FIELDWALK@KOZU: A Preliminary Report of the GPS/GIS-aided Walking Experiments for Remodelling Prehistoric Pathways at Kozushima Island (East Japan)

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Abstract

This paper reports the preliminary results of GPS-aided walking experiments conducted for examining the accuracy and availability of GIS-based least-cost travel models, which have often been applied in archaeological research to simulate the routes and time required for moving between archaeological settlements and natural resources. The examinee's walking, recorded in Kozushima Island, one of the major prehistoric obsidian procurement sites located ca. 180km offshore from Tokyo, Japan, indicates that the walking velocity is significantly affected by ground conditions such as paved roads, unpaved trails, sandy beaches, and rocky shores. In addition, the laboratory work before/after the field experiments reveals that different GIS packages and algorithms may create different least-cost paths, and the authors therefore suggest "least-cost corridor" as a fuzzy accumulation of possible paths. In the future, sociopolitical, cultural, religious and mental factors other than topographical ones should also be incorporated into least-cost modeling.

Keywords

Travel Cost, Digital Elevation Model (DEM), Least-Cost Path, Least-Cost Corridor, Field Experiments

1. Introduction

Least-cost path (LCP) is defined as "a route that minimises the total cost of moving between two locations on an accumulated cost surface" (Conolly and Lake 2006, 294). It has often been employed in the field of archaeology to simulate the most "economical" or easy-to-travel route between settlements and natural resources (e.g. Kantner 1996; Chiba *et al.* 2000). An accumulated (or cumulative) cost surface, a precursor of LCP, is created by a friction model to estimate the moving cost with elapsed time (Gorenflo and Gale 1990; Tobler 1993; Neteler and Mitasova 2008, 381) or energetic expenditure (Van Leusen 2002). Most models view slope of the terrain as a primary parameter of the travel cost. Thus far, however, little attention has been paid to the behavior and accuracy of the algorithms being used. Here, the authors present a few scientific questions. (1) To what extent does slope affect walking velocity? (2) Are there any other explanatory variables that can be incorporated into the model? (3) How accurately do the present GIS-based least-cost models reflect "real" human journeys, particularly the prehistoric ones that archaeologists deal with? One way of addressing these questions is to conduct onsite experiments to collect ground-truth data of human walking trips as performed in a British national park by Rahn (Rahn 2006). Similarly but more thoroughly, the authors conducted walking experiments in Japan in a different environment. Our walking experiments are aimed at (1) collecting basic data about human walking behavior, (2) examining the accuracy and availability of the previous least-cost models, (3) detecting friction factors other than slope of the terrain, (4) developing new solutions by incorporating the discovered factors, and (5) simulating past human travels more precisely.

2. Environmental and archaeological settings of Kozushima

Kozushima is a small volcanic island located in the Izu-Ogasawara Arc, approximately 180km offshore from Tokyo (*Fig. 1*). This island was selected as the site of experimentation because of its suitable size (ca. 18.5km^2) for GIS modeling and walking, as well as its archaeological significance.

In an archaeological context, Kozushima is known as one of the major sources of obsidian in eastern Japan. Thus far, three obsidian outcrops and ten Neolithic sites have been discovered here (*Fig. 1*). Most sites are dated to the end of the Early Jomon to Middle Jomon periods (4000–2500 cal. BC). Interestingly, during these periods, obsidian would be exported from Kozushima to a significant number of settlements on the mainland across the Kuroshio Current (Ikeya 2005).

3. Methodology

Our research focusses on reflexive interaction between GIS modeling and walking experiments (*Fig. 2*). A common dataset including the geographic route, path length, elapsed time, and average movement velocity are acquired in both routines. Before the onsite experiments, LCPs from the provisional departure points to the goals were created by GIS to predict the

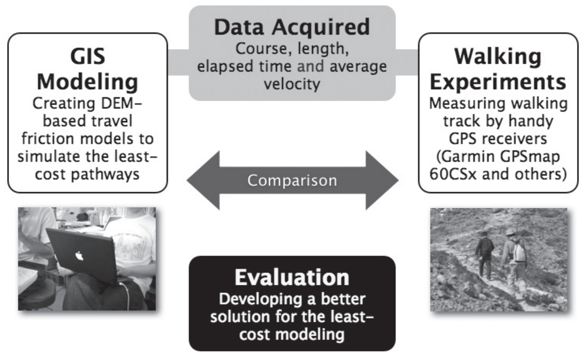

Fig. 2. Interactive framework of the research project.

