IDENTIFYING TRACKWAYS USING STEP LENGTH: BEHAVIORAL
INFERENCES FROM JAGUAR CAVE, TENNESSEE

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in
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by
Kyle Aidan McCormick
Spring 2010
IDENTIFYING TRACKWAYS USING STEP LENGTH: BEHAVIORAL INFERENCES FROM JAGUAR CAVE, TENNESSEE

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ABSTRACT

IDENTIFYING TRACKWAYS USING STEP LENGTH: BEHAVIORAL INFERENCES FROM JAGUAR CAVE, TENNESSEE

by

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Prehistoric behavior can be inferred through ephemeral forms of archaeological evidence including foot impressions. Traditionally, foot impressions have been analyzed metrically and morphologically to provide information about the individuals who created them, such as sex and age, and physical abnormalities of the foot. Foot impressions can also be analyzed as a group by examining the relationship of foot impressions to one other and the surrounding environment. In some instances, it is possible to track routes taken by prehistoric people. Foot impressions in a route form a trackway. The distance between two consecutive foot impressions of a trackway is step length. By analyzing step lengths, it is possible to infer the locomotory pattern and behavior that created the trackway. This study identifies trackways of prehistoric foot impressions found in a cave passage in Jaguar Cave, Tennessee, and assesses the behavior that created these trackways.
Jaguar Cave is a complex cave system in north-central Tennessee. An hour and a half travel into the cave, in a dead-end passage named Aborigine Avenue, 274 foot impressions were discovered by modern cavers in 1976. Radiocarbon dates from associated charcoal suggested these impressions were created by prehistoric cavers around 4500 B.P. Previous research on the number and distribution of inbound and outbound foot impressions indicated these prehistoric cavers explored the cave passage as they entered and then made a more direct and expedient exit. This study examines that assertion.

Sixteen trackways are identified from the Jaguar Cave foot impressions. On average, inbound step lengths are longer and more variable than outbound step lengths. Also, inbound foot impression lengths are longer than outbound.

The majority of trackways are located in the middle of Aborigine Avenue where surface level and consistency are uniform. This uniformity implies that surface properties do not affect locomotory patterns that created the inbound versus the outbound step lengths. Furthermore, longer inbound foot impressions and observations of Aborigine Avenue suggest that different individuals created the inbound and outbound trackways. More variable inbound step lengths and more inbound foot impressions than outbound (150 inbound and 123 outbound), however, demonstrate the individuals that created the inbound trackways took more steps and stopped more often than those who created the outbound trackways. These observations are consistent with exploring. This study supports the assertion that prehistoric cavers explored as they entered Aborigine
Avenue and then made a more direct and expedient exit. This study suggests that the earliest cave trips by humans in the southeastern United States were exploratory.
CHAPTER I

INTRODUCTION

Evidence of past human activity comes from many forms of archaeological materials. Typically, archaeological materials include artifacts, biofacts, and features that resist deterioration (e.g., lithics, bone, and building foundations). These materials provide archaeologists with evidence of past human behavior and are the byproduct of human activities. Archaeological knowledge is biased toward human activities that leave durable, non-perishable materials.

Under extraordinary circumstances, however, perishable or ephemeral materials and features are preserved, including organic remains and foot impressions. These rare forms of archaeological evidence provide valuable insight into aspects of past human activity typically lost in the archaeological record. Foot impressions are ephemeral archaeological features and are evidence of past walking patterns, and provide information about the evolution of bipedalism, hominid kinetics, population composition, gender- and age-related activity roles, resource exploitation, and land use (Allen et al. 2003; Leakey and Hay 1979; Scales 2002). To understand the information that foot impressions provide, data are examined metrically, morphologically, and in situ.

Traditionally, foot impressions have been analyzed metrically and morphologically to provide information about the individuals who created them, such as demographic information and physical abnormalities of the foot. This information can be
used to create demographic reconstructions, such as the minimum number of individuals, and sex and age distributions.

Foot impressions when analyzed in situ provide information about the locomotory pattern of the individuals who created them. Foot impressions are analyzed in situ by examining the relationship of foot impressions to each other and the substrate. In some instances, it is possible to follow the route of individuals. These routes are trackways. The distance between foot impressions of a trackway are measurements of step and stride length. Step length is the distance between two consecutive steps of left and right feet; stride length is the distance between two consecutive steps of the same foot. Step and stride lengths provide similar information regarding an individual’s locomotory pattern.

Different locomotory patterns, such as walking or running, cause predictable distances between foot impressions in a trackway. These distances, or step lengths, are influenced by extrinsic and intrinsic variables. By understanding how these variables influence the distance between foot impressions, reconstructions of locomotory patterns and interpretations of behavior are possible. For example, if an individual runs up a hill, the trackway created has different step lengths than a trackway left by someone walking down a slope. This thesis uses these variables to examine the relationships of the prehistoric foot impressions in Aborigine Avenue, a cave passage in Jaguar Cave, Tennessee. From these foot impressions, trackways are identified, and walking patterns and behaviors of these cavers (individuals who explore or otherwise travel through a cave) are inferred.
This chapter introduces foot impression research and its ability to expand our knowledge of past behaviors. These concepts are important for understanding human walking and provide background for evaluating variables that influence locomotory patterning. To understand the rare circumstances that preserve foot impressions, circumstances and environments where foot impressions may be preserved are described. Then, the route to Aborigine Avenue is described, followed by the purpose and structure of this thesis.

Creation and Preservation of Foot Impressions

Foot impressions are created when a foot comes in contact with a pliable substrate. Foot impressions typically occur in wet environments where water makes soil more pliable or makes sand more cohesive. Most times, subsequent environmental factors and other forces destroy foot impressions, although under rare circumstances, foot impressions are preserved in the archaeological record.

Foot impressions most often preserve in estuarine, flood plain, and coastal environments, where fine and coarse sediments are interlaminated. Preservation also occurs in environments where a layer of sediment with foot impressions is covered by contrasting sediment, such as sand covering laminated mud. And finally, foot impressions can be preserved in caves, where erosion and weathering have a minimal effect on preservation (Allen et al. 2003:56).

Three substrates are best for forming foot impressions. These substrates are mud, sand and aerated surfaces (Allen et al. 2004:60). Each of these substrates deform differently in response to forces applied by the foot. Mud created from natural bodies of
water, such as lakes, rivers and oceans, are deformable but incompressible (Allen et al. 2003:60). Instead of compressing, mud is displaced around and beneath the foot in response to contact (Allen et al. 2003:60). Fractures or breaks in the cohesion of the mud are small and localized (Allen et al. 2003:60). If mud is water-saturated, foot impressions can be distorted from adhesion, suction, and lateral inflow as the foot is lifted to take the next step (Allen et al. 2003:60). Sand and mud are incompressible. Distinct from mud, sand has low cohesion and plasticity unless sufficiently wet (Allen et al. 2003:60). Wet sand deforms through breaks in cohesion represented by microscopic, small-scale fractures over the surface of the foot impression (Allen et al. 2003:60). Aerated surfaces, such as peat, are oxygenated. Oxygenation makes surfaces highly compressible and cohesive. Air is displaced from aerated surfaces in response to contact, similar to squeezing a sponge. Aerated surfaces are compressed beneath the foot with little or no lateral displacement of the substrate (Allen et al. 2003:60).

