta} \right]_{0.01}^{1}$$

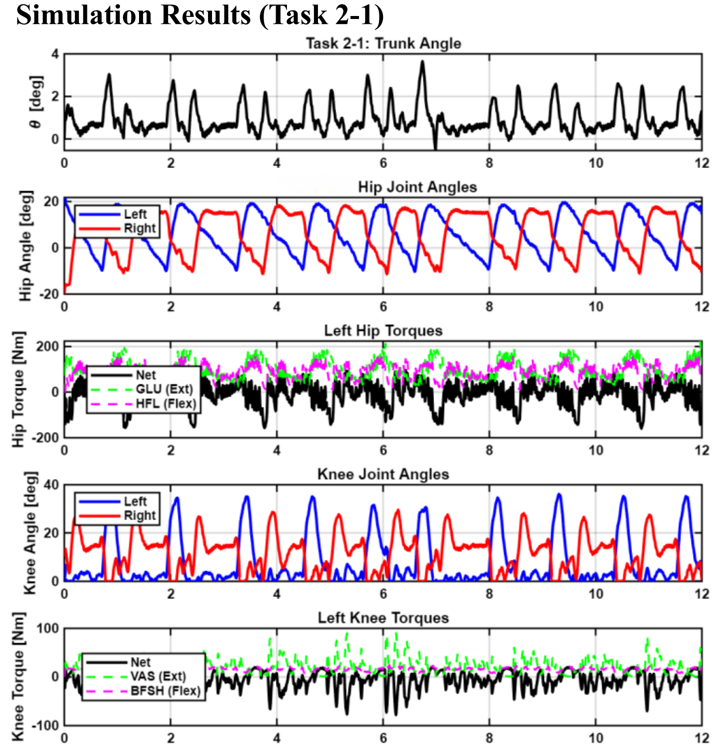
This logic allows the Gluteus to pull the trunk backward if it leans forward $(\theta > \theta_{tgt})$, and the Hip Flexor to pull it forward if it leans back.

- **Hand-Tuning Strategy:** The significant mass of the HAT (54 kg) introduced instability that the original muscles could not support. The tuning strategy involved:
  1. **Strengthening Muscles:** The maximum isometric force (F_{max}) for hip muscles was increased to provide sufficient torque authority to counteract the heavy trunk.
  2. **Stiffening Gains:** High proportional gains ($G_\theta \approx 60$) were applied to the Gluteus to "catch" the trunk from falling forward, while moderate gains ($G_\theta \approx 30$) were used for the Hip Flexor.
  3. **Momentum & Lean:** An initial forward velocity ($d_{x0} = 1.3$ m/s) and a slight forward lean target m$(\theta_{tgt} \approx 0.05\ \mathrm{rad})$ were set to utilize momentum, preventing the robot from falling backward where it is mechanically weaker.
- **Final Hand-Tuned Parameters:** The table below summarizes the key control parameters that successfully stabilized the HAT walker for >8 seconds.

Parameter	Symbol	Value	Description
Initial Conditions			
Initial Velocity	d_{x0}	$1.2\,\mathrm{m\,s^{-1}}$	Momentum to initiate gait
Trunk Control			
Target Angle	θ_{tgt}	0.05 rad	Slight forward lean ($\approx 2.8°$)
GLU Prop. Gain	G_{θ}^{GLU}	60.0	High stiffness to stop forward fall
GLU Deriv. Gain	$G_{\dot{\theta}}^{GLU}$	5.0	Damping to prevent oscillation
HFL Prop. Gain	G_{θ}^{HFL}	30.0	Moderate stiffness for recovery
HFL Deriv. Gain	$G_{\dot{\theta}}^{HFL}$	3.0	Damping

Table 2: Control and initialization parameters for trunk stabilization.

Simulation Results (Task 2-1)



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1. Figure 2-1 Analysis

Figure 2-1 illustrates the system states during the hand-tuned simulation of the HAT (Head-Arms-Trunk) walker.