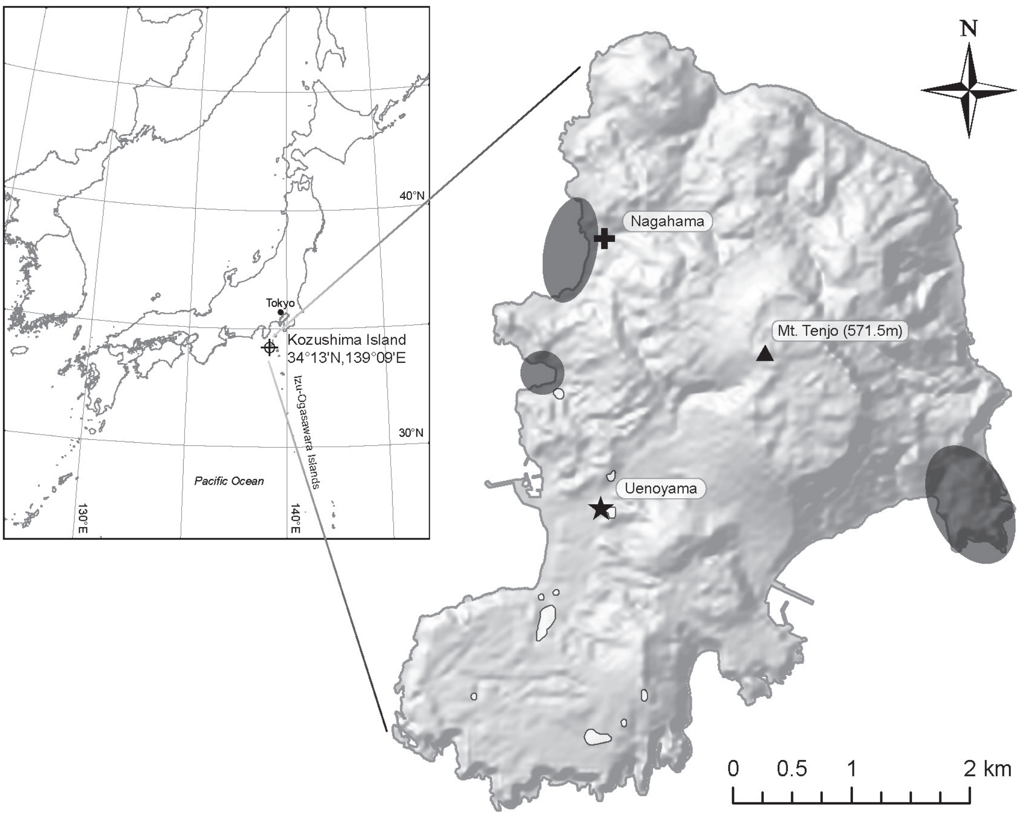

Fig. 1. Location and archaeological features of Kozushima. Darker circles indicate obsidian outcrop, whereas lighter polygons indicate Jomon site.

examinee's decision and elapsed times. Then, in the field, walking tracks and elapsed times were recorded by portable GPS receivers such as Garmin GPSmap 60CSx (mainly employed), Magellan Mobile Mapper, Garmin Legend, SONY GPS-CS1K, and the differential GPS of the Leica System 1200. After the experiments, the ground-truth data were integrated with GIS and compared with the modeled paths to evaluate how closely the previous models fit the actual data.

