Research Strategy

Significance

Successful human locomotion relies on robust communication between the visual and motor systems: the visual system finds and transfers relevant information about the world to the motor system, resulting in the finely tuned control of foot placement. An outstanding complexity of the *visuo-locomotor* system is understanding precisely how upcoming footholds are found during visual search. Independently, the study of visual search and the biomechanics of locomotion have both received a great deal of attention[1,2], but there is little research addressing their critical overlap. The lack of interdisciplinary research not only hinders progress in the independent fields of vision science and biomechanics, but additionally restricts our understanding of how the visuo-locomotor system might be affected by retinal[3] and motor diseases.

Recently, the sponsor of this proposal (Dr. Matthis) and his colleagues conducted the first investigation into eye movements made while traversing natural outdoor terrains of varying difficulty[4,5] (*Fig. 1*). Examination of this data demonstrates that eye movements made during visual search might be influenced by the biomechanical constraints of the locomotor system, such that participants fixate where they *want to step* as opposed to visually salient terrain. Critically, this observation – that the proprioceptive information of biomechanics might influence visual search – is substantiated by the current state of the visual search and biomechanical literatures.

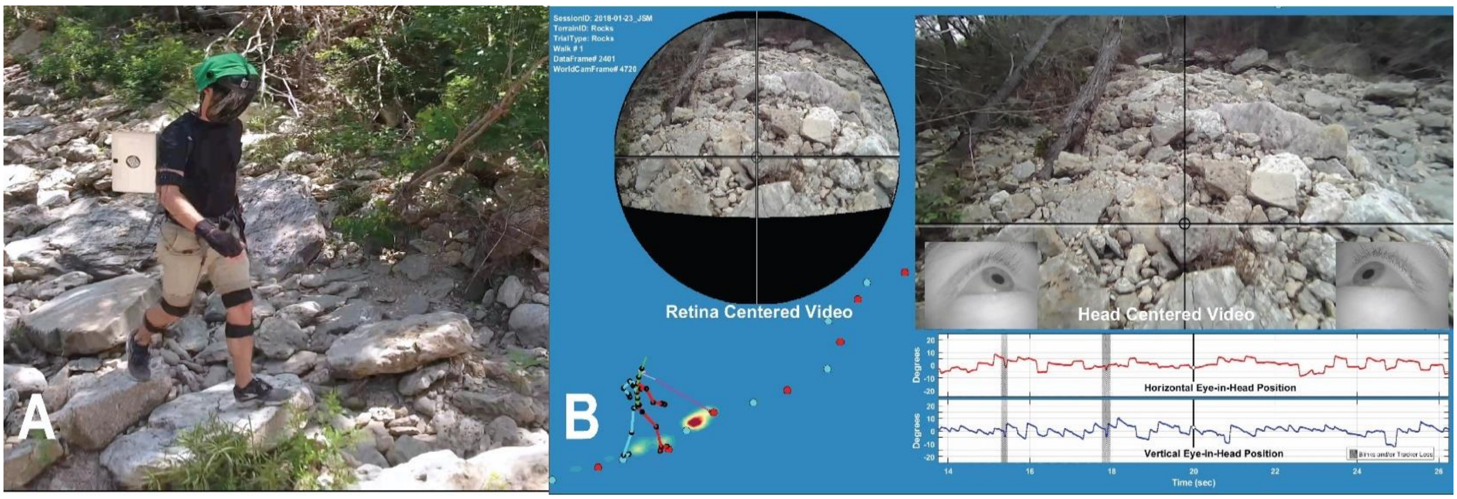

Figure 1. Outdoor measurements of the visuo-locomotor system (Matthis, Yates & Hayhoe 2018; used with permission from the sponsor, Dr. Matthis). A. A participant walking over a rocky creek bed, an example of "rough" terrain. B. Retinotopic mapping (top left) of eye movement data from a rough terrain condition, alongside corresponding head centered data and a mapping of the horizontal and vertical eye-in-head position (right side), as well as IMU-tracked body position with gaze-heatmap (bottom left). Investigations into natural eye movements suggest that the body might influence visual search during traversal of complex terrain – inspiring the proposed studies.