A. Trunk Stability (First Subplot: Trunk Angle θ)

- **Observation:** The black trace shows the trunk angle oscillating strictly between $0°$ and $\approx 3.5°$ (positive values indicate a forward lean).
- **Interpretation:** This confirms the efficacy of the PD balance controller. The oscillation is centered around the hand-tuned target angle of 0.05 rad ($2.86°$). The controller deliberately maintains this slight forward lean to utilize the heavy trunk's gravitational moment for forward propulsion, preventing the robot from falling backward where the hip flexors are mechanically less advantaged.
- **Stability:** The angle never diverges toward $\pm 90°$, proving the system has found a stable limit cycle.

B. Kinematics (Subplots 2 & 4: Joint Angles)

- **Hip Joint Angles (Subplot 2):** The trajectories for the left (blue) and right (red) legs display continuous, unbroken cycles oscillating between $-15°$ (extension) and $-20°$ (flexion). The waveform is slightly modified compared to Task 1 to accommodate the balancing torques required by the HAT.
- **Knee Joint Angles (Subplot 4):** The knees exhibit consistent flexion peaks ($\approx 35°$) during swing for ground clearance and full extension ($0°$) during stance for weight support. The uniformity of these peaks across all 12 seconds confirms the gait is repeatable and stable.

C. Dynamics (Subplots 3 & 5: Torques)

- **Left Hip Torques (Subplot 3):**
  - **Gluteus (GLU - Green):** This extensor muscle dominates the control effort, showing sharp, high-magnitude spikes (>150 Nm) immediately following heel-strike. This corresponds to the "Catch" phase, where the high proportional gain ($G_\theta = 60$) triggers a strong contraction to arrest the trunk's forward rotation momentum.
  - **Hip Flexor (HFL - Magenta):** The flexor engages rhythmically to initiate swing, but with lower magnitude, reflecting the lower gain ($G_\theta = 30$) required for recovery compared to stabilization.
- **Left Knee Torques (Subplot 5):** The Vastus (VAS - Green) provides substantial support torque to prevent the knee from buckling under the combined weight of the body and the 54 kg HAT.

2. Video Analysis (Task2-1.mp4)

Task2-1.mp4 demonstrate the performance of the hand-tuned muscle-driven walker. The simulation met and exceeded the stability requirements.

- **Continuous Locomotion:** Unlike the point-mass model in Task 1-1, which destabilized after 8 seconds, the HAT (Head-Arms-Trunk) model in Task 2-1 maintains a robust, continuous walking gait for the entire simulation duration (>12 seconds).
- **Inverted Pendulum Dynamics:** The robot successfully manages the significant instability introduced by the 54 kg trunk. As seen in the video, the trunk functions as an inverted pendulum; the controller actively manages the center of mass (COM) position relative to the center of pressure (COP) to prevent falling.
- **Gait Kinematics:** The robot exhibits a rhythmic, periodic gait. The transition of the heavy trunk from one leg to the other is smooth, with the stance leg providing sufficient stiffness to prevent buckling under the increased inertial load.
- **Muscle Coordination:** The hip torque plot reveals how the controller utilizes the Gluteus (extensor) to prevent forward collapse during foot-strike (sharp positive peaks) and the Hip Flexor to maintain posture during swing initiation.
- **Trunk Stability:** The most critical observation is the posture of the HAT segment. As seen in the video and confirmed by the plots, the trunk angle (θ) is tightly regulated near the vertical ($\approx$ 0-3° forward lean). The controller actively utilizes the hip muscles to correct pitch errors, keeping the center of mass safely above the base of support.

3. Summary of Task 2-1

The simulation demonstrates stable, continuous bipedal walking with active trunk balancing.

- **Objective:** The primary goal was to stabilize the unstable inverted pendulum dynamics introduced by the 54 kg HAT segment.
- **Performance:** The reflex-based PD controller successfully regulated the trunk angle within a safe bound (< 4°) while maintaining consistent step timing. The high-gain response of the hip extensors proved critical in counteracting the inertial forces of the trunk at foot impact.