In environments where exposure and erosion occur, preservation of foot impressions is dependent on infill from a contrasting layer of sediment. Infill by contrasting layers of sediment provides protection from erosion that may destroy foot impressions or lead to repeated exposure and reburial of foot impressions (Allen et al. 2003:62). In some cave environments, however, erosion may have a lesser effect on preservation. A passage in one of these caves, Aborigine Avenue in Jaguar Cave, Tennessee, has preserved foot impressions and is the focus of this thesis.
Jaguar Cave, Tennessee

Jaguar Cave is a complex cave system in north-central Tennessee (Figure 1; Willey et al. 2005:61). The entrance of Jaguar Cave is a large opening where a small stream flows from the cave’s interior. This portion of the cave is covered in wet, slippery mud and floods following heavy rains. Two roughly parallel passages are intersected sporadically by the stream. With many side-passages and direction changes, these passages are complex, which makes their navigation difficult. About 600 m from the entrance, cavers encounter the Towering Inferno, a steep breakdown pile of limestone boulders approximately 20 m high. This breakdown varies in size from small, and often sharp, pieces of rock to human-sized boulders. Until 1976, the Towering Inferno was thought to be the end of Jaguar Cave. However, in that year, members of the National Speleological Society discovered an underground connection leading to many more kilometers of passage beyond this point (Watson et al. 2005:26).

After climbing Towering Inferno, cavers enter more passages. One of these passages, the Only Crawl, is a low and wide passage about 1 m in height and 70 m in length. The low ceiling makes traveling through Only Crawl awkward; walking is impossible and cavers must crawl. Prehistoric cavers holding cane torches would have had a difficult time traversing this passage. In fact, their cane torches left the first evidence of prehistoric deep cave use in the form of charcoal and smudges or stoke marks in the Only Crawl (Willey et al. 2005:61). Archaeological evidence of early cave use closer to the cave entrance most likely has been destroyed by flooding and other hydrological processes (Willey et al. 2005:61).
Figure 1. Map of Jaguar Cave, emphasizing Aborigine Avenue (rectangle) where prehistoric foot impressions occur.

The Only Crawl provides access to two large passages: Tremendous Trunk and Horrendous Trunk (Watson et al. 2005:27). Horrendous Trunk leads to the southern end of the cave. Tremendous Trunk leads southwest and is the route to Aborigine Avenue. Tremendous Trunk is a large, dry passage, approximately 30 m wide, 10 m high, and 550 m long (Watson et al. 2005:27). The floor of Tremendous Trunk is covered by rock debris that has fallen from the walls and ceiling (Watson et al. 2005:27). This debris makes travel through the passage difficult. Large boulders, blocks, and slabs must be climbed around, over and between to reach a small and inconspicuous side passage in the west wall of Tremendous Trunk (Watson et al. 2005:27). This side passage is Aborigine Avenue, a 500-meter-long dead-end containing at least 274 impressions made by the feet of prehistoric cavers 4,500 years ago (Watson et al. 2005). If cavers are familiar with the cave and they travel directly from the entrance to Aborigine Avenue, the trip takes a little more than an hour, although the route is complex and confusing.

Aborigine Avenue is a relatively flat passage with an ancient stream bed running its length. The floor of Aborigine Avenue is sandy clay with scattered areas of breakdown and flowstone (Watson et al. 2005:29). This passage has two areas of low ceiling height where normal walking is impossible. The first and longer of these height changes occurs in the middle third of the passage; ceiling height decreases from more than 2 m in the front third of the passage to about 1 m for a distance of approximately 15 m. After this portion of the passage, the ceiling height increases to over 2 m and a pit, 20 m wide, is on the south side of the passage. This portion of the passage contains a few speleothems and many large stalactites. Near the end of the pit, the north wall juts toward the middle of the passage and the ceiling height decreases to less than 1.5 m. This portion
of the passage is the most difficult to traverse; one must negotiate a narrow path and low ceiling while avoiding the pit. The final section of the cave has a ceiling height slightly less than 2 m with areas of stalactites that leads to a dead-end, causing cavers to exit the passage the way they came. The possibility that the prehistoric cavers exited the cave passage by a different route than they entered has been eliminated by modern cavers. Modern cavers have not found a second exit to the passage and there are no indications prehistoric cavers found another exit either (Watson et al. 2005).

Following the prehistoric cavers’ journey, humans did not enter this passage again for thousands of years until the foot impressions were discovered in 1976 by modern cavers (Watson et al. 2005:25). Documentation of the foot impressions began in October 1976 and continued until August 1993. Each foot impression was measured and mapped. This documentation method was chosen for three reasons: the large number of impressions, possible damage to the impressions by modern cavers, and the information available about anatomical structures of these prehistoric cavers (Watson et al. 2005:31). As the above description of Jaguar Cave suggests, the trip to Aborigine Avenue is rigorous, especially when carrying recording equipment. Once there, the challenges continue. Aborigine Avenue is deep in the dark zone of Jaguar Cave; artificial light is essential. The cramped conditions, uneven working surface, and low ceilings of Aborigine Avenue make working in this passage uncomfortable and difficult. Documentation trips and the process of documenting the foot impressions are described in more detail in Chapter III.

Previous research on the distribution of these foot impressions by Watson et al. (2005) suggests that these prehistoric cavers explored as they entered Aborigine
Avenue and then made a direct and expedient exit (discussed in detail in Chapter III). This thesis examines the assertion of Watson et al. (2005) that the foot impressions in Aborigine Avenue are evidence of exploration.

Purpose of Study

The average step length from a contemporary sample of walking humans is used to identify trackways from the Jaguar Cave foot impressions. The locomotory patterns of these trackways are examined to make inferences about the behavior of the prehistoric cavers that created these impressions. The identification of trackways allows researchers to trace the route of individuals through a passage. How an individual walked throughout a route—whether slowly with repeated starts and stops or rapidly in constant motion—is preserved in the step lengths of a trackway. By understanding how step length varies in response to extrinsic and intrinsic variables, it is possible to reconstruct the walking pattern that created the trackway. This thesis identifies trackways of the prehistoric cavers and interprets differences in the walking patterns of trackways heading into (inbound) and out of (outbound) Aborigine Avenue. This analysis assesses the exploration assertion of Watson et al. (2005), and it increases the understanding of early cave use by interpreting the motivation of this prehistoric cave expedition from trackways.

Outline of Thesis

Chapter I has introduced foot impressions and trackways, explained the rare circumstances that lead to the preservation of foot impressions in the archaeological record, described Jaguar Cave, and presented the purpose of this study.
Chapter II reviews previous research on human locomotion, factors that influence walking, and archaeological sites containing foot impressions from caves in the southeastern United States and around the world. A review of the research on human walking patterns provides background needed to develop a method for identifying trackways and interpret behavior from step lengths. Chapter III describes the materials and explains the methodology used to identify trackways of prehistoric cavers in Jaguar Cave.