There is strong evidence from investigations into visual search for targets within natural scene statistics[6] that search patterns are highly fixation-efficient – as modeled by an *ideal observer* – where subsequent eye movements are made to maximize the probability of finding the target. Additionally, there is a body of research which demonstrates that visual search is highly task-dependent[7–12]. This research demonstrates that the visual system works to provide information relevant to the goals of the perceiver, such that eye movements are efficiently made to serve the current task demands and reduce uncertainty[4]. What information is most relevant to the locomotor system?

Examinations of bipedal biomechanics consistently demonstrate that human locomotion is energetically efficient[1,13]. Recently, researchers have shown that the humans are constantly adapting their gait to maintain energetically optimal movements even seconds after perturbation[14]. This, combined with evidence that humans can readily perceive energetically efficient[15] or optimal[16] body movements, suggests that the visual system must be seeking information which allows for energetically efficient foot placements.

<u>In this proposal we will determine the influence of biomechanical constraints in visual search strategies while walking across complex terrain</u>. To achieve this, we must investigate the visuo-locomotor system using a new paradigm designed to understand visual search in the unique context of locomotion, by manipulating explicit task-constraints (**Aim 1**) and visual search difficulty (**Aim 2**). Additionally, we will go outdoors in **Aim 3** to specifically investigate how visual search strategies might incorporate biomechanical information in natural environments.

Innovation: Previous laboratory investigations into the visual control of foot placement have been greatly restricted by the length of the walkable space[17–19], where only a few steps are recordable in a given trial and (in some cases) no feedback is provided to the participant to tell them if their foot placement was successful. Additionally, some of the best work investigating the visual control of foot placement took place at a time where there was a technological inability to measure precise eye movements in relation to the gait cycle in real time. Here, we develop our new experimental paradigm using an indoor, 14m long (3m wide) projector-based Augmented Reality (AR) groundplane (*Fig. 2*, *Fig. 3*), which participants will actively walk across, enabling us to measure ~25 footsteps made in a given trial. We will measure participant eye movements with a mobile, binocular eye tracker (Pupil Labs), as well as their full body kinematics and position tracking using maker based motion capture (Qualisys). By combining new technologies with a much larger laboratory space (as well as an improved capacity to measure visuo-locomotor in natural, outdoor terrains), we provide the first experimental designs which will be sufficient to understand the influence of biomechanical constraint in visual search.

Objectives:

In **Aim 1**, we target the *task-dependency* of visual search by manipulating the instructions participants receive while engaging with the same, 14m long, projected groundplane stimulus. In experiment 1, participants will receive different instructions in three different experimental blocks: 1. Standing still while watching the groundplane flow toward them, 2. Walking across the groundplane, searching for target circles, or 3. Walking across the groundplane while only stepping on circles and avoiding Landolt C's (*Fig.* 1). By measuring how visual search patterns change across these three task-dependent conditions, we will be able to parse influence that might be driven by self-motion, biomechanical constraint, and the fixation efficiency of investigating visually salient terrain features.

