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Short Paper

Inferring the routes of prehistoric humans

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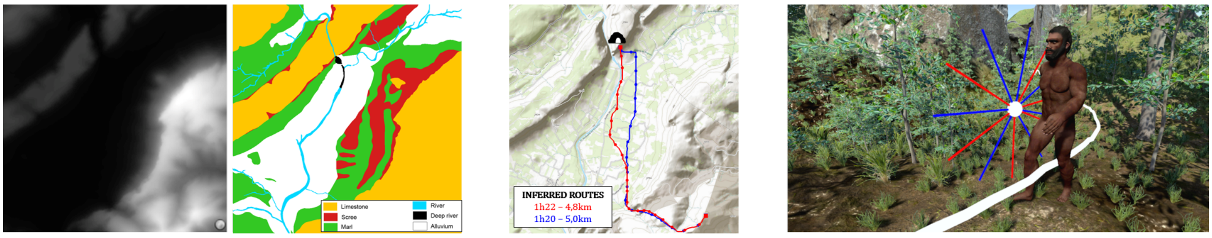

Figure 1: *From input environmental maps such as elevation and ground stiffness (left), we compute plausible routes for hominids to fetch resources and return (middle), based on a constant energy hypothesis and the analogy between a walking agent and a rimless wheel (right).*

Abstract

Prehistoric research is in high demand for 3D simulation to help validate hypotheses and enrich knowledge. While previous multidisciplinary studies focused on the reconstruction of ecosystems around excavation sites, this work takes up a new issue: deducing and visualizing the routes and the time taken by the hominids to reach the places where they harvested their resources, based on field data about raw material sources, the paleoclimate, and the surrounding ecosystem. We rely on the energy consumption of a simplified version of a walking character to compute the most likely locomotion speed and the best routes between input sites of interest, while taking into account local slopes, ground types and the presence of vegetation along the way. We show that this approach allows to evaluate the duration of the typical journeys of Homo heidelbergensis staying at the Caune de l'Arago (France) to collect lithic raw materials and to hunt - allowing archaeologists to deepen their knowledge of economic and territorial practices to the Lower Paleolithic and the Acheulean culture, 500,000 years ago.

CCS Concepts

• ***Computing methodologies*** → *Computer Graphics; Animation; Physical simulation;*

1. Introduction

Visualizing data and models has long been a key tool for archaeologists, both for communication and for helping them identify gaps or inconsistencies in their reasoning. In addition to visualization, computer graphics techniques can also be used for simulation, and thus help to enhance archaeological knowledge. In this work, we introduce a simulation method to study prehistoric mobility.

While artifacts found in excavations such as flint tools or bones provide evidence of hominids activities at a given time, the lack of knowledge on the duration of the journeys to collect resources makes them quite difficult for archaeologists to study. Fortunately, extra data and models are often available, from anatomical knowledge on the hominids and the closest sites for raw material, to the paleoclimate, flora and fauna in the surroundings. We thus address the following challenge: given sites of interest and maps encoding expert environmental knowledge, can we compute the most probable routes taken by the hominids and their duration?

We use an energy-based approach to solve this problem: from the power that hominids may have continuously expended on long walks, we estimate the most plausible route and travel time between any two locations, while accounting for the environmental conditions. Our contributions are threefold:

- A model to evaluate a plausible travelling speed given the local slope, the nature of the ground and the density of vegetation;
- An algorithm to deduce from this the best travelling routes and the duration of journeys between sites of interest;
- An application to the mobility of hominins of Acheulean culture staying at the Caune de l'Arago (France) 500,000 years ago.

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2. Related work

Reconstructing the routes of hominids requires precise information on the natural environment in which they lived. In 2021, a method was introduced to generate 3D landscapes with consistent flora and fauna from a set of maps such as elevation, type of ground, and hypotheses on the species in the ecosystem [ENCC*21]. In this work, we reuse their model of Tautavel valley 500,000 years ago based on archaeological data from a cave called the Caune de l'Arago.