Table 1 lists the GIS-based least-cost models examined in this project. The models were created by three different GIS packages – ArcGIS 9.2, IDRISI Andes, and GRASS 6.3. The so-called Tobler's Hiking Function (Gorenflo and Gale 1990; Tobler 1993) was selected as the main algorithm to be examined because it is the most widely applied slope-dependent cost equation in archaeology.

	software	equation	module	slope
1	ArcGIS 9.2	Tobler (1993)	----	isotropic
2	ArcGIS 9.2	Tobler (1993)	----	anisotropic
3	IDRISI Andes	Tobler (1993)	cost push	isotropic
4	IDRISI Andes	Tobler (1993)	cost grow	isotropic
5	IDRISI Andes	Tobler (1993)	varcost	anisotropic
6	GRASS 6.3	Tobler (1993)	r.cost	isotropic
7	GRASS 6.3	Neteler (2008)	r.walk	anisotropic

Table 1. Least-cost models to be compared with the walker's tracks.

The original equation is:

$$W = 6e^{-3.5\left|S+0.05\right|} \qquad \text{(a)}$$

where W is the walking velocity [km/h]; e, the base for natural logarithms; and S, slope of the terrain that can be converted from the slope angle (θ) as below:

$$S = \tan\theta = \frac{\pi}{180}\theta \qquad \text{(b)}$$

Using equations (a) and (b), the elapsed time to traverse a given raster cell is calculated:

$$t = \frac{d}{100e^{-3.5\left|\frac{\pi}{180}\theta+0.05\right|}} \qquad \text{(c)}$$

where t is the estimated time [min] and d is the raster cell size [m].

Tobler's function was originally based on the army march (Imhof 1968, 214–223). In this empirical model, different frictions are allocated to uphill and downhill movements. Theoretically, the maximum velocity, 6km/h, is attained at an angle of 2.87° (or 5%) when going downhill. The modeled walker moves at approximately 5km/h on the flat surface (Gorenflo and Gale 1990; Tobler 1993; see also *Figs. 7* and *8*). A slower movement is expected on a steeper slope. The off-path walking velocity is configured to be 60% of that of on-road travel (Tobler 1993; see also *Fig. 8*).

The slope of the terrain is calculated from the 5-m-resolution DEM of Kozushima, created by a spline interpolation from the Digital Map 50-m-grid Elevation of the Japan Geographical Survey Institute. The slope is treated in two different ways — isotropic and anisotropic. For an isotropic slope, the direction of movement at a given raster cell, for example, uphill or downhill, is not considered. IDRISI's "cost push", "cost grow", and GRASS "r.cost" modules deal with this type of slope. On the other hand, the anisotropic models, programmed by ArcGIS and IDRISI's "varcost" module, assign different friction values to uphill, downhill, and traverse movements in the same cell (effective slope; see also Conolly and Lake 2006, 217–218).

In addition, the GRASS "r.walk" module was employed for the purpose of comparison. It is also slope-dependent and anisotropic; however, it treats horizontal distances and uphill and downhill elevations as individual parameters:

$$t = \frac{a\cdot\Delta S + b\cdot\Delta H_u + c\cdot\Delta H_d + d\cdot\Delta H_s}{60} \qquad \text{(d)}$$

where t is the estimated time [min], ΔS is the cell size [m], and ΔH_u, H_d, and H_s are the elevations [m] when going uphill, downhill, and steep downhill, respectively. The parameters a, b, c, and d represent the underfoot condition and cost, and in a default configuration, a = 0.72, b = 6.0, c = 1.9998, and d = –1.9998 (Neteler and Mitasova 2008, 381). This model is comparable to that of Tobler because of the common output.

4. Results

Seven adult examinees participated in the walking experiments, conducted in early October 2007. One day, three examinees, accompanied by one or two supporters, independently walked from the Early Jomon settlement in Uenoyama (also called as Kaminoyama) to an obsidian outcrop in Nagahama, and then returned, simulating journeys made by the Jomon people to procure obsidian (*Fig. 1*). On another day, the participants trekked from Uenoyama to Mount Tenjo, ca. 571.5m above sea level, in order to obtain velocity data at different slopes.

4.1. Walkers' tracks vs. GIS-based LCPs

After the experiments, the walking tracks of examinees A, B, and C from Uenoyama to Nagahama were compared with the corresponding GIS-based LCPs (*Fig. 3*). The elapsed/estimated time, path length and average walking velocity of the recorded tracks and the models are summarized in *Table 2*. Although the walkers' paths were restricted to current roads for the purpose of safety, they can select their own paths. The elapsed time ranged from 81 to 86 minutes, and the average walking velocity lies within a range of 3.5 to 4km/h. These results indicate that: (1) there is no significant difference in time and velocity between the coastal and hillside routes; (2) length of the walker's tracks tends to be longer than that of the modeled paths; (3) the GIS-estimated velocity exhibits greater variety than the walker's actual velocities; and (4) among all the models, the estimated values of ArcGIS anisotropic and GRASS "r.walk" are relatively close to the actual data.