Chapter IV presents the results of Jaguar Cave trackway identification and trackway analysis. Descriptive data are provided for the trackways, including orientation in the cave (inbound or outbound), number of foot impressions in each trackway, trackway length and location of each trackway in Aborigine Avenue, and the relationship to surrounding trackways and features in the cave passage. Also, descriptive data are provided for foot impressions in trackways. Inferential statistical comparisons of step length and foot length for inbound and outbound trackways determine if differences between the two trackway directions exist.

Chapter V discusses the results and presents limitations of this study by using previous research to interpret behavior of the prehistoric cavers and other possible reasons for differences in inbound and outbound trackways. Finally, Chapter VI summarizes the study and suggests topics for further research.
CHAPTER II

LITERATURE REVIEW

The previous chapter introduced foot impressions and trackways, their rarity in the archaeological record, and previous research in anthropology and archaeology. As indicated in Chapter I, foot impressions and trackways are preserved only under special circumstances and provide insight into a variety of anthropological and archaeological topics. Anthropologists can infer past behavior from trackways by understanding factors that influence walking patterns.

This chapter discusses human bipedal locomotion and the use of foot impressions in archaeology beginning with a brief introduction to human locomotion and then discussing variables that influence its patterning. These variables form the basis for interpreting the behavior from the Jaguar Cave trackways developed in the discussion chapter. The last section of this chapter summarizes past archaeological foot impression research from the Southeast U.S. and other parts of the world.

Human Locomotion

Humans are capable of moving at a variety of speeds by adjusting their walking pattern through changes in step length and step frequency depending on the environment (Cavanagh and Kram 1989:467). These variables change the force applied to the ground to support and move the body’s center of mass (COM) during walking.
(Cooper et al. 2007:1). The mechanical work of walking is the energy required to produce this force over a distance. Walking force can be separated into vertical and horizontal components that change dynamically during the stride cycle (Cooper et al. 2007:1). Change in walking force is accomplished through the interaction of limb angle orientation, change of momentum of the COM, and muscle activity (Cooper et al. 2007:1).

The combination of step frequency, step length, and the mechanical work produced during walking are influenced by intrinsic and extrinsic variables (Cooper et al. 2007; Davies et al. 1974; Kerdok et al. 2002; Lejeune et al. 1998). Intrinsic factors are inherent to the individual and independent of the individual’s control. Intrinsic variables include anthropometric dimensions, age, and sex. Extrinsic factors, on the other hand, derive outside the individual. Extrinsic variables include grade, surface properties, and irregularity of terrain. Other factors (e.g., velocity and fatigue) that do not fit into either category are discussed separately.

Intrinsic Factors

Anthropometric Dimensions

Anthropometric dimensions that influence step length and frequency include height, leg length, and weight (Cavanagh and Kram 1989:474). These dimensions interact together to influence walking patterns. For example, two individuals of the same height but different weights and leg lengths have different walking patterns. Four studies, Murray et al. (1964), Cavanagh and Kram (1989), Jasuja (1993) and Jasuja et al. (1997), examined how anthropometric variables influence walking patterns.
Murray et al. (1964:341-342) found a statistically significant difference ($p < .01$) in stride lengths between tall and short individuals who walked at the same speed. At a standardized speed of 3.83 m/s, Cavanagh and Kram (1989:474) found weak positive correlations of stride length with stature ($r = 0.257$), leg length ($r = 0.310$) and weight ($r = 0.204$). Similar to Murray et al.’s results, Jasuja (1993:2) found a weak positive correlation of stride length with stature ($r = 0.224$). Subjects in Jasuja’s (1993:2) study were instructed to walk at a preferred speed. When subjects were asked to walk fast, Jasuja et al. (1997:183) found a moderate positive correlation of stride length with stature ($r = 0.433$). These results suggested that anthropometric variables have low correlations with walking patterns, with tall, heavy and long-legged individuals tending to have longer stride lengths than short, light and short-legged individuals.

Body proportion differences also influence the energetic cost of walking and running. Increased leg length decreases the energetic cost of running and walking (Steudel-Numbers et al. 2007:195). Webb (1996:524) reports a moderate positive correlation of leg length to maximum walking speed ($r = 0.540$). Long-legged individuals attain faster walking speeds than short-legged individuals do before being forced to run, although long-legged individuals do not have faster preferred walking speeds. Webb (1996:524) finds a weak positive correlation between leg length and preferred walking speed ($r = 0.14$).

**Age**

Walking patterns change with age. Children develop an adult walking pattern by five years of age (Grieve and Gear 1966:379). After the age of 55 years, degenerative changes and loss of muscle control cause differences in walking patterns. This section
describes how walking patterns of children and older adults differ from young adult patterns.

Before the age of five years, children have an erratic walking pattern. Young children’s relative stride lengths are shorter, step frequencies are quicker, and both stride lengths and step frequencies are more variable than adults (Grieve and Gear 1966:383). There is little or no correlation between step frequency and velocity in children younger than five (Grieve and Gear 1966:385). After five years of age, the correlation of step frequency and velocity is the same as adults \((r = 0.97; \text{ Grieve and Gear 1966:385})\).

Walking patterns change as the body deteriorates with increased age. These changes include the orientation of the lower body during walking, preferred walking speed, stride length, step frequency and angle of gait (McGibbon and Kerbs 2001; Murray et al. 1964). These changes affect control of the trunk, which is important in maintaining balance during walking (McGibbon and Kerbs 2001:1923). McGibbon and Kerbs (2001) report trunk control of younger adults \(< 55 \text{ years}\) and older adults \(> 55 \text{ years}\) by observing the relationship of the pelvis to the trunk during a stride. This relationship is the pelvis-trunk phase shift and is the angular velocity between the pelvis and trunk during a stride (McGibbon and Krebs 2001:1924). This relationship is quantified as the angular velocity \((\text{radians/sec})\) over the stride cycle \((1 \text{ cycle} = 2\pi \text{ radians} = 360^\circ)\), where positive values indicate the trunk is leading the pelvis during walking (McGibbon and Kerbs 2001:1924). The correlation of age to pelvis-trunk phase shift is moderate and significant \((r = 0.48, p < 0.001; \text{ McGibbon and Krebs 2001:1926})\). Upright posture of the trunk shows no age-related difference. Younger adults have negative pelvis-trunk phase shift values, which indicates their pelves are anterior to the trunk.
during walking; positive values and the reverse relationship are found in older adults (McGibbon and Kerbs 2001:1927). Decreased muscle control of older adults could be responsible for differences in walking between young and old adults (McGibbon and Kerbs 2001).

The muscles of the pelvis and lower limbs coordinate advancement, propulsion, and adduction of legs during walking (McGibbon and Kerbs 2001:1929). The muscle coordination of the lower body predominately controls walking in the pelvis-leading strategy employed by younger adults. The trunk makes up two-thirds of the total body weight and controls walking in the trunk-leading strategy employed by older adults (McGibbon and Kerbs 2001:1923). Lower back muscles contract eccentrically during trunk-led walking, and this action increases the eccentric mechanical energy expended by the lower back muscles. This expenditure reduces mechanical energy transfer from the trunk to lower limbs and concentric mechanical energy expense of the core muscles (McGibbon and Kerbs 2001:1929). Stabilizing the upper trunk in a position anterior to the pelvis increases tension in lower back muscles and helps propel older adults forward, reducing the need for lower limb muscle contraction during walking. A trunk-leading strategy suggests diminished lower limb muscle control, endurance and strength.