Character animation has been used for many years as an important tool to illustrate past life in digital heritage applications [LCG*13, Vos17, KPP*21]. Here, our objective is rather to use virtual characters as a means of simulation, *i.e.* to study the most plausible routes and the duration of the journeys.

Closer to our concerns, Bandi [BT00] introduced a 3D path-finding technique for virtual humans, considering differences of elevation but only rigid grounds and obstacles. In contrast, our goal of modelling prehistoric mobility requires accounting for the energy lost walking through soft grounds and vegetation. Although recently investigated for reinforcement-learning-based agents, energy-minimization did not prove a successful reward for navigation tasks [KKPC23]. In this work, we rather assume constant energy consumption over time, and rely on a shortest path algorithm to compute a plausible journey between sites of interest.

Evaluating the energy spent in interactions versus in locomotion requires some physically-based model of the walking hominids. While gait-energetic has been studied in Neanderthals [DMM*19], the lack of complete anatomical data makes this approach difficult to generalize to *Homo heidelbergensis*. Moreover, such precise models require muscle-based control of locomotion [RPPD16], which would be extremely challenging on sloppy and unstable grounds. In an extensive study of the prehistoric settlement of Sahul, it has been proposed to calculate paths through energy minimization based on metabolic data; however, it lacked the calculation of a realistic speed of the travellers according to the characteristics of the terrain (slope, type of soil, vegetation). In this work, we rather rely on the *Yoyo man*, a simple approximation of energy-efficient human locomotion [LBCB17], sufficient to evaluate energy usage in interaction with a complex terrain and correlate it with speed.

3. Overview of the method

Our objective is to determine the most likely path that an average *Homo heidelbergensis* would have taken between two given sites of interest, utilizing experts maps describing the landscape. Our approach factors in altitude, ground stiffness (computed from geological type and moisture), and vegetation density.

Our solution is based on two hypotheses from the archaeologists: during long journeys, the hominids tried to maintain a constant level of effort, which physically translates to expanding a constant power over time (where power is the rate at which energy is consumed). This allowed them to provide peaks of energy in emergency situations such as running away from predators. Thus, hominids most likely slowed down in the most difficult parts of the path to keep their effort constant. Second, given the resulting

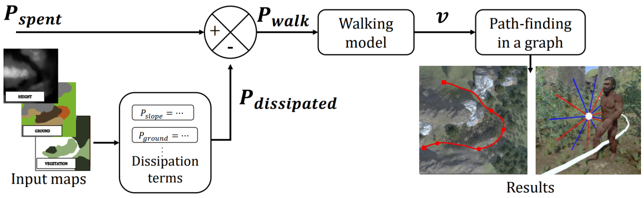

Figure 2: *Pipeline: From the input maps and power P_{spent} (left), a walking model is used to compute the preferred speed all over the terrain (middle), enabling to compute the best route (right).*

changes in speed, hominids likely took the fastest routes in time, rather than the shortest in distance.

Therefore, in addition to describing the hominid by its mass m, the length of its legs ℓ and the surface area of its foot A (used in interactions with the ground), we introduce P_{spent}, standing for the power, or rate at which muscular energy is expanded by the agent.

$$P_{spent} = P_{dissipated} + P_{walk}, \tag{1}$$

where $P_{dissipated}$ is the rate at which energy is dissipated in interactions with the environment (deforming ground, pushing aside vegetation, etc.) and P_{walk} is the muscular power used to move forward. This enables us to propose a solution in two steps (see Figure 2):

1. Speed and times over the terrain: Converting the terrain into a grid of locations, we use the input maps to compute $P_{dissipated}$ (in which we include the effect of slope) on each edge and in each direction, and compute P_{walk} using (1). A walking model then gives us the speed and thus the time it takes for traversing the edge. We store these times as weights in an oriented graph.
2. Fastest route: We use a shortest path algorithm to compute the best route in the resulting graph. The sum of weights along the route gives us the duration of the journey.