The variability between the models can also be observed on the map. First, the expected route and time of the ArcGIS isotropic and anisotropic models are completely different although they are created by the same GIS package using the same friction source. Second, with regard to the three IDRISI-based LCPs

Fig. 3	model	length [m]	time [min]	speed [km/h]
A	examinee A	5170.0	85.75	3.62
B	examinee B	4706.1	81.25	3.48
C	examinee C	5219.8	80.50	3.89
1	ArcGIS isotropic	3354.4	63.52	3.17
2	ArcGIS anisotropic	2693.8	41.46	3.90
3	IDRISI cost push	2874.6	80.09	2.15
4	IDRISI cost grow	2755.1	82.89	1.99
5	IDRISI varcost	2879.4	109.98	1.57
6	GRASS r.cost	2836.5	66.88	2.54
7	GRASS r.walk	3378.5	59.98	3.38

Table 2. Numerical aspects of the walking tracks and the GIS-based LCPs from Uenoyama to Nagahama.

Fig. 4	model	length [m]	time [min]	speed [km/h]
A	examinee A	4013.4	58.25	4.13
B	examinee B	4041.6	59.00	4.11
C	examinee C	4684.0	63.75	4.41
1	ArcGIS isotropic	3353.4	63.90	3.15
2	ArcGIS anisotropic	2272.0	43.00	3.17
3	IDRISI cost push	2773.1	80.75	2.06
4	IDRISI cost grow	2760.9	84.00	1.97
5	IDRISI varcost	2770.2	94.98	1.75
6	GRASS r.cost	2841.3	67.09	2.54
7	GRASS r.walk	2818.2	54.57	3.10

Table 3. Numerical aspects of the walking tracks and the GIS-based LCPs from Nagahama to Uenoyama.

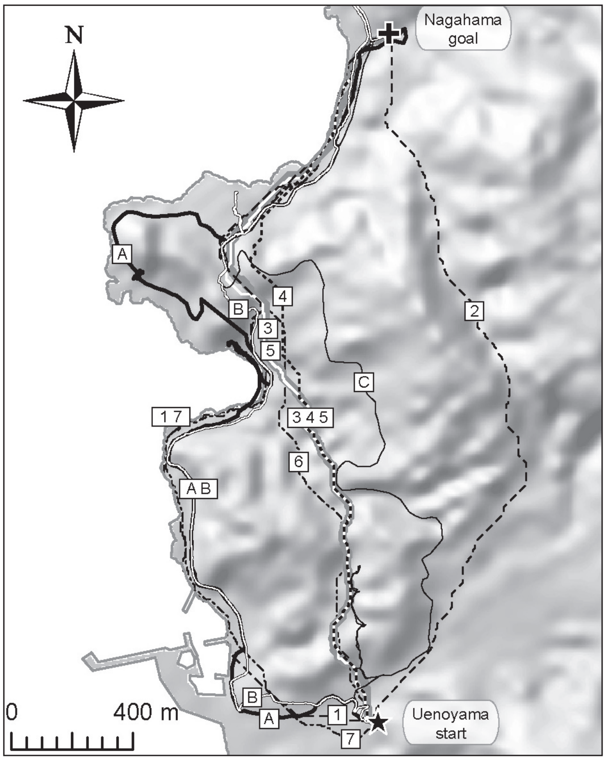

Fig. 3. Walking tracks and the GIS-based LCPs from Uenoyama to Nagahama (See Table 2 *for keys).*

