Adaptive exoskeleton assistance on a self-paced treadmill using game theory algorithms

Zijie Jin*, Jason Isa, Annika Pfister, Sam Burden and Kim Ingraham

*Correspondence to zijiejin@uw.edu

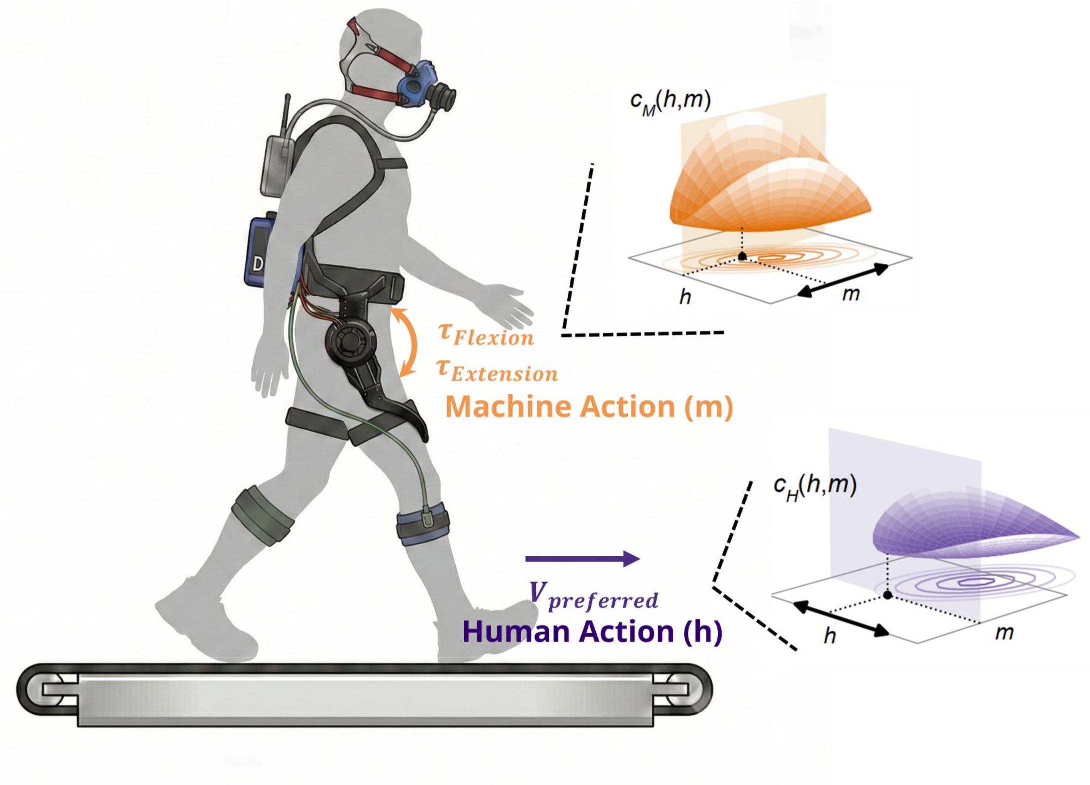
Department of Electrical and Computer Engineering, University of Washington, Seattle, WA

Introduction

- Lower limb exoskeletons are often limited by humans' complex responses to external assistance.
- Human-in-the-Loop (HILO) optimization can optimize assistance for a human's goals (e.g., minimize energy cost) but are insufficient for cases when the human interacts with an adaptive robot.
- Game theory can offer a new framework to examine how exoskeletons can influence a human's actions using only observations of such actions.