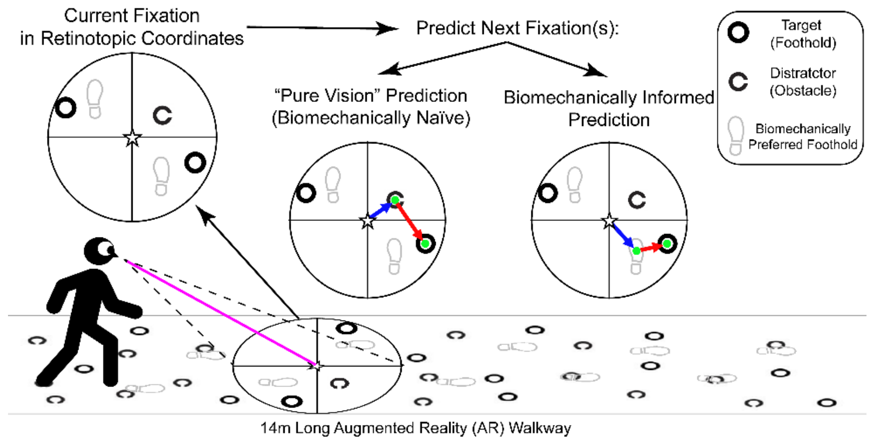

Figure 2. A diagram of our experimental paradigm depicting a subject walking on an AR-projected terrain of target footholds (circles) and distractors (Landolt C's), where the gray footprints represent the subject's biomechanically preferred footholds which would maintain the energetically preferred gait cycle. The subject's gaze vector is represented as the magenta line forming a segmented cone of central vision (dashed lines) with the current fixation represented by the star. We then blow out the segmented cone of vision into retinotopic coordinates, representing the visual information on the ground at a given point in time as they are walking. Our goal is to measure the participants next fixation(s) (represented as the green dots) in the visual search for footholds, thereby understanding how the visual system acquires the information necessary for planning foot placement. In our experiment, we test two potential hypotheses, the "*Pure Vision*" prediction vs. the "*Biomechanically Informed*" prediction. "*Pure Vision*" predicts that visual search pattern will be driven by the visual information in the scene, saccading towards the most salient objects on the path to find the target (blue and red arrows represent the first and second searching fixations, respectively). "*Biomechanically Informed*" predicts that the visual search pattern will be biased by the biomechanically preferred foothold, saccading to potentially visually non-salient space to initiate the search process, and then from there looking for the nearest salient object – finding the target.

In **Aim 2**, we investigate the hypothesis that the difficulty of visual search (acuity of distractors) will force participants to use an alternative foothold planning strategy. Investigation of eye movements made while traversing outdoor terrain[4,5] demonstrates that as terrain difficulty increases, the more precise information about the second and third upcoming foothold is required for appropriate step planning. It is unclear, however, if this is driven by the difficulty of the terrain, or alternatively the difficulty of the visual search task itself. As visual search difficulty increases, and more certainty is required out of each fixation, are more careful visual search patterns adapted, like what has been observed in rough terrains[4,5]? We address this question in experiment 2: Participants will walk across our AR projected terrain, where they will be tasked with only stepping on circles and avoiding C's, and from trial to trial we will manipulate the acuity of the distractor "Landolt C", thus increasing the difficulty of identifying circle footholds[20].

In **Aim 3** we observe the visuo-locomotor system in natural outdoor terrains in unprecedented detail, combining binocular eye tracking, IMU-based motion capture, and 3-D terrain Photogrammetry mapping (*Fig. 4*). By combining these three different methodologies, we will be able to measure visual search patterns made during locomotion of complex, 3-D terrains, mapping where precise eye movements fall onto complex 3-D objects (e.g., rocks). This exploratory aim explores the generalizability of the previous two aims, attempting to demonstrate that biomechanical information influences visual search in natural environments as well as laboratory settings.

Approach

Aim 1. Manipulate task-constraints to investigate visual search strategies in pure-visual vs. locomotor-constrained visual search tasks, with and without self-motion.

Experiment 1. How do explicit task demands elicit change in visual search patterns?

Rationale: Previous studies examining patterns of visual search have shown that an ideal observer model is capable of replicating search patterns while searching for Gabor patches in 1/*f* noise[6]. This study demonstrates that individual eye movements seek to maximize the information gained with each fixation. Additionally, there is a wealth of research from Hayhoe and colleagues which further demonstrates that visual search is highly information-efficient[7–11] (i.e., uncertainty reducing) and task dependent; eye movements made in natural environments seek the most pertinent information for the task at hand. Given that the locomotor system optimizes for energetic efficiency, it is plausible that during locomotion that the visual system uses relevant biomechanical information to aide the visual search process. Under what circumstances does visual search incorporate influence from the biomechanical constraints? Is it the task of looking for target-footholds which will impose biomechanical influence, or is it the act of self-motion itself?

Self-motion by alone might be sufficient to recruit neural mechanisms that influence visual search patterns: there is strong evidence that many motor systems (and perhaps the oculomotor system) are *softly assembled*[21], meaning that the components of the system are not "hard-coded", but rather are flexible, recruiting different muscles or neural systems based on task demands[22]. In experiment 1, we investigate layers of task demands in three different within-subjects conditions: Condition 1 – visual search while standing still; Condition 2 – visual search while walking straight forward; Condition 3 – visual search for footholds.