Stride length, step frequency, preferred walking speed and angle of gait show age-related differences as individuals switch from a pelvis-leading to a trunk-leading strategy (Murray et al. 1964:343-344). After 55 years of age, stride length becomes shorter, angle of gait increases, and step frequency and preferred walking speed all decrease (McGibbon and Kerbs 2001:1926; Murray et al. 1964:343-344). These changes
are ways older adults mitigate decreased stability as muscle control of the lower extremities decreases (Murray et al. 1964).

Sex

There is little research on the differences in walking patterns between men and women. Only one study (McGibbon and Kerbs 2001) investigated these differences. This study examined upper body posture, range of motion and gait speed between males and females. Only step frequency showed a statistically significant difference between males and females ($p = 0.007$; McGibbon and Krebs 2001:1926). Females walked faster per unit height than males (McGibbon and Krebs 2001:1926). More research might identify if other walking pattern differences exist between males and females.

Extrinsic Factors

Surface Grade

The effect of gravity on locomotory patterns changes with surface grade (Davies et al. 1974). On a flat surface, the force of gravity on the body is perpendicular to the ground and gravitational force on the body remains constant as the body moves horizontally. On an incline, the body must overcome gravity as it moves vertically as well as horizontally, thereby increasing mechanical work (Cavanagh et al. 2000). On a decline, gravity decreases the mechanical work of walking by providing kinetic energy to move the body downward (Cavanagh et al. 2000; Davies et al. 1974). These changes in mechanical work in relation to surface grade also affect step frequency and length.

Leroux et al. (2002) examined the relationship of step frequency and length to surface grade change. Over a grade change of -10 percent to +10 percent, subjects in
Leroux et al.’s (2002) study walked at a self-selected comfortable speed, which ranged from 0.76 to 1.34 m/s (average = 1.03 +/-0.19 m/s). A progressive increase of step length was found with grade increase from 0 percent to +5 percent to +10 percent ($p < 0.05$). Step length decreased as grade decreased from 0 percent to -5 to -10 percent ($p < 0.05$).

Differences in step length are related to changes in the trunk and pelvic orientation relative to the surface (Leroux et al. 2002:70). As the grade increases, the trunk becomes progressively more anterior in relationship to the pelvis. The anterior position of the trunk and increased step length produce greater momentum to counteract the increased resistance of gravity that accompanies grade increase. As the grade decreases, the trunk becomes progressively more posterior in relationship to the pelvis. The posterior position of the trunk and decreased step length counteract the increased forward momentum of gravity that accompanies grade decrease. These walking pattern changes help maintain balance on an incline.

**Surface Properties**

Similar to changes in surface grade, properties of the walking surface affect walking patterns. These properties include substrate stiffness, damping ratio and coefficient of friction. Surface stiffness is a surface’s ability to resist deformation from an applied force. For example, a hardwood floor is a stiff surface and does not deform in response to contact. Sand, on the other hand, is a pliable surface and when walked on, deforms significantly. Damping is a surface’s ability to dissipate energy transferred from the foot to the surface during walking. A surface with a low damping ratio, such as a running track, returns more energy to the walker than a surface with a high damping ratio, such as sand, which dissipates mechanical energy into the ground. A surface’s
The coefficient of friction is the amount of friction produced between the foot and surface during walking. Rough surfaces, such as carpet, produce much friction between the foot and surface, while slippery surfaces, such as ice, produce little friction. Studies by Kerdok et al. (2002), Cooper et al. (2007), and Cham and Redfern (2002) examine how surface properties affect walking patterns.

Step length and step frequency increase slightly as the surface stiffness increases. A study by Kerdok et al. (2002) was conducted on running track surfaces with different stiffness. Track surfaces have low damping ratios and are designed to store and return mechanical energy to the athlete, similar to a trampoline returning the energy of a jump back to the jumper (Kerdok et al. 2002:475). Surfaces with high damping ratios, such as sand, which disperse the energy of a step into the ground, increase the mechanical work required to walk.

Kerdok et al. (2002:472) found significant differences in both stride length \( (p = 0.0001) \) and step frequency \( (p = 0.0001) \) across a 12.5-fold change in surface stiffness. Although significant differences occurred in stride length and step frequency, these differences were not substantial. A 12.5-fold increase in surface stiffness resulted in less than a 5 mm increase in step length and .25 Hz increase in step frequency, which was a minimal change to these variables (Kerdok et al. 2002:472).

Slippery surfaces, which produce little friction between the foot and surface, increase the chance of falling. Individuals can produce more friction on slippery surfaces by changing their walking pattern. Cooper et al. (2007) examined how shod individuals changed their walking pattern while walking on slippery surfaces. The authors found a strong correlation of step length to friction for safe walking \( (r^2 = 0.907, p < 0.0001) \);
Cooper et al. 2007:2). As surface properties increased the risk of slipping, individuals shortened their stride by increasing the horizontal angle of foot contact and horizontal force to increase the amount of friction between the foot and the surface (Cooper et al. 2007).

Cooper et al. (2007:2) found much interpersonal variation in the magnitude of the coefficient of friction between the foot and surface. With the same step length, some individuals produced 50 percent more friction than others (Cooper et al. 2007:2). Interpersonal differences in the amount of friction produced were independent of mass and were explained partially by lower limb length (Cooper et al. 2007:2).

Perception of the walking surface also affects walking patterns (Cham and Redfern 2002; Pijnappels et al. 2001). In Cham and Redfern’s (2002) study, a significant difference was observed in stride length when an individual was unsure of the surface properties ($p < 0.01$). Supporting the findings of Cooper et al. (2007), Cham and Redfern (2002) found that shorter stride lengths were due to the increase in the horizontal angle of contact and horizontal force. Simply put, when people were unsure of the surface properties, they placed their feet to the ground closer to a 90º angle with the lower leg and with more force than when walking normally. Shortening stride length by increasing angle and force resulted in a 16-33 percent reduction in the minimum required coefficient of friction between the foot and the surface (Cooper et al. 2007:163).

**Irregular Terrain**

Rhythmic movements, such as walking at preferred speed across flat terrain, minimize muscle use (Danion et al. 2003:70). As surface grade undulates, an individual must adapt his or her walking pattern. An individual’s response to these terrain
irregularities requires muscles not typically used, which results in more variable walking (Menz et al. 2003). Menz et al. (2003) found significant differences in step frequency, average step length and step timing between walking on a level surface and walking on an irregular surface ($p < .01$). When walking on an irregular surface, step frequency was reduced, average step length was greater and step timing became more variable, contrasted with walking on a level surface (Menz et al. 2003:42).