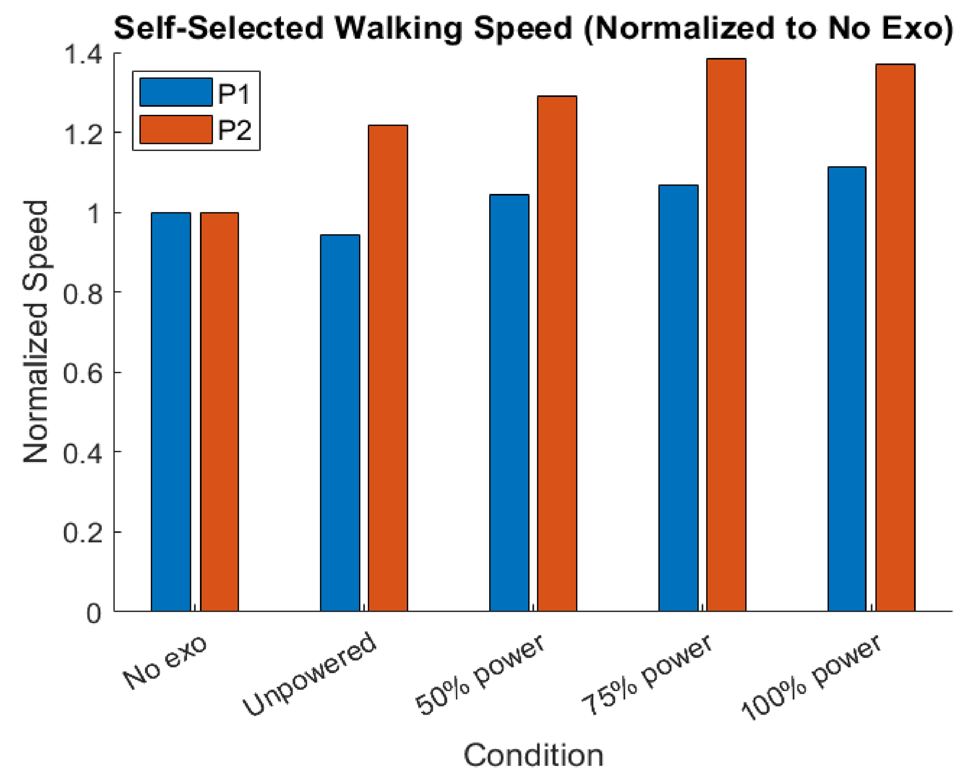
Objective: Develop exoskeleton controllers that steer the human-robot system towards game theory equilibria

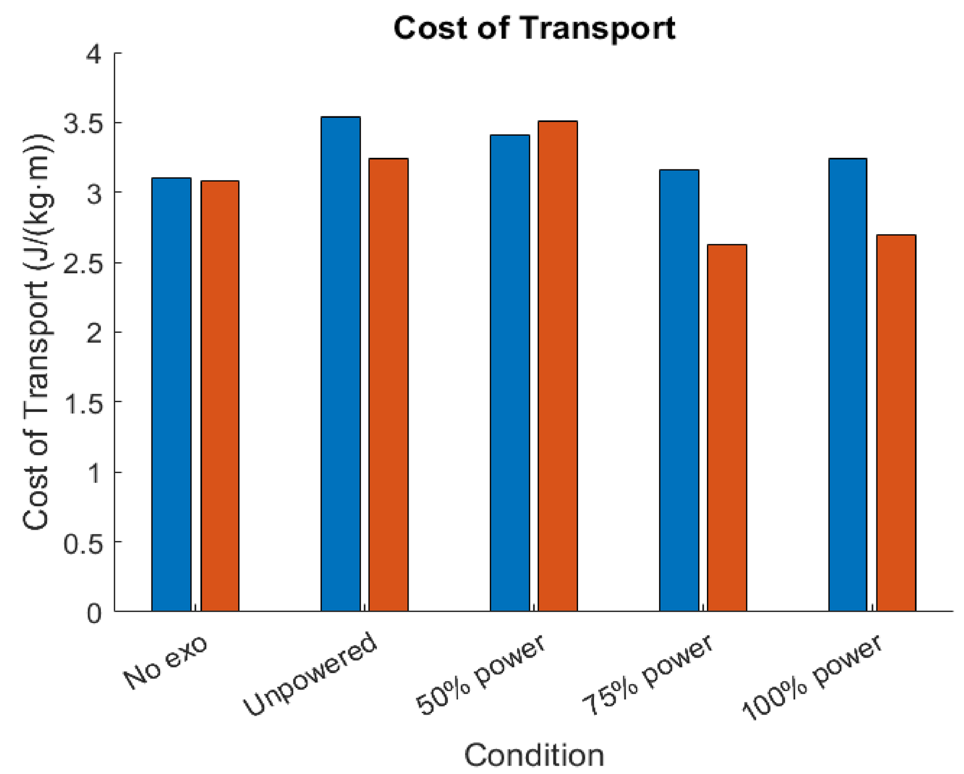
Methods



- A self-paced treadmill [1] measured human self-selected walking speed as human action (h)
- A customized 1-DOF hip exoskeleton provided bidirectional assistive torque as machine action (m)

Self-selected speed as human action?





- We measured naïve participants' (n = 2) self-selected walking speed and cost of transport as a function of increasing levels of exoskeleton assistance.
- Both participants' preferred walking speed increased with increasing assistance.
- Both participants' cost of transport decreased below unpowered condition with increasing assistance. P2 reached lower level than normal walking baseline.