We hypothesize that visual system is optimizing for the locomotor task (condition 3) – where targets that could serve as footholds will attract fixations, and other potential targets will be ignored. When the same targets are merely objectives for visual search (conditions 1 and 2), independent of biomechanical constraint, participant visual search patterns will stretch beyond targets that they might step on. While it is possible that self-motion (condition 2) could impose biomechanical influence on the search process, we anticipate that because the targets are independent from where the participant is stepping, that biomechanical information will not influence visual search in this condition.

Methods and Stimuli: We will use pilot data to conduct a power analysis to assess the number of subjects required for this study – anticipating that 6 subjects will be sufficient[4]. During the experiment, we will record each participant's binocular eye movements (Pupil Labs) and full body kinematics (Qualisys) over approximately one hour and thirty minutes of data collection. Prior to the start of the experiment, 10 free walking trials will be recorded to serve as a baseline measure for each participant's preferred gait cycle and biomechanics – where participants are asked to simply walk at their preferred walking speed across the 14m tracking space ten times. Each subject will participate in three 30 minute condition blocks, presented in random order. The groundplane stimulus will be made up of target circles and distractor Landolt C's (*Fig. 2*) (diameter and line width for both circles and C's: 20cm diameter, 5cm line width). The precise ratio of target-Circles to distractor-Landolt C's per square meter will be determined in a pilot study such that the visual search task is challenging, but also so that the participants can successfully walk across the 3x14m groundplane without stopping or making more than 2 missteps. The stimuli will be the repeated in the three different blocks, but the task-instructions given to our participants will change. There will be 60 trials in each condition, for a total of 180 trials per subject.

Condition 1: Participants will be told to stand at the beginning of the AR projector terrain, and that their only task is to look for circles among distractor C's (Landolt C's), and to click a button on a remote clicker indicating that they are fixating on a circle (target). In this condition (1), the participants will stand still at the beginning of the ground plane display as the stimulus flows towards them at the speed which the terrain would move if they were walking comfortably (measured during the 10 free-walking trials for each subject before the experiment begins).

Condition 2: Participants will be given the same stimuli and search instructions as in Condition 1, but now are told that they must walk at a comfortable walking speed across the stimulus to the other side of the room, indicating when they find a circle with their remote clicker.

Condition 3: Participants will be given the same stimuli as in Condition 1, but now are told that they are required to cross the 14m walkway by only stepping on circles. Participants will receive auditory feedback for each step (happy beeps for successful foot placement, buzzer sound for a miss) and will have to repeat the trial if they have three or more missteps. Participants will not use the clicker in this condition.

While the clicker data in condition 1 and 2 will be collected and observed, it serves primarily to engage our subjects with the visual search task; no specific hypotheses have been formed around differences between clicker responses in the two conditions.

Data Analysis: For our initial analysis, we will first time match the eye movement and kinematic data. We will perform an analysis on the motion capture data to identify the current phase of gait in time (double support, early swing, or late swing; in Condition 1, the gait will be identified simply as “standing”), so that we can categorize fixations relative to these three phases of the gait cycle. Additionally, by combining the eye movement and motion capture datasets, we will be able to calculate where the participant was in the room, and where their 3-D gaze vector intersects with the groundplane (a la *Fig. 1*). Fixations will be defined as moments the world-relative gaze position is maintained for greater than 100ms (fixation length determined by examination of eye movements made in natural terrains[4,5]). We will treat every fixation as a sample marking the search time (time since a previous target fixation), phase of gait, and the task condition in which the fixation occurred. We will map the fixation data in two different reference frames: world-centered and retinotopic (polar coordinates: amplitude, direction) space. We will conduct two analyses to assess the potential influence of biomechanical information on patterns of visual search.