Other Variables

**Velocity**

Velocity is speed in a particular direction, and locomotory velocity is influenced by the physical ability and choice of the individual and environmental variables. Typical adult gait patterns can be divided into two basic speeds, walking and running (Abernethy et al. 2002:256). For most adults, preferred walking speeds are slower than 2.0 m/s and running speeds occur above 2.5 m/s, with the walk-to-run transition speeds happening between 2.0 and 2.5 m/s (Abernethy et al. 2002:258). These two locomotory forms have different combinations of step length and frequency for increasing velocity, and these differences are described in the following paragraphs.

Both stride length and step frequency increase with increasing velocity (Danion et al. 2003; Jasuja et al. 1997). At speeds less than 4.0 m/s, stride length increases more than step frequency (Cavanagh and Kram 1989:470). Cavanagh and Kram (1989:470) found an increase in stride length of 28 percent as velocity increases from 3.0 to 4.0 m/s. For this same velocity interval, step frequency only increased 4% (Cavanagh and Kram 1989:470).
Similar to the combination of step length and step frequency with increasing velocity at low speed running, Jasuja et al. (1997) found an average increase of 12 cm in step length between preferred walking and maximum walking speed. The findings of Jasuja et al. (1997) supported Cavanagh and Krans’s (1989) conclusion. At speeds less than 4.0 m/s, typically found in walking and low speed running, individuals increased stride length more than step frequency to increase velocity.

Variability in stride length and step frequency is reduced as walking speed increases beyond a preferred speed (Jasuja et al. 1997:183; Jordan et al. 2007:132). Jordan et al. (2007) found significant differences ($p < 0.05$) in the coefficient of variation of stride length and step frequency for velocities deviating from 60 percent to 140 percent of preferred walking speed, with the lowest variability in stride length occurring at 140 percent of preferred walking. The results of Jordan et al. (2007) were supported by the findings of Jasuja et al. (1997). In that study (Jasuja et al. 1997), variability in step length was reduced from a standard deviation of 7.4 cm for preferred walking speed to 6.8 cm for maximum walking speed, although the statistical significance of this difference was not reported.

Jasuja et al. (1997) and Jordan et al. (2007) also examined the correlation of step length and stature during walking. In Jasuja et al.’s (1997) study, correlations of step length and stature increased from an average of 0.289 for walking at a preferred speed to 0.433 for walking as fast as possible. Similar to these results, Jordan et al. (2007) found correlations of stride length and step frequency for walking velocities varying from 80 percent to 120 percent of an individual’s preferred walking speed. Correlations exhibited a curvilinear change with speed, with the weakest correlations falling between 100
percent and 110 percent of preferred walking speed (Jordan et al. 2007:132). These findings suggested that as walking speed increased from a preferred speed, step length became less variable and an individual’s walking pattern became more standardized.

Step length and frequency both increase with increasing velocity. At walking and low-speed running velocities (<4.0 m/s), step length mainly contributes to velocity increase. As walking speed increases, step length becomes less variable. Correlations of step length to stature, and stride length and step frequency to velocity increase as an individual walks faster than his or her preferred speed.

**Fatigue**

Another variable influenced by environmental and personal factors is fatigue. Fatigue produces irregularities in the timing and patterning of walking (Elliott and Roberts 1980:203). Individuals slow their walking speed as they tire. Fatigue affects walking through decreased and more variable step length (Elliott and Roberts 1980).

**Archaeological Studies of Foot Impressions**

Anthropological foot impression research has two areas of focus: early hominid kinetics and the demographic composition and behavior of more recent past humans. Hominid kinetic research on foot impressions is based on hominid trackways from Laetoli, a site in Tanzania. Behavioral inferences and demographic composition of more recent humans are based on cave sites in the southeastern U.S. and other sites from around the world. The research of archaeological sites in the Southeast is summarized first, followed by demographic and behavioral inferences from other sites around the
Beginning at least 4,500 years ago, caves in the southeastern U.S. were used by prehistoric people. The earliest cave trips made by humans appear to be mainly exploratory in nature (Watson et al. 2005:40). Beginning around 2,800 years ago, however, humans used these caves as mineral and chert quarries, for religious practices and funeral ceremonies (Crothers et al. 2002:502; Watson et al. 2005:40). This section discusses cave sites in the southeastern U.S. that contain foot impressions. These sites provide a context for prehistoric cave use in the region.

These Southeast cave sites are Lon Odel Memorial Cave, Missouri; Sequoyah Caverns, Alabama; Fisher Ridge Cave, Kentucky; Upper Crouchway in Unknown Cave, Kentucky; and Third Unnamed Cave, Tennessee. Other sites outside the Southeast U.S. containing foot impressions are Severn Estuary in Wales; Mersey Estuary in Formby Point, England; Willandra Lakes in western New South Wales; Monte Hermoso 1 on the Argentinean coast; and Oro Grande in the Mojave Desert, California.

Lon Odel Memorial Cave

Lon Odel Memorial Cave, Missouri, was discovered in 1985 when a vertical sinkhole opened into the cave. The prehistoric horizontal entrance had collapsed by the time Europeans settled the area over 150 years ago (Beard 1997:44-45). A few hundred yards from the modern entrance, torch remains, stoke marks, charcoal, and foot impressions were left by one or more prehistoric cavers (Beard 1997:44). Based on foot
size, this prehistoric caver was estimated to be a 4-foot-10-inch young adult (Beard 1997:44). No other evidence of prehistoric human activity, such as worked stone or pottery, was found.

**Sequoyah Caverns**

Prehistoric human activity in the form of several torch fragments and human foot impressions was found in a small passage deep in the dark zone of Sequoyah Caverns, Alabama (Sneed 1984:180). The seven foot impressions in this cave passage were left by a large male, and a radiocarbon date of 520 +/- 50 B.P. was determined from charcoal associated with the foot impressions (Sneed 1984:180). Other evidence of prehistoric human activity included prehistoric artifacts, such as worked flint, pottery, bone, and shells (Sneed 1984:181). These artifacts were found in another part of the cave and were not associated with the foot impressions and torch fragments. There is also evidence of saltpeter mining, most likely associated with historic human activity.

**Third Unnamed Cave**

Near a waterfall, at the top of a climb deep inside Third Unnamed Cave, Tennessee, six foot impressions were left by at least one prehistoric caver (Crothers et al. 2002:510). These foot impressions were not the only evidence of prehistoric human activity at Third Unnamed Cave. Other prehistoric human activities included chert quarrying, lithic manufacturing, and engravings on a cave wall (Simek et al. 1998). Radiocarbon dates from charcoal found in association with the chert lithics suggested the cave was used briefly around 3000 B.P. (Crothers et al. 2002:509; Simek et al. 1998:670).
Fisher Ridge

At least 18 slippered foot impressions, charcoal and torch fragments were found in Raccoon Trail and Aborigine Way, two cave passages an hour into the dark zone of Fisher Ridge Cave, Kentucky. These materials were left by a least two prehistoric cavers on one or two trips (Watson 1982:1-2). These foot impressions were made in sand and several other areas of sediment crust were broken, possibly by the prehistoric cavers’ feet, although no distinct impressions were left (Watson 1982:3). A radiocarbon date of 3175 +/- 90 B.P. was estimated from charcoal associated with the foot impressions (Beta Analytic Inc., August 12, 1996).

