A SIMPLE SWING LEG CONTROL STRATEGY FOR LIMIT CYCLE WALKERS

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INTRODUCTION

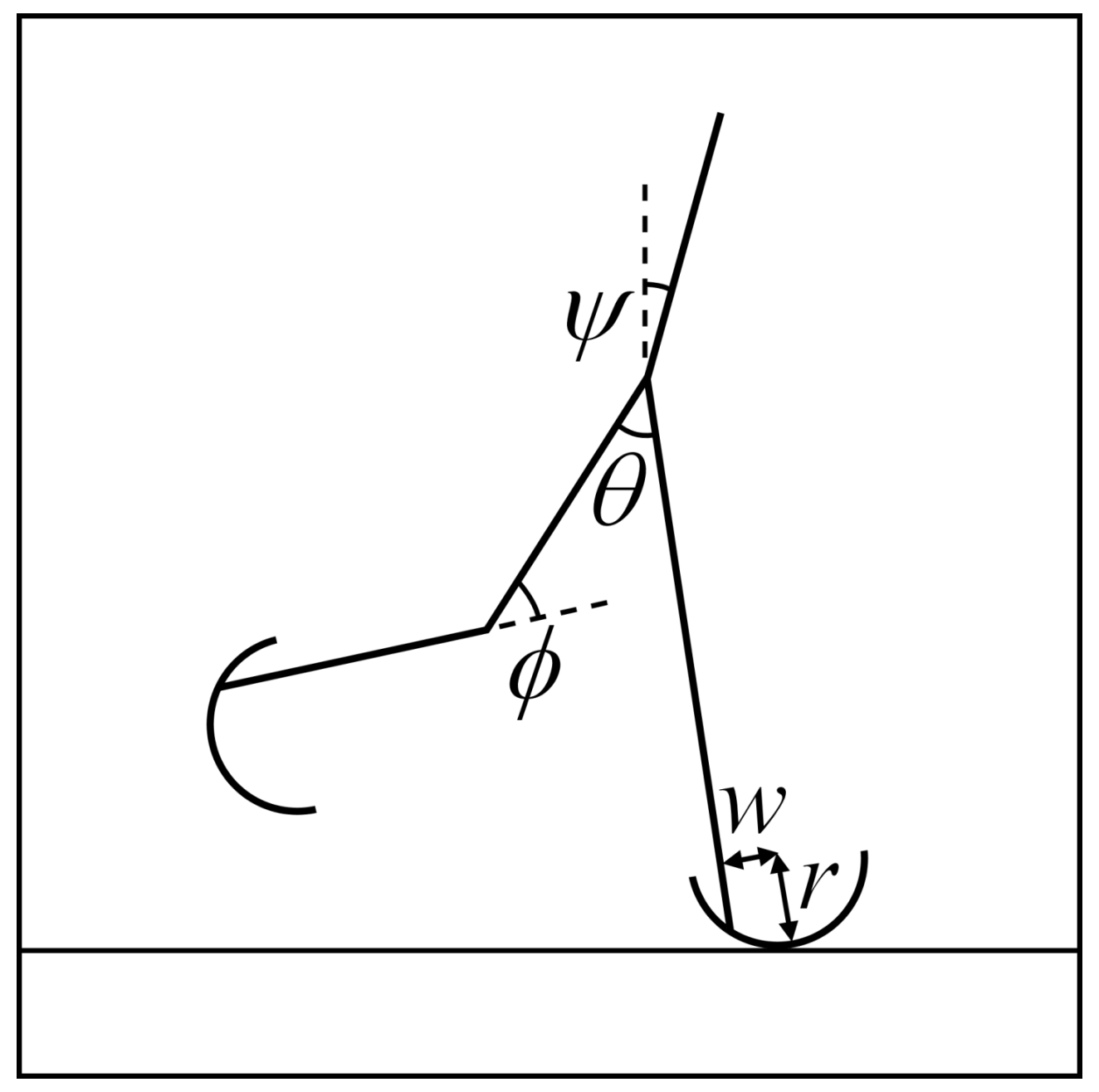
- Actuated limit cycle walkers hold the potential for unparalleled efficiency, stability and versatility in bipedal locomotion.