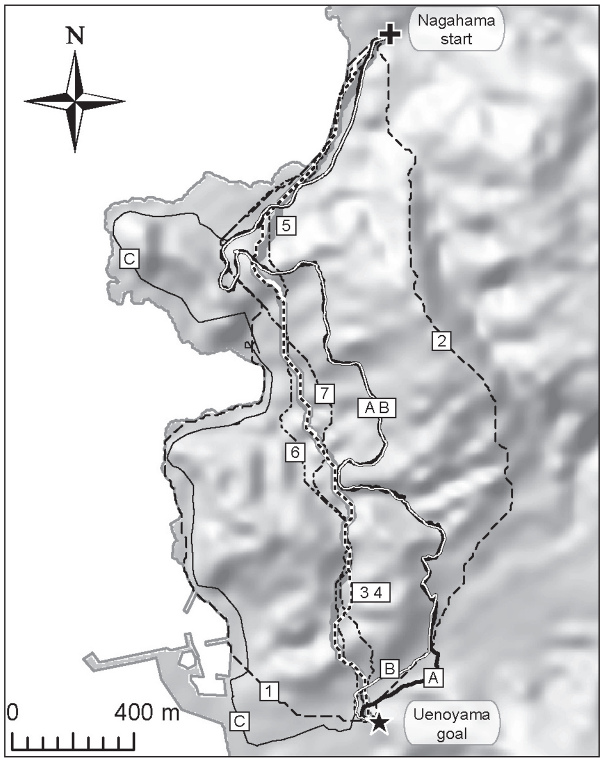

Fig. 4. Walking tracks and the GIS-based LCPs from Nagahama to Uenoyama (See Table 3 *for keys).*

movements by the anisotropic "varcost" module are significantly slower than those by the isotropic "cost push" and "cost grow" modules. Third, the GRASS "r.cost" module predicts an inland route, while the "r.walk-based" LCP goes along the coastline. These results indicate that different GIS applications and different algorithms may yield different LCPs.

4.2. Outward trip vs. homeward trip

When the walkers' homeward paths are compared with the outward trips, the average speed in the homeward session is generally 0.5km/h faster than those in the outward one despite the 4 to 6kg additional load as substitute for obsidian nodules (*Figs. 3* and *4*; *Tables 2* and *3*). This result may be explained by two factors: first, the examinees tended to walk more quickly when carrying their loads on the homeward trip, and second, they had become accustomed to the route topography and conditions.

It has also been revealed that the isotropic and anisotropic models yield different results (*Figs. 3* and *4*). For the isotropic slope models, namely, ArcGIS, IDRISI "cost push" and "cost grow", and GRASS "r.cost", there is theoretically no difference between the outward and homeward trips. In contrast, as exemplified by the ArcGIS and GRASS "r.walk" modules, the anisotropic slope models may output different routes and times between the outward and homeward trips. It is also evident that all the GIS models figure out slower movements than the actual walking velocities.

5. Discussion

5.1. Least-cost corridor

As described above, different GIS packages and algorithms may create different LCPs, and the homeward LCPs obtained from the anisotropic slope models may differ from the outward ones. Instead of considering "potentially multiple" LCPs, the authors suggest "cost corridor" as a fuzzy accumulation of possible paths. It can be provisionally created by adding the raster value of the outward cumulative cost surface to the homeward one, as performed by the "Corridor" module of the Spatial Analyst Tools in ArcToolbox (ESRI 2008a). It is true that the "Corridor" module was originally designed for predicting an intermediate point or area between two locations (ESRI 2008b), but it can also be applied to the least-cost modeling when considering a to-and-fro trip because it may indicate the isotropically optimal areas that can be accessed from the two given locations at the least cost.