4. Walking model relating P_{walk} to speed

Step 1 requires calculating the 2D speed v of the agent on the map as a function of P_{walk}, the rate at which the agent uses energy for walking. To achieve this, a gait model complex enough to calculate the power expended in the alternating leg movement is needed. As explained in Section 2, using P_{walk} to activate the muscles of a 3D physical hominid would be extremely difficult. Instead, we use the Yoyo man model [LBCB17], leading to a closed-form solution for v that makes computations efficient enough for large terrains [Spr16].

The Yoyo Man offers an analogy for bipedal walking, where a walker of mass m and leg length ℓ is represented by a "rimless wheel" of same mass and spokes length (see Figure 3). When this wheel takes support on one of its spokes, it first uses energy to raise its centre of mass above this spoke, and then simply lets it fall forward (with no energy expenditure) until the next spoke hits the ground. This model expresses the fact that, during a relaxed and therefore energy-efficient walk, bipeds act like an inverted pendulum: they use their support leg as a pivot for their centre of mass, which allows them to only use the necessary energy for raising their center of mass above the support foot.

We add the following extra assumption, consistent with relaxed

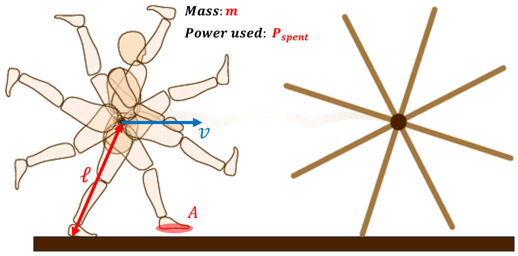

Figure 3: *Yoyo-man (@Laumond) with our input parameters in red, enabling to compute the speed value v (norm of velocity).*

walk: legs swing at their natural frequency $T = 2\pi\sqrt{\frac{2\ell}{3g}}$ where g is the gravity constant. The distance d between two consecutive feet positions is thus $d = \frac{vT}{2}$, and the height h at the lowest centre of mass position is $h = \ell\sqrt{1 - \frac{d^2}{4\ell^2}} = \ell\sqrt{1 - \left(\frac{vT}{4\ell}\right)^2}$.

The power for raising a mass m from h to l (above support) in a time interval Δt being $\frac{mg(l-h)}{\Delta t}$, and Δt being here the duration of a step $T/2$, this gives P_{walk} from v, which we then invert:

$$P_{walk} = \frac{2mg\ell}{T}\left(1 - \sqrt{1 - \left(\frac{vT}{4\ell}\right)^2}\right) \tag{2}$$

$$v = \frac{4\ell}{T}\sqrt{1 - \left(1 - \frac{TP_{walk}}{2mg\ell}\right)^2} \tag{3}$$

5. Energy dissipated in interactions

To get P_{walk} from P_{spent} using Eq. (1) while accounting for the local nature of the terrain, we need to compute $P_{dissipated}$. In our model, it encompasses any energy expenditure which does not contribute to forward motion at speed v across the map. We thus consider terrain slope in addition to ground stiffness and vegetation:

$$P_{dissipated} = P_{slope} + P_{ground} + P_{vegetation} \tag{4}$$

Terrain slope: In the rimless wheel model, the trajectory of the walker's centre of mass is a series of circular arcs. When the floor is not horizontal, the highest (resp. lowest) position along this trajectory is increased (resp. decreased) by the height difference Δz between two consecutive feet positions. P_{slope} is thus the power used to achieve this extra height change during a step:

$$P_{slope} = \frac{mg\Delta z}{T/2} \tag{5}$$

Note that the sign of this term, which will affect P_{walk}, depends on positive vs. negative slope. Therefore, local terrain height variations can lead to either acceleration or deceleration of the walking agent.