- Several different control methodologies are being investigated by various groups, with a range of levels of complexity.

- We are interested in finding the simplest possible control schemes that allow stable and efficient walking.

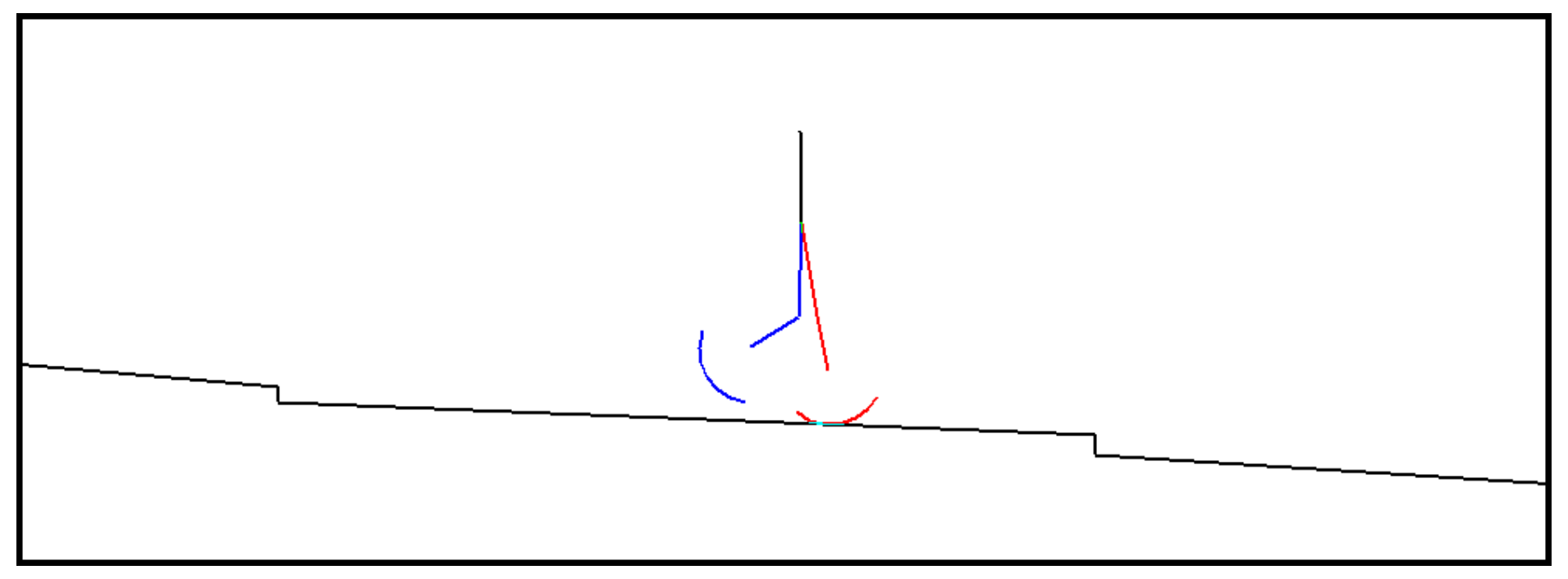
METHODS

- A five-link walking model with arc-shaped feet was used.
  - 1.83 m tall with anthropomorphic limb lengths and centers of mass
  - Upper body orientation constrained to bisect thigh segments
  - Knee-stop holds swing leg straight after full extension ($\phi = 0$)