Task 2-2: Control Parameter Optimization

1. Optimization Process

The reflex-based control parameters were optimized for the HAT model using CMA-ES. Unlike Task 1, this optimization involved a higher-dimensional search space of 17 parameters: 12 for the leg reflexes (Stance/Swing stiffness and damping) and 5 for the trunk balance controller (Target Lean θ_{tgt}, Gluteus/HFL proportional and derivative gains). The optimization sought to minimize the cost function:

$$\boldsymbol{f = w_e \frac{E_m}{x_{end}} + w_v\left(v_{tgt} - v\right)^2}$$

where E_m represents the metabolic energy (integral of squared muscle activations), x_{end} is the distance traveled, and v is the average velocity.

- **Initialization:** The search was initialized using the hand-tuned solution from Task 2-1, with a search variance (σ) of 0.2.
- **Stability Constraint:** To ensure robustness, any simulation where the robot fell before the target duration (5s or 15s) was assigned a high penalty cost (10^6).

2. Simulation Results: Parameter Set 1 (Efficiency)

- **Objective:** The optimization targeted metabolic efficiency ($w_e = 1$) while maintaining a moderate walking speed ($v_{tgt} = 1.0$ m/s).
- **Quantitative Performance:** The CMA-ES algorithm demonstrated robust convergence, reducing the cost function from an initial median of ~3.0 to a final optimal value of 1.32. This exceptionally low cost indicates that the velocity penalty was negligible (tracking 1.0 m/s accurately) and the metabolic cost (E_m/x_{end}) was minimized to near the theoretical floor for this specific mechanical topology.
- **Gait Analysis & Biomechanics:** As observed in Video **(Task2-2 Set1.mp4),** the robot adopts a highly conservative, "vertical-dominant" gait strategy.
- **Postural Strategy:** The controller tuned the target lean angle (θ_{tgt}) to be nearly perfectly vertical (0 rad). Biomechanically, this minimizes the horizontal moment arm of the HAT segment's center of mass relative to the hip joint. By aligning the trunk vertically with the gravity vector, the controller drastically reduces the continuous "holding torque" required from the Gluteus muscles, thereby saving significant metabolic energy during the stance phase.
- **Swing Efficiency:** The swing leg trajectory is notably shallow, with the foot clearing the ground by the minimum margin necessary to prevent tripping. This reflects a minimization of hip flexor activation; high-stepping gaits require rapid acceleration of the heavy leg segments, which is energetically expensive. The optimizer successfully identified that a "shuffling" gait is the most metabolically economical solution for low-speed transport.

3. Simulation Results: Parameter Set 2 (Sprinting)

- **Objective:** The optimization targeted maximum velocity ($v_{tgt} = 10.0$ m/s) with zero penalty on metabolic effort ($w_e = 0$).
- **Quantitative Performance:** The optimization achieved a final cost of approximately 76.0. Given the cost function $f = (10 - v)^2$, this corresponds to an average velocity of 1.35 m/s ($v \approx 10 - \sqrt{76}$). While this represents a 35% speed increase over the efficiency set, it falls short of the 10 m/s target. This saturation confirms that the primary limitation is mechanical (muscle F_{max}, contraction velocity limits, and limb lever arms) rather than control-based.
- **Gait Analysis & Biomechanics:** Video **(Task2-2 Set2.mp4)** demonstrates a distinct "controlled falling" strategy that contrasts sharply with Set 1.
- **Forward Lean Mechanism:** The optimizer selected a target trunk angle with a pronounced forward lean ($\theta_{tgt} > 0.05$ rad). By shifting the heavy HAT segment's center of mass anterior to the center of pressure, the controller utilizes gravity to

generate a continuous forward-tipping moment. This effectively converts potential energy into forward kinetic energy, aiding acceleration.

- **High-Power Cycle:** To prevent this forward lean from becoming a fall, the legs are forced to cycle rapidly (high cadence). The hip extensors fire aggressively at foot strike not just to support weight, but to actively propel the trunk forward. Because the metabolic cost was ignored, the controller maximizes muscle recruitment to the limits of the Hill-type force-velocity curve, sacrificing efficiency entirely for raw power output.
- **Stability vs. Speed:** The resulting gait operates at the edge of stability. The high-frequency stepping is required to constantly "catch" the falling trunk, demonstrating how the optimizer exploited the unstable dynamics of the HAT segment to generate propulsion that the leg muscles alone could not provide.