Ground stiffness: Soft grounds such as mud, snow or unstable, granular material can greatly affect the speed of a walker, since a part of its energy is dissipated in deforming the ground. As in [APRC22], we model soft ground as a deformable material of Young modulus E. The dissipated power is calculated by dividing the variation in potential energy caused by the formation of a footprint of surface A, by the duration of a step $T/2$. The depth ΔL of the footprint in a layer of loose ground of thickness L_0 is calculated as the depth at which the weight of the walker mg counteracts the elastic reaction force of the ground, given by Hooke's law : $\frac{EA}{L_0}\Delta L$. Given that $\Delta L = \frac{mgL_0}{EA}$, this leads to:

$$P_{ground} = \frac{\Delta E_{Hooke}}{T/2} = \frac{EA\,(\Delta L)^2}{L_0 T} = \frac{(mg)^2 L_0}{EAT} \tag{6}$$

Vegetation: In natural environments, dense but passable vegetation such as tall grasses or bushes can slow a walker's movement. We represent the interactions between an agent of drag coefficient C_d (set to 1.2 as in [AOK13]) and vegetation of density ρ as friction with a turbulent fluid. The viscous force $F_{vegetation}$ is thus:

$$P_{vegetation} = F_{vegetation} \cdot v = \frac{1}{2}\rho v^3 C_d S \tag{7}$$

where S is the friction area between the agent and the vegetation. We compute S using characteristics of the agent and of the environment as $S = w_{hips} \cdot h_{vegetation}$ with w_h being the width of the walker's hips and $h_{vegetation}$ the average height of the vegetation.

6. Best route computation and visualization

The terrain is represented as an oriented graph using a 2D grid of vertices. To precisely account for the information on the altitude, ground stiffness and vegetation, we use one vertex per map pixel.

For each edge of the resulting graph, and in both directions, we use P_{spent} and Eqs. (1) and (4) to compute P_{walk} and deduce a speed value from (3). Speed is then used to compute the time taken to traverse the oriented edge, which defines a weight. Finally, we use Dijkstra's algorithm to compute the fastest route between two sites, and sum the weights to get the total duration of this journey.

For visualization purposes, we drive 3D agents on a smoothed version of the route, computed as a Catmull-Rom spline. At run time, we use our walking model along this path to get the agent's speed changes at a finer resolution than the pre-computed ones.

Validation: See Figure 1. We first tested our method by calculating the best route in the Tautavel valley, from the Caune d'Arago cave to a ridge that allows to cross the limestone massif and descend into the neighboring valley, allowing us compare the results to current trails. On the way from the cave (red), the computed path favours walking in the flat part of the valley, which reduces effort. Near the ancient pathway, the agent gets on the mountain crest from its most accessible entry point, and walks along it, similarly to what a seasoned hiker would do. A slightly different route is used on the way back (blue), due to the inverse effects of topography. The routes found are about 5km long and take about 1h30 to walk, which seems consistent given the elevation. Generating the graph and computing 8 pairs of round trips on a 16km^2 map of resolution 964x964 took about 4 minutes using an i7-11800H @ 2.30GHz and 16GB of RAM.

7. *Homo heidelbergensis*'s routes at Caune de l'Arago

As an application to prehistoric research, we provided our system to our archaeologist co-authors, studying the mobility of the *Homo* *heidelbergensis* staying at Caune de l'Arago. They focused on three archaeologically prehuman activities, identified in level L dated to 500,000 years ago (see Figure 4):

1. Collection of quartz pebbles in the alluvial deposits on the right bank of the Verdouble river (crossing required);
2. A supply of Aptian flint whose deposit is located in a nearby valley to the north of the cave;
3. Two reindeer hunts, the first one at the mouth of the ford on the Verdouble, and the second one on the plateau.