1. Five-link walking model

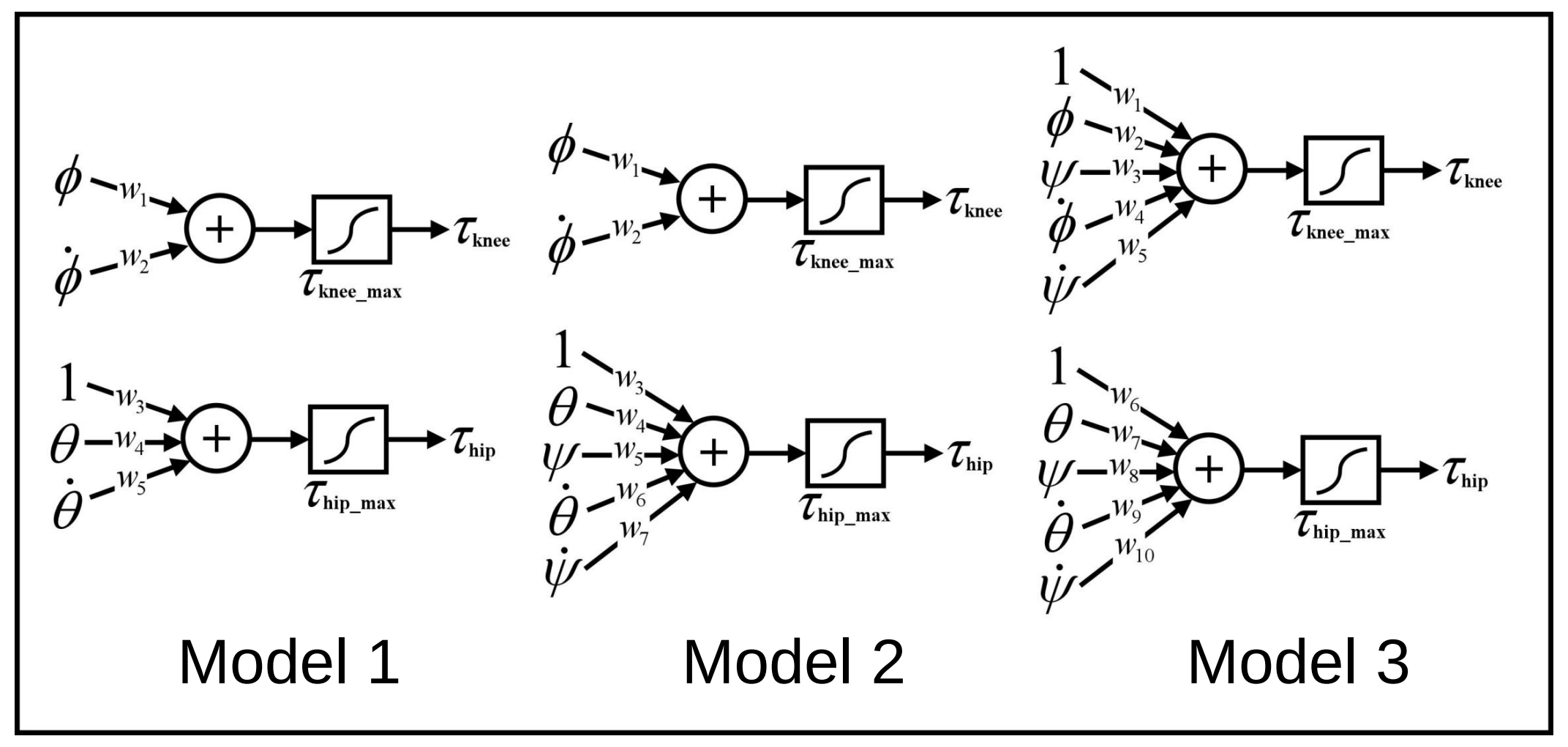
- The task of the walker is to traverse a terrain that has both variations in slope and abrupt step-downs. Every 3-6 m, a step down of 0-20 cm occurs and the slope is changed to a value between 1-5º (all three values from uniform random distributions). Foot scuffing after step-downs is ignored.



2. Example of simulated terrain

- Control is exerted through torques applied at the hip (τ_{hip}) and at the knee (τ_{knee}).

- Three control architectures are investigated. Each involves taking a weighted sum of various combinations of $(\theta, \phi, \psi, \dot{\theta}, \dot{\phi}, \dot{\psi}, 1)$, and thresholding the output to reasonable limits with a sigmoid function.