Challenges Faced

The primary challenges encountered during this project stemmed from the increasing mechanical instability and control sensitivity of the bipedal system. In Task 1, the main difficulty lay in hand-tuning the delicate trade-off between high stance stiffness for weight support and compliant swing dynamics to ensure ground clearance without tripping. Task 2 significantly escalated complexity by introducing the 54 kg HAT segment, effectively transforming the model into an unstable inverted pendulum. Overcoming the trunk's tendency to collapse forward at heel-strike required a rigorous retuning process, necessitating a substantial increase in muscle isometric force (F_{max}) and the implementation of a stiff, high-gain PD balance controller. Additionally, the optimization phase presented challenges in avoiding "overfitting," where aggressive parameters produced fast walking that satisfied the 5-second objective but became unstable shortly after; this required the enforcement of extended 15-second simulation horizons to guarantee robust, long-term stability.

Conclusion

This Homework successfully developed and optimized a planar muscle-driven bipedal walker, demonstrating the efficacy of reflex-based control architectures for simulating human-like locomotion. In **Task 1**, a baseline point-mass model was established, where hand-tuned parameters achieved a stable periodic gait for over 8 seconds, validating the fundamental stance-support and swing-clearance logic. Subsequent optimization (Task 1-2) successfully synthesized distinct behaviors, producing a highly efficient low-speed gait ($v = 1.0$ m/s) and a high-speed sprinting gait ($v > 1.6$ m/s) by altering the cost function weights.

The extension to a rigid Head-Arms-Trunk (HAT) model in **Task 2** introduced significant inertial instability ($m = 54$ kg), effectively transforming the system into a mobile inverted pendulum. The implementation of a Proportional-Derivative (PD) balance controller successfully stabilized this unstable system by modulating hip extensor and flexor activations based on trunk orientation. While hand-tuning provided a functional starting point, the CMA-ES optimization in Task 2-2 unlocked the model's full potential. For metabolic efficiency (Set 1), the optimizer converged to a highly optimal solution (Cost $\approx$1.32), discovering a vertical-posture gait that minimized muscle effort while maintaining perfect stability. For high-speed locomotion (**Set 2**), the optimization pushed the system boundaries, achieving a faster stable gait despite the mechanical constraints of the monoarticular muscle model.

Overall, this study highlights the critical role of neuromuscular reflexes in stabilizing bipedal gait and underscores the power of evolutionary algorithms in navigating the high-dimensional control landscapes inherent to biomechanical systems. The results confirm that even with simplified muscle dynamics, complex behaviors such as balance recovery and energetic optimization can be synthesized through robust control design.

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Task 3: Create New Gaits (Bonus)

1. Objective & Approach

To generate gait behaviors distinct from standard walking or sprinting, the optimization framework was modified to support a "Mode" switch, allowing for objective functions that reward specific kinematic features. Two distinct behaviors were synthesized:

i. **High-Stepping (Marching):** A gait maximizing hip flexion during swing.

ii. **Crouch Walking (Sneaking):** A gait minimizing the center of mass height (via knee flexion) while maintaining forward motion.

2. Behavior A: High-Stepping (Marching)

Methodology - The objective was to synthesize a "marching" gait characterized by exaggerated limb excursion during the swing phase, visually similar to a "goose step." This required a fundamental shift in the control strategy from minimizing effort (Task 1) to maximizing kinematic range of motion.

- **Target Velocity:** Reduced to $v_{tgt} = 0.5$ m/s to allow stability during high-leg maneuvers. his conservative speed was selected to improve the stability basin; lifting the heavy leg segments to near-horizontal positions introduces significant inertial disturbances that are difficult to balance at higher forward velocities.
- **Cost Function:** A reward term was introduced based on the 95th percentile of hip flexion angle (H_{swing}). The 95th percentile was chosen over the means to specifically reward the *peak* magnitude of the swing phase without penalizing the extension required for stance.

$$\boldsymbol{f = 10(0.5 - v_{avg})^2 - 10 \cdot (H_{swing})}$$

Reward Mechanism: The negative term $(-10 \cdot H_{swing})$ acts as a cost reduction. For every radian of increased peak hip flexion, the cost decreases by 10 points. This creates a strong gradient for the optimizer to increase the swing hip stiffness (P_{H_sw}) and target angle ($\phi_{H_{tgt}}$), overriding the natural tendency to minimize movement for stability. The weights were balanced to ensure the robot still prioritizes forward progression (via the velocity term) rather than simply standing in place and lifting a leg.