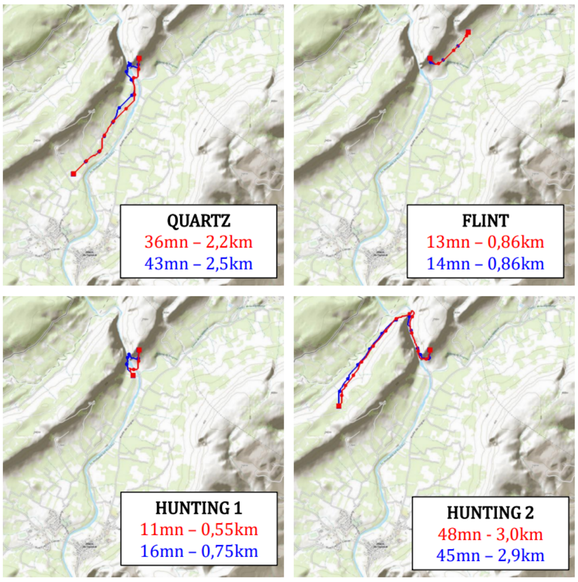

Figure 4: *Red: Outbound journey. Blue: Return journey. Two consecutive dots represent a 4 minutes time interval.*

Archaeologists' feedback: To fetch quartz, the agent chooses to descend straight from the cave by an easy, straight path, crosses the river at the natural ford formed by a cord of pebbles, then walks on the alluvial deposits close to the river to the collection point. The trip takes about 40 minutes, which seems consistent. On the way back, the agent moves on a similar trajectory but decides to cross the river at the limit of the deep waters at the mouth of the gorges, requiring a swim. This shows a first limit of the current model: the depth of water was not considered and we did not model the fact that bringing back resources weighs down the agent, making swimming impossible. For flint supply, the outward and return trajectories are similar: the agent stays near the foot of the cliff, except near the cave where it is forced to follow the terrain relief. For flint supply, the agent's outward and return trajectories exhibit similarity as they remain close to the foot of the cliff, except for when they reach the cave. For the first hunt, the agent takes the easiest descent from the cave and crosses the river at the ford to trap reindeer herds on the right bank, which takes about 11mn. The return path takes more time which is coherent with the agent returning to the elevated cave. The second hunting course descends into the gorges and crosses them going up the river to join the neighbouring valley and climb to the plateau. The terrain topography and the narrow water-filled gorges make this route rather impractical.

While explicitly modelling obstacles such as steep cliffs or deep rivers and considering an increased mass for the agent on return trips would improve our solution, the computed paths and trip duration seemed coherent to the archaeologists, enabling the following interpretation: the total travel time for quartz, flint, and hunting 1 being of approximately 1 hour and 30 minutes, to which must be added the time on site - estimated to 1 hour to collect minerals and 4 hours to hunt, the three activities could be conducted in about 7 hours. A group of several hunters, with probable task sharing, could thus have tackled all of them the same day. This supports the hypothesis that the archaeological layer L is a brief hunting camp of only a few days, during which many reindeers were hunted and brought to the cave. Ultimately, these results contribute to the understanding of the seasonal mobility cycle in which these subsistence activities took place.

8. Conclusion and future work

The study of a Paleolithic site raises many multidisciplinary challenges. Being able to evaluate the duration of activities identified through archaeological excavations, enriches knowledge of the mobility of fossil human species and makes it possible to refine hypotheses on their territorial, economic and social organization. We have presented a general pipeline to assess the most likely routes and time taken by hominids to fetch their resources. Based on a simple physical analogy for a walker, our method led to a first evaluation of the main routes of *Homo heidelbergensis* staying at the Caune de l'Arago (France). In the future, our pipeline would deserve to be used with more accurate biomechanical models of these hominids as knowledge about their morphology and muscular strength becomes available. The terrain models also deserve to be updated, to reverse the process of geomorphological evolution due to erosion and human action. Finally, extending the principle of our method to a larger geographical scale would make it possible to identify potential migratory routes, which could explain the processes of settlement from Africa to other continents, and phenomena of cultural diffusion or convergence.

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