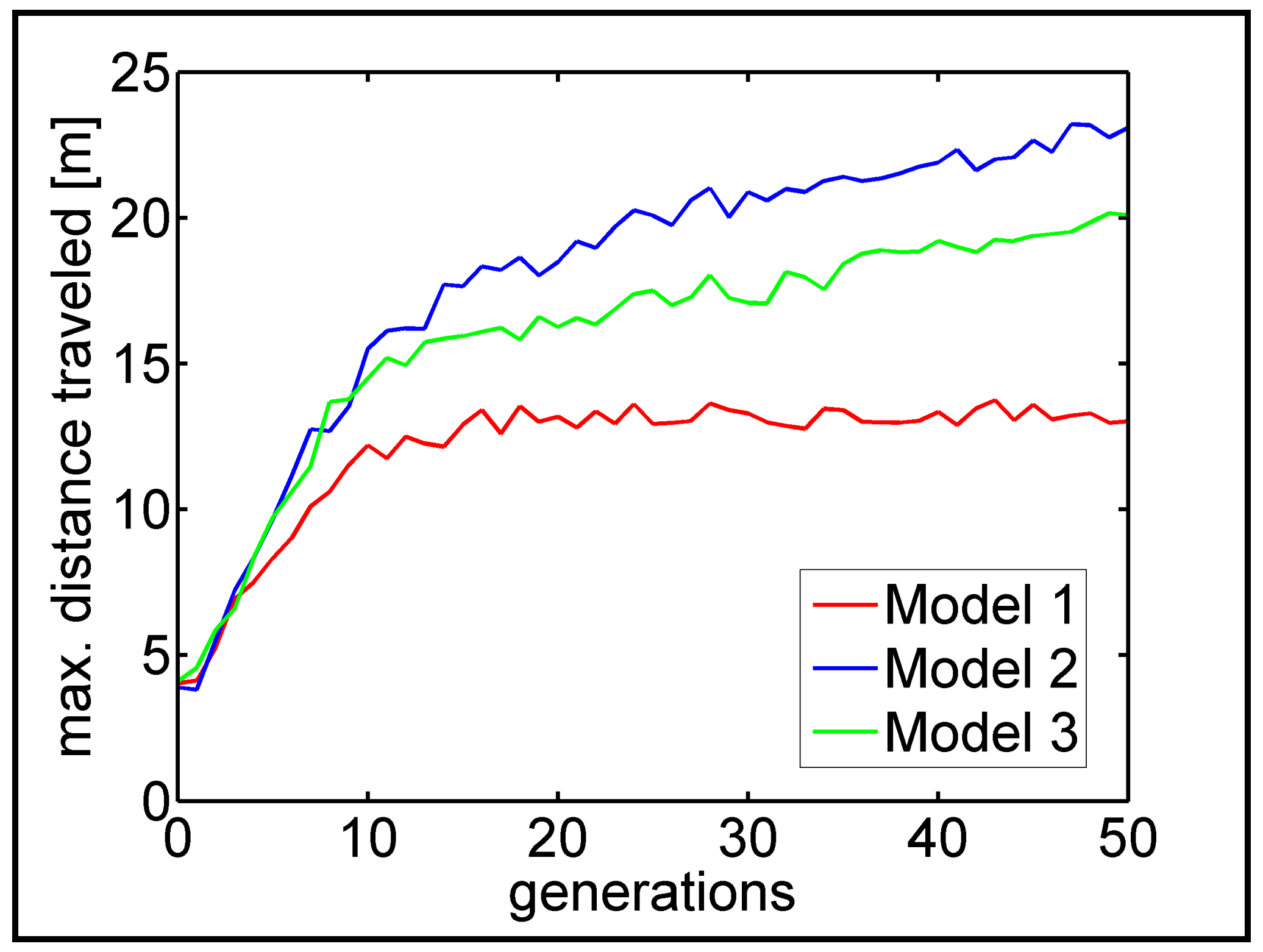


3. Basic control structures

- An evolution strategy (similar to a genetic algorithm) was used to tune the weights, as well as rollover shape parameters *r* and *w*.
  - Fitness function: distance traveled before falling down or using a fixed amount of energy
  - Terrain is regenerated each generation
  - 50 generations per run
  - Population size is 50, and the best of 100 offspring are retained each generation
  - Discrete, local recombination on half of parents
  - Gaussian mutation on all offspring
  - One strategy (step size) variable
  - 50 runs were conducted for each model
  - At the conclusion of each run, a tournament was held between the best individuals of the last 20 generations (20 trials each), and the winner was tested for an additional 100 trials

RESULTS

- Averaging the results of the 50 runs, it is clear that Model 2 performs the best, followed by Model 3.