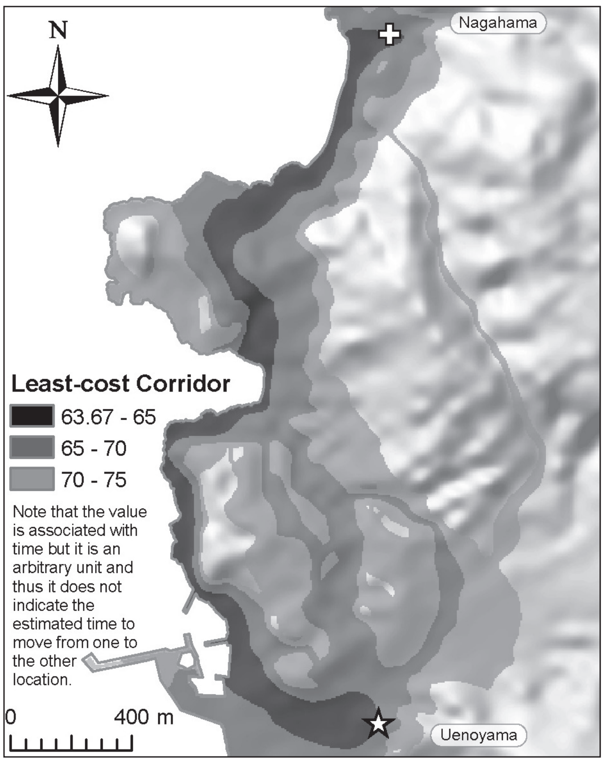

Fig. 5. Least-cost corridor from Uenoyama to Nagahama based on the ArcGIS isotropic model.

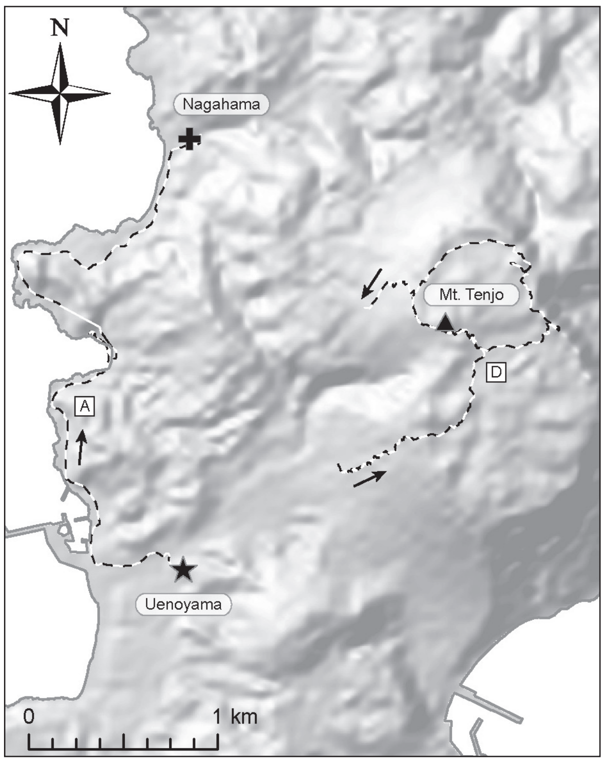

Fig. 6. 50-m-walking segments of Examinees A and D.

In fact, this module works well in the case of Kozushima. The least-cost corridor (based on the ArcGIS isotropic model) between Uenoyama and Nagahama (*Fig. 5*, the darkest zone) appears in the coastal area, and the second and third least-cost corridors (brighter zones) pass through the adjacent area and the mountainous inland. It is notable that these least-cost corridors include most of the walking tracks and GIS-based LCPs (*Fig. 5*, as compared to *Figs. 3* and *4*).

5.2. Ground conditions and walking velocity

In order to evaluate the correlation between the ground conditions and the walking velocity, the walking track of examinee A is split into 96 segments that are each approximately 50m long (*Fig. 6*). The track passed through sandy beaches and rocky shore zones as well as paved roads and unpaved paths. In the dot chart (*Fig. 7*), the horizontal axis represents the ground walking velocity, while the vertical axis represents the DEM-based average anisotropic slope of the segment. The gray curve represents Tobler's Hiking Function. The dots are symbolized in accordance with the ground type. It is noteworthy that the walking velocity significantly decreases on unpaved paths (indicated by white triangles), sandy beaches (indicated by circles), and rocky shores (indicated by black diamonds). These three groups appear to fit Tobler's curve to some extent.

For further verification of this notation, examinee D's track around Mount Tenjo is analyzed in the same manner (*Fig. 6*). The entire path is unpaved. The plotted data points roughly fit Tobler's model, but we could hardly attain the highest velocity in this model, approximately 6km/h at 2.87° downhill (*Fig. 8*). It is also notable that walking velocity may range from 2 to 4km/h up to 20° uphill, while it is restricted to 2km/h over 20°.