Our first analysis will focus on fixations made in world-centered coordinates where we calculate the distance between each fixation and the nearest biomechanically preferred foothold (in Condition 1, this will be the location of the subjects first step). Three biomechanically preferred footholds will be estimated using the previous two footholds and predictions based on a powered walking model[1]. Fixation distance to preferred foothold (DtPF) will serve as our dependent variable. We will then analyze DtPF using a linear mixed effects regression (LMER) model, regressing the task condition, time from last target fixation, and the phase of the gait cycle onto DtPF – where individual trial and subject variance is accounted for in the random effects structure. If our hypothesis is correct that biomechanical information will be utilized in condition 3 but not in conditions 1 and 2, then we should see a significant decrease in DtPF relative to conditions 1 and 2. Additionally, if biomechanically preferred footholds are used at the onset of the visual search process, we should see in condition 3 that, relative to search time, that the DtPF increases as time from previous target fixation increases. Finally, if there is an effect of self-motion on the utilization of biomechanical information, we should see a significant difference between DtPF in condition 2 relative to condition 1.

Our second analysis will assess the general shape of visual search strategies in retinotopic coordinates, where each saccades amplitude and direction will be recorded along with the corresponding task-condition and the phase of the gait cycle during which the saccade was made. Saccade amplitudes and directions will be analyzed using similar LMER structure in the previous analysis. We hypothesize that the overall shape of visual search strategies, i.e. the statistics of the amplitude and direction, will be strongly reflected by the task demands: In conditions 1 and 2, where subjects are free of biomechanical constraint, we expect larger amplitudes and variable saccade directions compared to condition 3, where the visual search strategy will be constrained by serving locomotor demands. Additionally, in condition 3 but not conditions 1 and 2, we anticipate that saccade direction will have a meaningful relationship to the current phase of the gait cycle. Saccade directions in condition 2 should be independent of the gait cycle because visual information is independent from biomechanical constraint – but if pure self-motion is sufficient to activate biomechanical influence, we should see a meaningful relationship between saccade direction and the gait cycle in this condition as well.

Potential Problems & Solutions: Properly segmenting gaze relative to the gait cycle, measuring time relative to target fixations, as well as calibrating independent pieces of equipment is methodologically nontrivial. Given the combined technical expertise of Dr. Matthis and myself, where Dr. Matthis has extensive experience calibrating multiple measurement systems and the two of us have a combined 18 years of experience with Augmented/Virtual Reality experiments, we are confident in our ability to conduct the research as described.

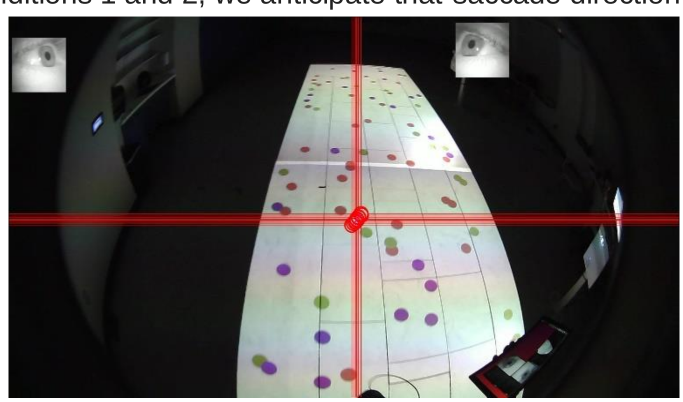

Figure 3. A time slice of a first person perspective while traversing a pilot AR groundplane. This stimulus will not be used in our experiments (see Fig. 1) but it provides a preliminary glimpse of a participant’s perspective of the AR groundplane. Projectors are mounted at the side of the motion capture space, and the stimulus will be projected onto a matte white background (such that lines of the floor will not distract from the displays). The red cross hair represents the actively measured fixation of the two eyes from the Pupil Labs binocular mobile eye tracker.

Aim 2. Parametrize the relationship between eye movements and locomotor constraints by manipulating the difficulty of the visual search.

Experiment 2. Measure the relationship between visual search difficulty and biomechanically informed route planning strategies.

Rationale: Previous laboratory studies have demonstrated that humans tend to look around two steps ahead while walking, and that this look-ahead window provides the visuo-locomotor system with the information it needs to actively adjust the biomechanics of locomotion efficiently[17–19,23,24]. More recent work examining visuo-locomotor behavior in natural terrains[4,5] shows how the foothold that participants tend to fixate on changes relative to the difficulty of the terrains. Matthis et al.[4] show pertinent differences between medium and rough terrain conditions: participants are most likely to fixate around the second upcoming foothold in medium terrains, but gaze probability is evenly shared between the second and third upcoming foothold for the rough terrains. This finding suggests a greater need for path planning in difficult terrain, with fewer viable footholds. It is unclear if a different gaze-allocation strategy – i.e. visual search pattern – is adopted because of the difficulty of the terrain itself, or the difficulty of the visual search task.

