Modelling Affordance based on Physical Characteristics

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Abstract

As climbing continues to grow rapidly in popularity, climbers must develop a heightened awareness of their own physical capabilities and limitations. Unlike disciplines that rely on standardized motion patterns, climbing demands that climbers dynamically and quickly adjust their movement strategies to reach the goal as quickly as possible based on their individual physical characteristics such as height, arm span, and leg span, and requires continuous decisions about which holds are reachable by the hands or feet and how to progress towards a target while remaining balanced. We study this problem on multiple fixed walls whose annotations consist only of hold shapes. We estimate the center coordinates of the grab point by using the coordinates provided for each vertex, and we synthesize a start configuration by randomly selecting holds because no start holds are provided. A Graph Neural Network (GNN) is utilized to label every hold as unreachable (0), only hands reachable (1), only feet reachable (2), and both hands and feet reachable (3) by using geometric features derived from the current limb positions and normalized by the climber’s anthropometrics, such as height, ape index, arm span, and flexibility. On top of these predictions we compare two planners, the first one is a greedy baseline that moves hands and feet simultaneously toward the goal while keeping feet below hands and always select the furthest holds, and the other one is a posture-aware planner that moves one limb type at a time, prefers hands above feet, and encourages vertical alignment between hands and feet centers via an angle threshold and alignment cost.

We evaluate three different cohorts, which are casual, skilled, and elite, and each cohort is with 100 simulated climbers on the same wall, start, and goal. Using bar charts, we summarize completion rate, and average steps to goal for successful trials, including stratifications by key anthropometric factors. The results show that performance differences are driven primarily by individual body attributes, such as arm span, leg span, height, and ape index, rather than the cohort label alone. Climbers with larger effective reach complete more frequently and in fewer steps. The greedy planner achieves higher completion rates, whereas the posture-aware planner yields more vertically balanced sequences at the cost of success on some instances, which reveals a practical trade-off between progress and stability. We provide an evaluation protocol and analysis that can inform route setting and training feedback for different ability levels.

Ethics Statement

After discussing with my supervisor, we plan to use the dataset that contains the climbing route with hold points from [Kaggle](https://www.kaggle.com/datasets/tomasslama/indoor-climbing-gym-hold-segmentation/data) and simulate the climbers with different attributes in our research. Therefore, this project that do not require ethical approval at all, because it does not collect or process any relevant data.

Supporting Technologies

* Programming Environment: Code was developed using a recent version of Python 3 with Jupyter notebooks and plain scripts, utilizing data science libraries such as NumPy and Pandas.
* Deep Leaning Framework: PyTorch for model definition, training, and inference, tensors for moving CPU/GPU, and PyTorch Geometric for graph ops and batching.
* Version Control: Git with a GitHub repository was used to ensure that the project is securely stored and documented in the cloud.
* I used LaTeX through the online service Overleaf for the formatting of the thesis.

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Chapter 1

Introduction

This chapter opens with background on indoor climbing and motivates climber-conditional reachability analysis as a tool for route setting and training. We then discuss the limitations of evaluations based on hierarchical or single-strategy assessments and introduce our approach. A graph neural network based on anthropometric data is combined with two planners, which are a greedy baseline planner and a pose-aware strategy planner. Finally, we highlight development challenges (centroid approximation, synthetic starts, and planner hyperparameters) and outline the research aims on ability-group differences, policy trade-offs, and sensitivity.

* 1. Project context and problem

Indoor climbing success depends jointly on wall geometry, holds affordances, and a climber’s body[1]. Route levels summarize difficulty for an average person, but for setters and coaches, they often need a more precise answer to who can do what, how can do it, and in how many steps[2]. A computational pipeline is built for a fixed wall with annotated holds, a start and goal, and simulated climbers described by anthropometrics, which is to predict whether the goal is reachable, and how many steps it will take under a chosen movement strategy.

We represent the wall as hold graph whose nodes hold centroids that are derived from the provided shapes and whose edges connect spatial neighbors. A reachability model is built by graph neural network, labels each hold as unreachable, hand-reachable, foot-reachable, or reachable by both, which is inspired by Nishad[3]. On top of these predictions, we generate motion sequences using two planners. One is a greedy baseline that moves hands and feet simultaneously toward the goal and keeps feet below hands. The other one is a posture-aware planner that moves hands or feet at a time, and encourages vertical alignment between hand and foot centers through an angle threshold and alignment cost. For evaluation, we simulate three cohorts (casual, skilled, elite) of 100 climbers each, sampled over realistic anthropometric ranges[5][6][7], such as height, ape index, weight, and strength.

* 1. Practical and Methodological Implications

Simulating reachability rather than relying on rough grades brings two immediate benefits, which are route setting and training feedback. For route setting, setters can test whether a proposed route is unfairly biased towards a specific body type, especially the climbers who are taller and have longer arm spans[2][8], and identify where to add intermediate footholds or handholds to reduce the impact of physical differences[4]. For training feedback, coaches and climbers receive targeted guidance. For instance, when performance is limited by poor foot follow-through rather than hand reach[1], or when movement patterns consistently violate upright posture and cause instability[9]. Coaches and climbers can use this feedback to tailor training, such as building strength or improving hold point selection.

The broader significance of this work lies in its methodological contribution. We present a light-weight and transparent tool that integrates two complementary components: a learned model of local hold affordances, which is implemented as a graph neural network, and a set of explicit motion rules encoded in path planning algorithms. This design allows performance results to be clearly traced back to the decision logic of the GNN’s predictions or planner, e.g. whether the goal can be reached by climber or the number of moves required. This traceability not only facilitates targeted optimization of models or rules, but also enhances the system's interpretability and reliability for setters, coaches, and researchers.

* 1. Prior work and selected approach

The classic difficulty assessment method is a combination of expert judgement and coarse statistical data, such as height and grade[8]. Recent research on accessibility and posture planning has prompted us to learn about the reachability of each grip point based on the climber’s condition, and then plan based on these predictions[1][12]. Our approach follows the two-stage design for transparency and speed: Climber-conditioned reachability and Policy-level simulation.

For Climber-conditioned reachability, the GNN predicts unreachable, hand reachable, foot reachable, and both reachable labels for each hold by mixing features of the distance between the current position and the current hands/feet position, and normalizes them based on the range of arm and leg reach. Anthropometric vectors, such as height, ape index, spans, flexibility, and leg-length factor, modulate the node embeddings. Thus, the same wall will produce different reach maps for different climbers[3][11].

For Policy-level simulation, we apply two simple and interpretable planners, rather than solving full-body dynamics. The first planner is greedy progress, which can achieve the fast expansion of the reachable frontier[4]. The second planner is posture-aware, which achieves softer progress but higher likelihood of hands-over-feet and near-vertical alignment[12].

This kind of separated design allows us to study trade-off between progress and stability and attribute failure to limitations in model coverage or conservative movement choices by planners.

* 1. Central Challenges
* Sparse supervision and geometry: The dataset from Kaggle contains hold shapes (the coordinates of each vertex) but no official start configuration. We approximate each hold by its centroid and generate a synthetic start, which may miss directionality/friction effects of real holds.
* Coupling perception and policy: A model will mark many holds reachable based on provided position, but a conservative strategy may result in a deadlock. Conversely, an aggressive strategy may succeed without strict posture control. It is hard to clarify these relationships.
* Fair comparisons across abilities: To ensure differences reflect body attributes and policy rather than random initialization, we fix the walls and goals and evaluate all cohorts on the same, and seed-controlled set of initial states. In contrast, randomized positions of climbers were employed in training to produce labels and broaden coverage.

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