4. Evolution strategy results

- Model 1 stops improving after about 15 generations, while Models 2 and 3 are continuing to improve after 50.

- Testing the performance of the best individual from each run confirms that Model 2 evolves better solutions than Models 1 and 3.

	Model 1	Model 2	Model 3
Dist. [m]	8.6 ±1.5	20.3 ±3.5	18.0 ±4.1
Fall %	65 ±21	13 ±10	10 ±9
r [cm]	23.5 ±2.7	19.0 ±5.2	21.5 ±4.8
w [cm]	6.6 ±3.7	1.7 ±1.6	2.2 ±2.2

5. Performance of the three models (averaged from 50 runs)

- Models 2 and 3 are extremely stable, falling in only about 10% of trials, while Model 1 falls in 65% of trials. This discrepancy in stability helps to explain the large gap in distance traveled.

- The large standard deviations in distance and fall % indicate that several runs got stuck in significantly suboptimal local minima.

- The relatively small standard deviations for *r* and *w* (compared to the possible range) indicates that there is a correlation between these parameters and walking stability/efficiency, and that good values can be found with an evolutionary algorithm.

- The best set of weights evolved by Models 2 and 3 resulted in travel distances of 27.5 and 25.9 m, and had corresponding fall percentages of 3 and 6%, respectively.

DISCUSSION

- The improvement of Model 2 over Model 1 clearly indicates that incorporation of upper body angle and/or angular velocity into hip torque control greatly improves bipedal stability. Although this was expected, the degree of stability that is possible using this linear weighted sum of sensory inputs is surprising.

- The lack of improvement of Model 3 over Model 2 indicates that upper body angle and angular velocity are not critical variables for swing knee control, and that direct PD control is sufficient. However, it should be noted that both Models 2 and 3 were continuing to improve after 50 generations, so a small benefit regarding ψ and $\dot{\psi}$ may be possible with further optimization, or perhaps using a nonlinear control mapping.

- Inspecting the weights evolved for the hip controller for Model 2, it is clear that the $\theta, \dot{\theta}$ and 1 (“bias”) terms amount to a form of PD control, while ψ and $\dot{\psi}$ together cause additional hip torque to be applied when the walker is moving down a steep slope or recovering from a step-down, thus swinging the leg forward faster.

- It remains unclear whether both ψ and $\dot{\psi}$ are needed for robust hip torque control, or if either variable alone might lead to similar or better performance to Model 2 (using an evolutionary algorithm). This is currently being investigated.

- The hip angle θ could reach over 90º for large step-downs using these controllers. This is much larger than occurs with humans and would likely lead to loss of balance in a robotic model. Using an ankle push-off instead of gravity as a source of energy might help to mitigate this issue.

- The rollover radii for Models 2 and 3 were typically about 11% of the walking model’s total height – within the low-normal range for a human.

CONCLUSION

- The weighted linear sum of sensory variables is sufficient for robust and efficient swing leg control of a five-link 2-D walking model. Specifically, simple PD control works well for the knee, while control of the hip benefits greatly from incorporation of the tilt angle of the upper-body and its derivative.

- Evolutionary robotics – the application of evolutionary algorithms to robot control – is a very powerful yet relatively easy-to-implement way to tune controllers for limit cycle walkers.

- The fitness function used here – distance traveled before falling down or using a fixed amount of energy – is useful because it promotes evolution of a controller that is both stable and efficient (multi-objective optimization) through a single measure. Inclusion of additional objectives such as walking speed is straightforward.

- The superior performance of Model 2 compared to Model 1 demonstrates the importance of including appropriate variables or features (combinations of variables) into the control structure. Similarly, the inferior performance of Model 3 compared to Model 2 demonstrates that the inclusion of extraneous control variables can impede evolutionary parameter optimization. This motivates further studies on basic walking models to find control structures well-suited to limit cycle walking.

- Evolutionary algorithms afford the ability to concurrently find good solutions for parameters that encode morphological characteristics of the system along with the control parameters. In this study, the radius and offset of the foot rollover shape was successfully evolved. This is not possible with other control methodologies.