Unknown Cave

Over an hour’s travel into Unknown Cave, part of the Flint Ridge portion of the Mammoth Cave System, is Upper Crouchway. Two prehistoric cavers left 12 distinct foot impressions in this passage (Watson 1996). The cavers walked in and out of the passage, leaving trackways in both directions. Due to significant pronation, the first prehistoric caver’s feet left deep impressions of the big toe but no impressions of the other toes (Watson 1996:3). The second prehistoric caver left impressions of all toes and had shorter and proportionately wider feet (Watson 1996:3). Initial inspection suggested the second prehistoric caver was following the first, matching step length and foot placement (Watson 1996). A radiocarbon date of 3670 +/- 50 B.P. was determined from charcoal found near an isolated foot impression about 100 m from the 12 other foot impressions (Watson 1996).
Other Foot Impression Sites

Most of the foot impressions from the cave sites just discussed are deep in the dark zone and many are far from the cave entrances believed to have been used by the prehistoric cavers. The stable environment of these caves preserved the foot impressions. The next section presents archaeological sites, other than cave sites where foot impressions have been preserved. Each site is discussed using the following format. First, the site is introduced. Second, the depositional processes leading to the preservation of the foot impressions are examined. Third, information about the site’s trackways, such as number of impressions, number of trackways and step length measurements, is presented. Fourth, interpretations based on available trackway information are discussed.

Laetoli

Laetoli is a paleontological site in northern Tanzania that has produced hominid fossils since the late 1930s. It was not until 1975, however, when early hominid trackways dating to 3.6 mya were discovered, that the significance of Laetoli was realized by paleoanthropologists (White and Suwa 1987:485-486).

The Laetoli foot impressions were created at the beginning stages of a volcanic eruption in compressed volcanic tuffs (Hay and Leakey 1982:55; Leakey and Hay 1979; White and Suwa 1987:488). These tuffs have two distinct layers. The lower unit is characterized by ash layers with rain-printed surfaces, generally 7.0-8.6 cm thick (Leakey and Hay 1979:317). The upper layer is a flat, damp, sand-like limestone that is more varied in depth. It is thinnest in higher areas and thickest in depressions, filling the foot impressions preserved in the lower layer (Leakey and Hay 1979:317). The protective
ash layers covered the foot impressions for more than three million years until they were
discovered in 1975.

The hominid foot impressions at Laetoli are separated into three trackways
located at two sites, Site A and B (Leakey and Hay 1979:319-320). The first trackway
(A1) is located at Site A in the northern region of the Laetoli fossil beds (Leakey and Hay
1979:319). Trackway A1 is 1.5 m long and contains five impressions (Leakey and Hay
1979:319). The average step length of Trackway A1 is 31 cm (Leakey and Hay
1979:319). The other two trackways are located at Site G (G1 and G2) in the
southwestern region of the Laetoli fossil beds (Leakey and Hay 1979:320). Trackways
G1 and G2 are 23.54 m long; Trackway G1 is composed of 22 impressions and Trackway
G2 is composed of 12 impressions (Leakey and Hay 1979:320). The average step length
of Trackway G1 is 38.7 cm; Trackway G2 has an average step length of 47.2 cm (Leakey
and Hay 1979:320).

The first published study of the Laetoli foot impressions was descriptive
(Leakey and Hay 1979). The first study of the evolutionary implications of bipedalism
from the Laetoli foot impressions was by Day and Wickens (1980) and focused on the
depth of the Laetoli foot impressions to determine body weight transfer. In both Laetoli
and modern human foot impressions, weight, and force were transferred from the heel to
ball of the foot (Day and Wickens 1980:386). The Laetoli impressions were deepest at
the heel strike, ball of the foot and big toe (Day and Wickens 1980:386). Day and
Wickens (1980:387) concluded that the weight transfer measurements from the Laetoli
foot impressions were similar to modern humans, which suggested that bipedalism
reached an advanced form early in hominid evolution.
Instead of analyzing the depth of the Laetoli foot impressions, White (1980) used the Laetoli foot impressions to estimate the stature of early hominids. Based on average foot length-to-height percentages of modern populations, White (1980) estimated the Laetoli hominids were between 1.18-1.56 m tall. These estimations are consistent with stature estimations from skeletal remains of *Australopithecus afarensis*, the species that most likely made the Laetoli foot impressions (White 1980:175).

Using the stature estimations of White (1980), Charteris et al. (1981) constructed the relative stride length of the Laetoli hominids. Based on relative stride length, Charteris et al. (1981:497) estimated the walking velocity of Trackway G1 was 0.56 m/s and Trackway G2 was 0.72 m/s. The estimated speed of the Laetoli hominids was slower than the preferred walking speed of modern humans (0.76 to 1.34 m/s; Leroux et al. 2002).

In a subsequent study, Charteris et al. (1982) analyzed the walking patterns of the Laetoli hominids by estimating relative stride, speed, and cadence based on normal walking patterns of modern humans. These walking patterns fall within the range of modern humans only if the estimated walking speed of the Laetoli hominids was slower than modern humans (Charteris et al. 1982:143). If the Laetoli hominids walked at speeds preferred by modern humans, their relative stride lengths (the ratio of stride length to leg length) were shorter than modern humans (Charteris et al. 1982:143).

Reynolds (1987) examined the determinants of stride length in quadrupedal mammals, quadrupedal and bipedal non-human primates, and humans. Humans and other primates have longer strides than quadrupedal mammals of the same size (Reynolds 1987). During quadrupedal locomotion, due to longer limb length, stride lengths of non-
human primates are longer than other quadrupedal mammals of similar size (Reynolds 1987:112). Extending this principle to bipedal locomotion, *A. afarensis* should have had shorter relative stride lengths than modern humans because *A. afarensis* had shorter lower leg lengths (Reynolds 1987:113-114). Reynolds (1987) concluded that the stride lengths of the Laetoli hominids were short due to shorter lower limbs and not because they were walking slowly as concluded by Charteris et al. (1981, 1982).

Raichlen et al. (2007) further studied the Laetoli Trackways by comparing the Laetoli stride lengths to those of modern humans and bipedal chimpanzees. Using kinematic data from humans and chimpanzees, the probability that the Laetoli hominids walked with a chimpanzee-like bent-hip, bent-knee walking pattern or a human-like extended-hind limb walking pattern was assessed. The authors concluded the Laetoli trackways could have been created using either the chimpanzee or human walking pattern (Raichlen et al. 2007:4-5). Thus, the locomotory pattern of the Laetoli hominids could not be resolved using stride length alone.

The hominid trackways at Laetoli presented an important form of evidence for understanding the evolution of bipedalism. Various authors reconstructed the walking patterns of the Laetoli hominids using depth analyses of foot impressions and step lengths. Foot impression depths suggested the Laetoli hominids transferred weight while walking in a manner similar to modern humans. The Laetoli hominids had shorter relative step lengths than modern humans. These shorter step lengths suggested the Laetoli hominids were either walking very slowly or were walking at a normal pace but had shorter relative stride lengths than modern humans due to differences in limb proportions between the two species.
Pleistocene foot impressions from the Willandra Lakes region of western New South Wales, Australia, were reported by Webb et al. (2005). The 124 foot impressions date between 19-23 kya and are the greatest number of Pleistocene human foot impressions from a single site in the world. Of the 124 foot impressions, 78 were in eight trackways; the remaining 46 foot impressions were isolated and not in any identifiable trackways (Webb et al. 2005:2).