Here, we seek to understand the influence of visual search difficulty on foothold searching strategies by having participants walk across an AR projected groundplane, like condition 3 of experiment 1, where they can only step on circles. To manipulate the difficulty of visual search, we decide to manipulate the acuity of the Landolt C distractor by changing the size of the "C" gap, thus manipulating the difficulty of discriminating between targets and distractors.

Methods and Stimuli: The number of participants recruited for this study will be based on a power analysis from a pilot study. During the experiment, we will record each participant's binocular eye movements (Pupil Labs) and full body kinematics (Qualisys) over approximately one hour of data collection. Prior to the start of the experiment, 10 free walking trials will be recorded to serve as a baseline measure for each participant's preferred gait cycle and biomechanics. In the pilot study, we will identify the upper boundaries of the acuity of the "C" gap which a participant can perceive while walking (without stopping) across our groundplane stimulus, using that as the ceiling for our experiment and having a half-circle "C" as the easiest acuity condition. We will manipulate the acuity in experiment 2 by sampling 10 values in mm that are evenly distributed from the most difficult acuity condition to the easiest, so that we can sample from a psychometric function. We will then repeat each of the 10 acuity conditions 12 times, providing 120 recorded trials. Participants will be shown 130 trials total, including the free walking trials. The 120 experimental trials will be pre-generated based on the "C" gap (mm) for that trial.

At the beginning of every trial, participants will be told to cross the AR terrain while only stepping on Circles, avoiding Landolt C's, and that the trial will end when they have successfully navigated to the end of the AR-walkway. They will also be told that if they misstep (defined as placing their foot on anything but a target circle) three times, they must restart the trial. Participants will receive real-time auditory feedback, positive for foothold successes (happy beeps) and negative for missteps (buzzer sound). Foothold configurations will be vetted prior to the experiment to be sure that none of them are prone to excessive failures. Once the participant has reached the other side of the room, the trial ends and the next configuration of footholds will appear.

Data Analysis: The primary analysis of this dataset will consider fixations made in a world-centered frame of reference, so that we can precisely identify the relationships between fixations and upcoming footholds (identified in post-processing) in time and space, assessing how this relationship might change based on the difficulty of the visual search task. To test this, we will calculate the distance between each fixation and its nearest upcoming foothold, seeing how gaze distribution changes relative to the acuity of the distractor "C". We predict that as acuity increases, participants will spend a greater amount of time looking at footholds that are further ahead (3+) when compared to when the discrimination task to find target foothold circles is easy, where participants will be most likely to look at the second upcoming foothold. Gaze distributions will be compared using Bayes T-tests.

We will also fit a psychometric function of participant walking speed and visual acuity: as visual search difficulty increases, and the participant needs longer fixations to increase certainty of each foothold, we should be able to find a critical value of acuity such that movement speed decreases dramatically. This represents the visual system informing the body that it needs more time to be certain – demonstrating another aspect of the role of the body in visual search.

Potential Problems & Solutions: Identifying the best manipulation to change the visual search difficulty is difficult, especially due to the novelty of this paradigm. Landolt C's were chosen because of how easy they are to parameterize, but other stimuli have been considered and could be used instead (e.g., Gabor patches hidden in 1/f noise[6]).

Aim 3. Observe the visuo-locomotor system in natural, unconstrained environments

Experiment 3: Do locomotor constraints influence visual search in natural environments?

<u>Rationale</u>: A critical test of how well our experimental insights generalize to locomotion across complex terrains in natural environments is to attempt to show that the biomechanical constraints influence visual search in the real world.

When measuring walking in outdoor terrains, can we use a dynamic walking model to predict participants biomechanically preferred foothold, and does this point in retinotopic space drive visual search behavior? How might the natural constraints of terrain difficulty interact with where participants would prefer to step?