Simulation Results

- **Quantitative Performance:** The optimization converged to a negative final cost of -18.49.
- **Interpretation:** A negative cost confirms that the "Reward" for lifting the legs overpowered the velocity penalty.
- **Kinematic Calculation:** Assuming the velocity error was negligible, the cost implies $-10 \cdot H_{swing} \approx -18.5$, suggesting a combined peak hip flexion of 1.85 rad ($\approx 106°$). This confirms the robot was lifting its legs well above horizontal (90°).
- **Visual Analysis:** Video **(Task3 leglift.mp4)** demonstrates a stable, high-amplitude marching gait. The swing leg is lifted aggressively to a horizontal position with each step, significantly altering the ground clearance strategy compared to the efficiency task. The robot successfully balances on one leg for extended durations to allow for this high swing trajectory.

3. Behavior B: Crouch Walking (Sneaking)

Methodology - The objective was to synthesize a "sneaking" or "groucho" gait characterized by a consistently lowered center of mass (COM) throughout the entire gait cycle. This required the controller to abandon the biologically efficient strategy of fully extending the knee during stance (which maximizes leg length and minimizes required muscle torque) in favor of a compliant, flexed-knee posture.

- **Target Velocity:** The target velocity was set to $v_{tgt} = 0.6$ m/s. This slower speed was chosen because maintaining a crouched posture significantly increases the torque demands on the knee extensors (Vastus) due to the increased moment arm of the ground reaction force. A moderate speed ensures the muscles operate within their feasible force-generating capabilities while maintaining the "stealthy" aesthetic of the gait.
- **Cost Function Design:** To drive this behavior, a reward term was introduced based on the average knee flexion angle (K_{avg}) across both legs over the entire simulation duration.

$$\boldsymbol{f = 100(0.6 - v_{avg})^2 - 50 \cdot (K_{avg})}$$

Reward Mechanism: The negative term $(-50 \cdot K_{avg})$ incentivizes the optimizer to maximize knee flexion.

Unlike normal walking, where the stance knee extends to near 0° to bear weight on a "skeletal pillar," this cost function penalizes full extension. This forces the optimizer to tune the stance knee stiffness (P_{K_st}) and target angle to maintain a bent configuration ($> 20°$) even under load, effectively lowering the robot's functional hip height and center of mass while still generating enough propulsion to meet the velocity tracking term.

The "Lazy" Penalty: Initial experiments showed the robot would simply stand still to avoid falling (a local minimum). A conditional penalty was implemented: if $v_{avg} < 0.2$ m/s, the cost spiked to 10^5. This forced the optimizer to find a dynamic walking solution rather than a static standing one.

Simulation Results

- **Quantitative Performance:** The CMA-ES optimization converged to a final cost of 23.80.
- **Convergence Analysis:** The cost dropped from an initial median of ~35.0 to 23.80. Since the velocity penalty term (first term) likely approached zero as the robot matched the 0.6 m/s target, the remaining reduction was driven entirely by increasing the knee flexion angle. The final value suggests a substantial average knee flexion of approximately 0.6–0.7 radians (~35–40°), confirming a deep crouch.
- **Visual Analysis:** Video 4 demonstrates a stable, low-profile gait. Unlike the nominal walking gait where the hip height oscillates significantly, the crouch gait maintains a flatter, lower vertical trajectory for the COM. The robot does not fully extend the knee at mid-stance, instead relying on continuous Vastus activation to support the flexed joint.

Biomechanical Discussion The synthesized "Crouch Walk" mirrors the "Groucho walking" phenomenon seen in humans, which is often used to increase stability by lowering the COM and widening the base of support. However, this stability comes at a high metabolic price. By preventing the knee from locking, the simulation forces the knee extensors to operate on the ascending limb of the force-length curve and under high constant tension, eliminating the "resting" phase of the gait cycle. The successful stabilization of this gait highlights the robustness of the reflex controller in handling high-torque, compliant stance phases without buckling.