The foot impressions were located in a calcareous silty clay hardpan substrate in a swale surrounded by sand dunes (Webb et al. 2005:2). Fluctuating groundwater moistened the hardpan during the formation of the foot impressions (Webb et al. 2005:4). The hardpan formed during repeated cycles of wetting and drying (Webb et al. 2005:4). Carbonate hardened the drying mud and a final layer of calcareous silty clay covered the foot impressions (Webb et al. 2005:4). After the hardpan hardened, it was covered by 6 m of aeolian clayey sand (Webb et al. 2005:2). Recent wind erosion exposed 89 foot impressions; 35 more were excavated from the sand (Webb et al. 2005:2).

Based on foot impression measurements and context, at least eight individuals—men, women and children—created the foot impressions. All eight trackways were moving toward the northeast. Statures were estimated using a regression formula based on the foot lengths of 162 central Australian Aborigines (Webb et al. 2005:5). Speeds indicated by the trackways were estimated using a regression equation from Cavanagh and Kram (1989). The results of these estimates suggested the trackways were created by tall, fast-moving individuals. The individuals who created Trackways 1 through 4 were estimated to be around 6 ft tall and traveled at speeds of 12-14 km/h.
The stride lengths of these trackways showed little variation, which suggested that these people were running in the same southwest-to-northeast direction (Webb et al. 2005:7). The directions of Trackways 5 through 8 converged with Trackways 1 through 4 (Webb et al. 2005:7). Trackways 5 and 8 were left by individuals estimated to be over 6 ft tall and who traveled at 17 km/h and 20 km/h, respectively (Webb et al. 2005:6). Trackways 6 and 7 were created by a woman and child, respectively, who walked at speeds of approximately 5 km/h (Webb et al. 2005:6).

Analysis of foot impressions at Willandra Lakes indicated tall, fast-moving males and a slower traveling woman and child moved in the same direction and suggested shared group activities (Webb et al. 2005:8).

Monte Hermoso 1

Monte Hermoso 1 is an archaeological site on the Argentinean coast (Politis and Bayon 1995). The site contains human foot impressions scattered over an 800 m² area and has yielded 420 human foot impressions as well as bird and artiodactyl prints (Politis and Bayon 1995:6). Foot impressions at Monte Hermoso 1 were radiocarbon dated to 7125 +/- 75 B.P. (Politis and Bayon 1995:6). Foot impressions at Monte Hermoso 1 were formed in silt-clay laminas with intercalated sand layers and preserved in hardened clay-lime deposits (Politis and Bayon 1995:5-6). The clay-lime deposits were covered by daily high tides (Politis and Bayon 1995:6).

Statistical analysis suggested the majority of the foot impressions were created by children walking at a slow speed (Politis and Bayon 1995:6). The nonlinear distribution of the foot impressions was consistent with children playing (Politis and Bayon 1995:6). Because only children were represented and the foot impressions lacked
an apparent direction or pattern, it was concluded that children played at Monte Hermoso
1, which is peripheral to the living site of La Olla, located 200 to 1,000 m to the east
(Politis and Bayon 1995:6).

Severn Estuary

Severn Estuary, in southeastern Wales, has a series of archeological sites.

Three sites (Uskmouth, Magor Pill, and Goldcliff East) contain foot impressions
(Aldhouse-Green et al. 1992, Scales 2002). Foot impressions from Uskmouth are
radiocarbon dated to 6250 +/- 80 B.P.; impressions from Goldcliff East are radiocarbon
dated to 5950 +/- 80 B.P.; and impressions from Magor Pill are radiocarbon dated to

Foot impressions from Uskmouth and Magor Pill were formed in similar
substrates, a thin layer of mud on top of estuarine clay with scattered peats. Goldcliff East
foot impressions, on the other hand, were made in a coarser and more lamented substrate
of estuarine silt and sand (Alderhouse-Green et al. 1992; Scales 2002). The shallow depth
of the Uskmouth and Magor Pill foot impressions and frequent cracks on their surfaces
indicated a high intertidal position with moderate seasonal drying (Aldhouse-Green et al.
1992:43). Organic mud and peat filled the Uskmouth and Magor Pill foot impressions,
preserving them until erosion led to their discovery in 1986 and 1990, respectively
(Aldhouse-Green et al. 1992:16). The Goldcliff East foot impressions were filled by
similar organic mud and peat and were uncovered by a combination of erosion due to
tidal movement and archaeological excavation (Scales 2002:33).

Three trackways occur at Uskmouth. Trackways 1 and 2 parallel each other in
a southeasterly direction (Aldhouse-Green et al. 1992:33). Trackway 3 parallels the first
two trackways, but heads in the opposite direction (Aldhouse-Green et al. 1992:33).

Trackway 1 consists of 24 foot impressions that occur in a straight but discontinuous line. Trackway 2 and Trackway 3 are both continuous straight trackways, consisting of 14 and 6 foot impressions, respectively.

Extensive analysis was undertaken on the Uskmouth trackways. Published trackway data included average step length and stride length, estimated height, walking speed, and relative speed (Table 1). Statures were estimated using foot length as a percentage of stature; 15 percent and 15.5 percent values were employed (Aldhouse-Green et al. 1992:36). Walking speed was estimated using regression formulae from Grieve and Gear (1966).

Uskmouth Trackways 1 and 2 were made by average-sized males walking at a slow speed. Uskmouth Trackway 3 was created by a smaller individual than the other two

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**Table 1.** Severn Estuary trackway data. Uskmouth and Magor Pill trackways from Aldhouse-Green et al. (1992).

<table>
<thead>
<tr>
<th>Trackway</th>
<th>Est. Stature (m)</th>
<th>Mean Step Length (m)</th>
<th>Walking Speed (m/s)</th>
<th>Relative Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Uskmouth</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.74</td>
<td>0.77</td>
<td>1.41</td>
<td>0.82</td>
</tr>
<tr>
<td>2</td>
<td>1.67</td>
<td>0.68</td>
<td>0.71</td>
<td>0.82</td>
</tr>
<tr>
<td>3</td>
<td>1.35</td>
<td>0.66</td>
<td>1.37</td>
<td>1.04</td>
</tr>
<tr>
<td><strong>Magor Pill</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.94</td>
<td>0.81</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

trackways. The small size and morphology of these impressions suggested the trackway was made by a juvenile. The longer average step length of Uskmouth Trackway 3 showed this person walked at a faster relative speed than the other Uskmouth individuals (Aldhouse-Green et al. 1992:36). This longer average step length indicated that the Uskmouth Trackway 3 individual was either under different environmental constraints than the Uskmouth Trackway 1 and 2 individuals, or that some other factor caused the Uskmouth Trackway 3 individual to increase his/her speed despite the muddy conditions.