6. Conclusion and future tasks

The discoveries made in both the GIS modeling and field experiments are potentially significant for further archaeological research that may apply the least-cost travel model. It is very important to note that the comparative GIS modeling suggests that different software programs and algorithms may create different cost distance models and LCPs. On the other hand, the GPS-aided experiments indicate that: (1) at least in this case, the actual walking tracks may be longer than the GIS-based cost models, although the walking velocity is faster than that estimated; (2) the use of the least-cost corridor appears to be more effective than the use of many different LCPs; and (3) the walking velocity is significantly affected by the ground slope, as previously suggested, although we should also consider the significant effect of ground conditions such as unpaved trails and rocky shores. In order to evaluate these results appropriately, it is highly recommended that the theory and methods of LCP analysis be reexamined and that more precise data be collected.

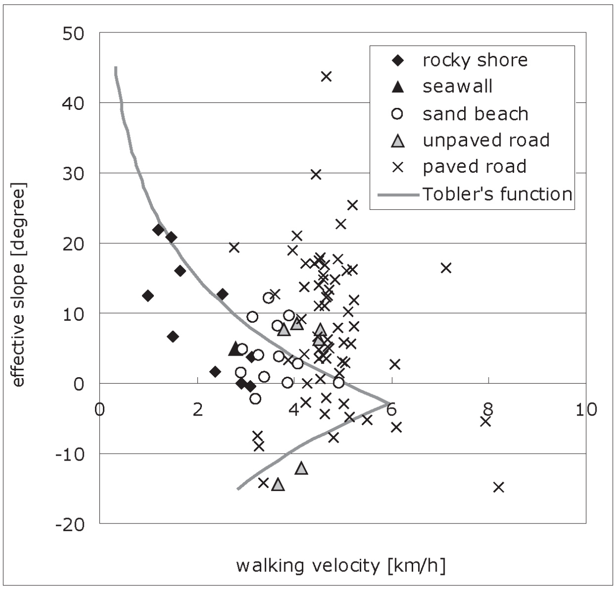

Fig. 7. Correlation between the slope of the terrain and the walking velocity. 50-m-walking segment of examinee A from Uenoyama to Nagahama.

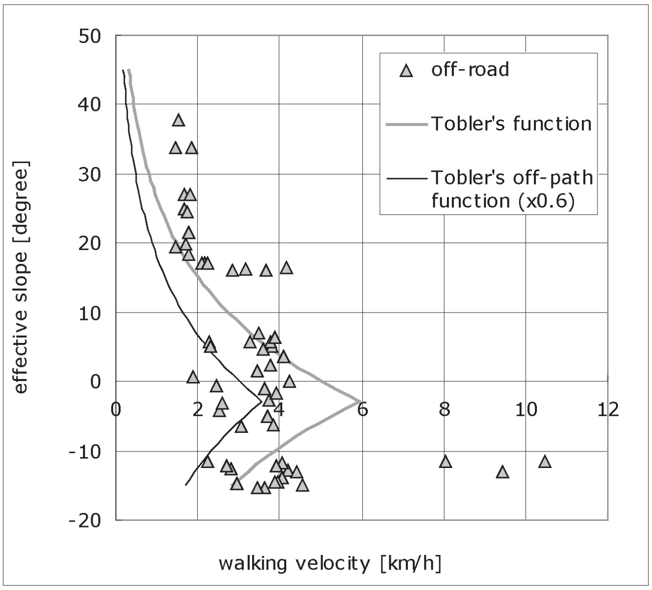

Fig. 8. Correlation between the slope of the terrain and the walking velocity. 50-m-walking segment of examinee D around Mt. Tenjo.

The field experiments of the first season also indicate what our future tasks should be. First, GIS-based least-cost models should be compared with preserved prehistoric roads and ethnoarchaeological records. Second, sociopolitical, cultural, religious, and mental factors other than "economical" ones should be incorporated into the travel cost modeling to the greatest extent. Third, "tailor-made" friction algorithms should be prepared for specific geographical areas and time periods so as to fit the different LCP settings. In addition, the cruising speed of kayak should be measured for reconstructing water transportation in the past. Finally, it should be noted that a continuous discussion for theoretical and methodological refinements is essential for the better understanding of the past human travels.

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