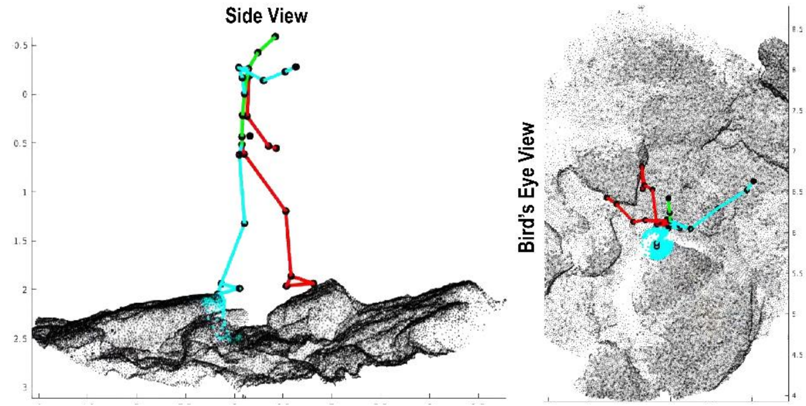

Figure 4. **3-D terrain mapping (AliceVision Photogrammetry and Inertial Measurement Unit -based motion capture**. Used with permission from Dr. Mary Hayhoe and Karl Muller, University of Texas, Austin. Combining recorded body tracking with real-world terrain maps and binocular eye tracking technologies, we will be able to measure the visuo-locomotor system in real world terrain traversal at unprecedented levels of detail. Red lines represent the left side of the body, and blue lines represent the right side.

Furthermore, experiment 3 will provide us with opportunities to assess where our previous experiments fail to equip us with the understanding needed to understand the full scope of visuo-locomotor behavior, likely due to complexity of 3-D terrain which has highly variable, uncontrolled visual information. From this experiment, we will be able to generate hypotheses to bring back into the laboratory, testing new visual components of the visuo-locomotor system that previously went unexplored.

<u>*Methods & Terrain*</u>: We will employ methods similar to previous research conducted by the sponsor[4], collecting data from 6 subjects exploring various terrain in publicly available (Blue Hills Reservation, MA; Beavertail State Park, RI) outdoor environments outdoor environments: flat, medium, and rough (rough example, *Fig. 1*). Using IMU-based motion capture (Motion Shadow) and mobile binocular eye tracking (Pupil Labs), we will combine body and eye information with a reconstructed 3-D terrain map (post-processed) generated by a combined images from a variety of go-pro cameras which will be set up around the outdoor tracking spaces. In each terrain condition, participants will walk for approximately 400m in a roughly straight trajectory; to obtain this outdoors, participants might have to walk over the same area multiple times. We will ensure that there is a comparable amount of data in all three terrain conditions.

<u>*Data Analysis*</u>: Our primary analysis of this dataset will be similar to our analysis of the distance to preferred foothold (DtPF) in experiment 1. By using 3-D terrain reconstruction, we will be able to map fixations in 3-D space, and calculate the distance between each fixation and the preferred upcoming foothold(s). As terrain becomes more complicated, that and the momentum of the walker varies more greatly Medial-Laterally, that the preferred next foothold will change from what one might expect; rather than being straight ahead, based on the past couple steps, it might be biomechanically preferable to step to the side. We predict then that biomechanically preferred foothold locations will change greatly with the difficulty of the terrain, but eye movements will still be driven by the preferred biomechanics as long as there is some level of uncertainty involved with the task of finding viable footholds (e.g., in medium and rough conditions, but not in easy). DtPF will be analyzed using an LMER analysis, regressing the terrain difficulty and the phase of the gait cycle (double support, early swing, or late swing), onto DtPF.

<u>*Potential Problems & Solutions*</u>: Accurately predicting the biomechanically preferred foothold in rough terrain could be difficult, and is a substantial challenge within this aim. If calculating the body's precise preferred foot placement proves too complex, we can alternatively use the body's momentum instead, assessing how that might drive saccade directions. Additionally, conducting high quality research in natural environments is difficult – but Dr. Matthis has experience doing precisely this. 3-D reconstruction of the environment should also prove challenging, but Dr. Matthis's lab (the Human Movement Neuroscience lab) employs Northeastern Co-Op students in computer graphics and image processing, students who will provide critical expertise in the reconstruction of 3-D environments.