An adaptive exoskeleton controller based on game theory

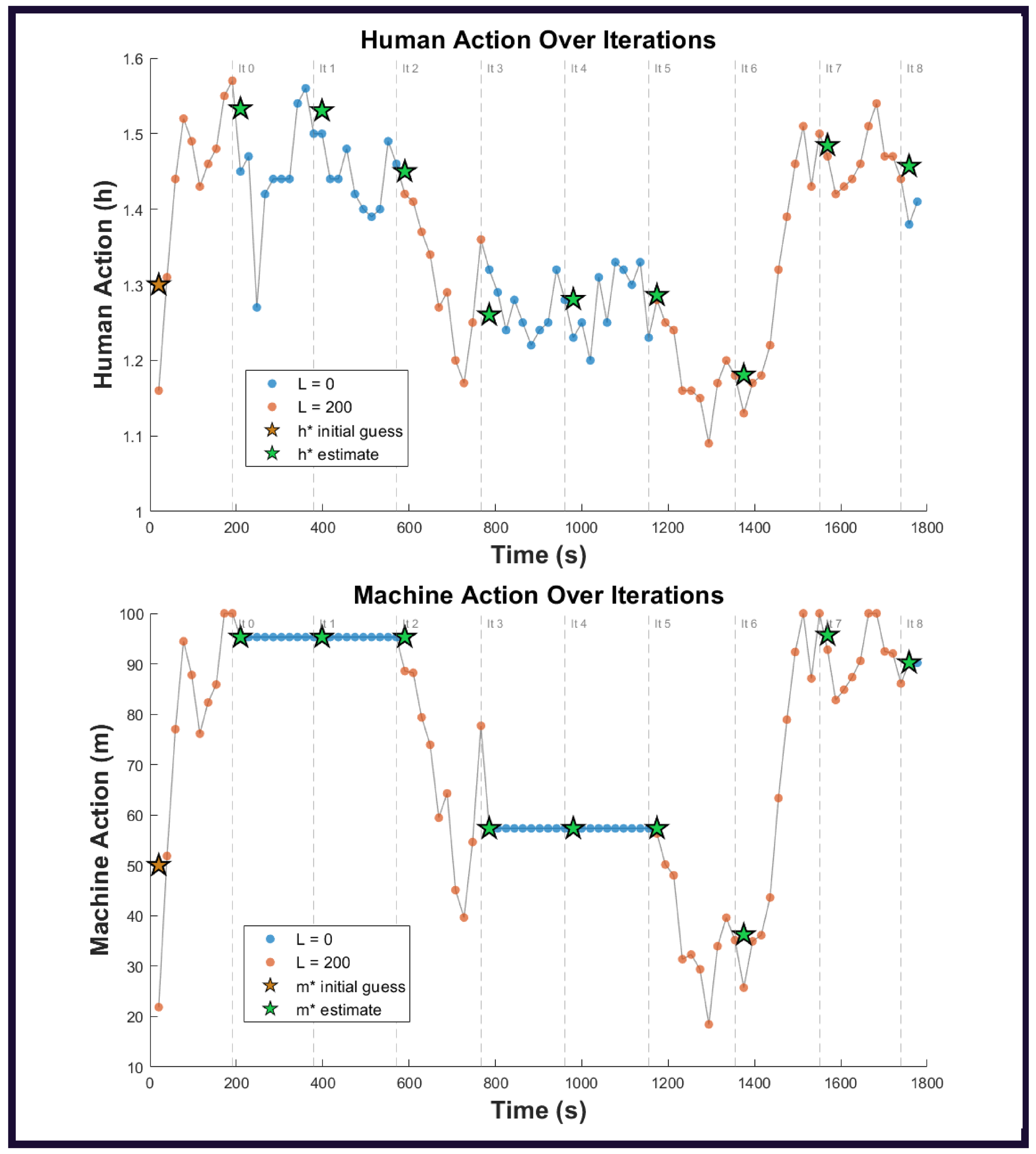
Pseudo code:

Algorithm 1 Human-in-the-loop Optimization

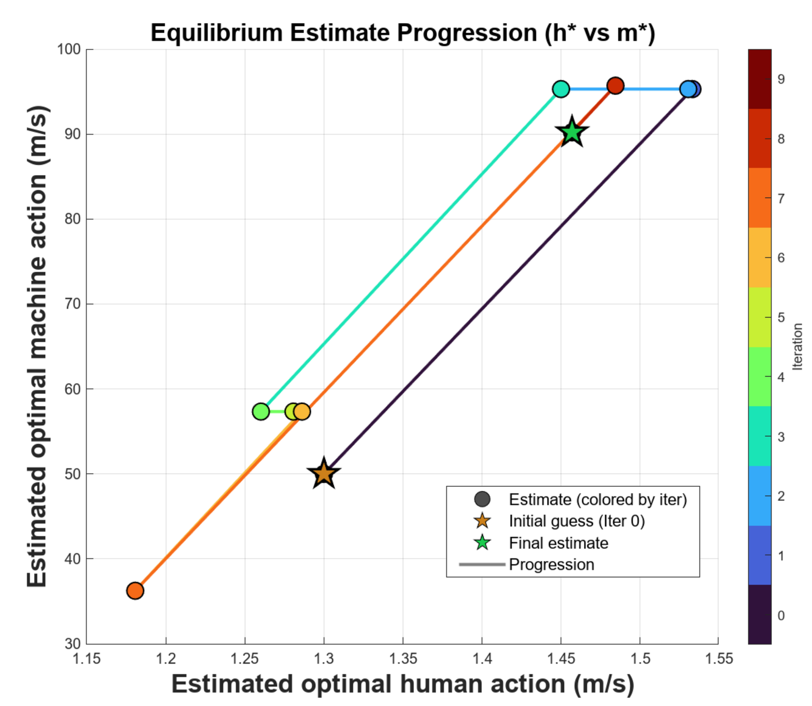
Require: Initialize $\widehat{h}^*[0]$, $\widehat{m}^*[0]$
for $k = 0, 1, \ldots, K-1$ **do**
  Randomly sample $L[k] \in \mathbb{R}^{d_M \times d_H}$
  $(\widehat{h}^*[k+1], \widehat{m}^*[k+1]) \leftarrow \texttt{Trial}(L[k], \widehat{h}^*[k], \widehat{m}^*[k])$
end for

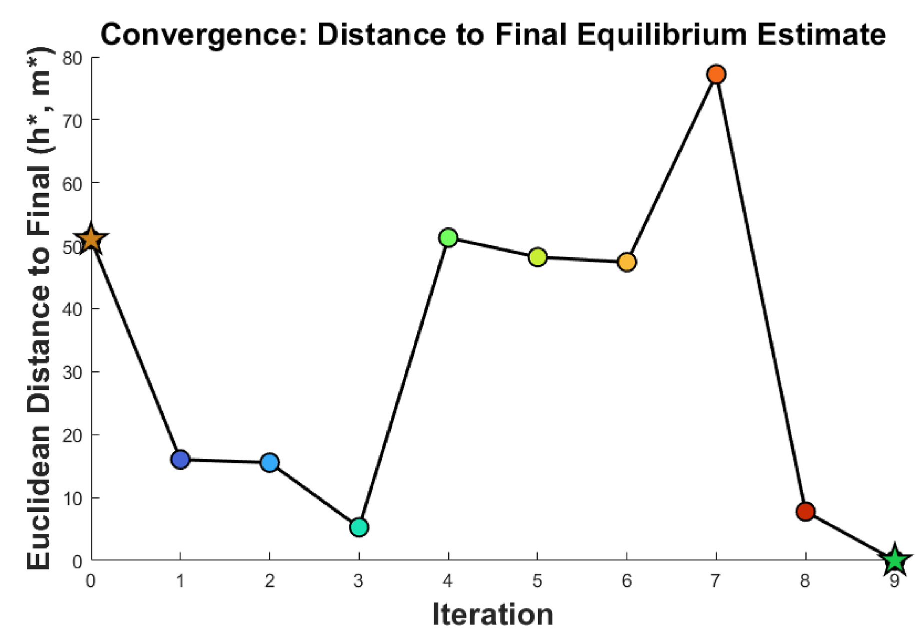
Algorithm 2 `Trial` Subroutine

Require: $\widetilde{L}$, $\widetilde{h}^*$, $\widetilde{m}^*$
for $t = 0, 1, \ldots, T-1$ **do**
  $h[t] \leftarrow \texttt{get\_manual\_input}(t)$
  $m[t] \leftarrow \widetilde{L}(h[t] - \widetilde{h}^*) + \widetilde{m}^*$
  $\texttt{display\_cost\_to\_H}(c(h[t], m[t]))$
end for
return Mean of last t iterations of h and m



- Machine played a policy affine to human action, with the policy parameter L = {0,200}.
- Machine estimated human adaptation during L = 0 and tracked human response to varying assistive torque during L = 200.





- Evolution of Euclidean distance to final estimate shows that the current iteration number isn't enough to reach convergence

Conclusions and next steps

- Exoskeleton assistance shows promise to increase human's self-selected walking speed while decreasing their overall cost of transport, and the pair can be a combination of actions for a game-theory-based exoskeleton controller
- Future work needs to recruit more participants, explore hyperparameters for game-theory controller for improved convergence and compare baseline and convergence point for cost of transport performance

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References

[1] Song, S., Choi, H. & Collins, S. H. Using force data to self-pace an instrumented treadmill and measure self-selected walking speed. J. NeuroEngineering Rehabil. 17, 68 (2020).
[2]Jason T. Isa, Samuel A. Burden, Lillian J. Ratliff. Achieving Alignment Through Adaptive Play: Helping Optimize Objectives Without Observing Them. Uncertainty in Artificial Intelligence (UAI 2026). Submitted