Magor Pill had one trackway (Table 1). This trackway consisted of nine foot impressions and was associated with other foot impressions that lacked an identifiable pattern (Aldhouse-Green et al. 1992:43). A report about the Magor Pill trackway was less extensive than for the Uskmouth trackways. Data from the Magor Pill trackway included average step length, stride length, and estimated height (Aldhouse-Green et al. 1992:43-46).

Overall, 88 foot impressions were discovered at Goldcliff East. Seventy-five foot impressions form six trackways; the remaining 13 foot impressions had no identifiable pattern. Three of the Goldcliff East trackways, consisting of 34 foot impressions, were created by adults walking toward the estuary (Scales 2002:33). The fourth Goldcliff East trackway was created by a young adult; this trackway consisted of 16 foot impressions and was oriented in the direction of Goldcliff Island (Scales 2002:33-34). The fifth and sixth trackways at Goldcliff East consisted of 25 foot impressions and were made by a very young child and an adult as they walked inland from the estuary (Scales 2002:34). The Goldcliff East trackways suggested that diverse age groups were responsible for creating them. A report about the Goldcliff East foot impressions
provided only qualitative assessment of the trackways. No measurements of the foot impressions, gait parameters, or stature estimations were provided; only the number of trackways, total number of foot impressions, and age estimations were given (Scales 2002).

**Oro Grande**

While excavating Oro Grande, a prehistoric site in California, 54 human and a number of animal foot impressions were found (Rector 1979). Associated charcoal dates the foot impressions from Oro Grande dated to 5070 +/- 140 B.P. (Rector 1979).

The foot impressions at Oro Grande were located close to the Oro Grande River. A swampy area with silt and clay was created when the flow of the river caused water to rise above the riverbanks. When the water level fell, coarse river sand was deposited that preserved the foot impressions.

The 54 foot impressions were created by at least five individuals. Three individuals were juvenile, two individuals were adult, and all were barefoot (Rector 1979:150). Only one trackway, consisting of three foot impressions, was identified from the 54 human foot impressions (Rector 1999:54). Some of the foot impressions, not associated with the trackway, showed interesting morphologies. One individual appeared to have an extra little toe (Rector 1999:54). Based on the depth of some foot impressions, another individual may have been pigeon-toed, those foot impressions having deep big toe depressions (Rector 1999:54).

**Formby Point**

Holocene mudflats of Formby Point, located at the mouth of the Mersey Estuary in northwest England, contained both human foot and animal impressions
Human foot impressions, in 145 trackways, were dated to 3649 +/- 109 B.P. (Roberts et al. 1998:647).

The human foot impressions at Formby Point were made in black, organic-rich sands with very fine layers of blue silt. The foot impressions were covered by a meter of white sand with a top layer of roughly 1 m of dark sandy peat. These layers were buried by over 4 m of sand (Roberts et al. 1998:650). Accelerated erosion of the beach during the 1970s exposed the foot impressions (Roberts et al. 1998:647).

Preliminary analysis was conducted on 75 trackways (Roberts et al. 1998:647). Stature was estimated using foot length as a percentage of stature; a 15 percent value was employed (Roberts et al. 1998:647). The mean adult male height was 1.66 m and the mean adult female height was 1.45 m (Roberts et al. 1998:647).

Although no height estimations for children were given, a majority of the foot impressions at Formby Point was made by children; women were less frequently represented and males were the least frequent (Roberts et al. 1998:648). Several trackways were created by fast-traveling adult males following a deer trackway (Roberts et al. 1998:648-650). Trackways created by women and children indicated a much slower speed (Roberts et al. 1998:650).

Differences in location and locomotory pattern of the trackways of men, women and children suggested different activities (Roberts et al. 1998:650). The tracks of fast-walking males associated with deer tracks suggested males used the mud flats as a hunting area (Roberts et al. 1998:650). The slower movement and scattered trackways of women and children showed they exploited the mud flats to gather resources, such as shellfish (Roberts et al. 1998:650).
Summary

Step lengths from trackways are evidence of past locomotory patterns. Step length varies in predictable ways, influenced by intrinsic and extrinsic variables. While foot impression analysis in archaeology has focused on metric and morphological assessment of individual impressions, when impressions form a trackway, step length can provide additional information concerning past behavior. For example, it is possible to identify whether a trackway was created by a walking or running individual. Step length increases with speed. As speed increases, variation in step length decreases. The low variation and long step length from some Willandra Lakes trackways suggest the people who made them ran. Other trackways from Willandra Lakes, however, had shorter and more variable step lengths, which indicate they walked. The different velocities of these trackways suggest these people were behaving differently while traveling in a common direction.

Willandra Lakes is just one archaeological site with foot impressions presented in this chapter. These other locations include cave sites in the southeastern U.S. and sites from elsewhere in the world. These foot impressions are the basis for two areas of research: early hominid kinetics, and the demographic composition and behavior of more recent past humans. Early hominid kinetics are based on trackways at Laetoli, Tanzania. Behavioral inferences and demographic composition of more recent humans are based on foot impressions from cave sites in the southeastern U.S. and other sites elsewhere.
CHAPTER III

MATERIALS AND METHODS

As mentioned earlier, previous research on the shape and distribution of the Jaguar Cave foot impressions by Watson et al. (2005) suggested that the prehistoric cavers explored as they entered Aborigine Avenue and then made a direct and expedient exit. This study identifies trackways of the prehistoric cavers and interprets their behavior to examine that assertion. The materials used in this study and the methodology used to identify trackways are explained in this chapter. First, the research hypothesis and walking pattern expectations are discussed. Then, the materials used are presented. Finally, the methods used to identify trackways are described, followed by descriptive and inferential statistics used to evaluate the research hypothesis.

Expectations

This thesis uses step length analysis to examine the assertion by Watson et al. (2005) that prehistoric cavers explored Aborigine Avenue on the way into the passage and took a more direct and expedient route when exiting. Watson et al. (2005:35) stated that when entering a new cave passage, modern cavers tend to wander, inspect and explore, but when exiting the same passage, they travel quickly. Watson et al. (2005) proposed that prehistoric cavers may have employed a similar approach when entering and exiting Aborigine Avenue.
Watson et al. (2005) used a chi square test to compare the shape, location, and orientation of the Jaguar Cave foot impressions to investigate this hypothesis. The authors found a difference between the shape distribution of foot impressions in the front and back of the passage \((p = 0.01)\). Foot impressions in the front of the passage were more linearly distributed than those in the back of the passage for both inbound and outbound foot impressions (Watson et al. 2005:35). Furthermore, there was a greater number of inbound foot impressions \((n = 150)\) than outbound \((n = 123; \text{Watson et al. 2005:35})\). Based on shape differences in the distribution of foot impressions at the front and back of the passage and differences in the number of inbound and outbound foot impressions, Watson et al. (2005) proposed that, just as modern cavers do, prehistoric cavers explored as they entered the cave passage and made a direct and expedient exit.

This thesis examines the differences in step lengths of inbound and outbound trackways in order to examine further the exploring-exiting hypothesis proposed by Watson et al. (2005).

Certain walking patterns are consistent with exploring which supports this hypothesis. The first few steps of a walking sequence have the greatest variability in step length (Jasuja et al. 1997). Also, step lengths shorten when people are uncertain of their surroundings (Cham and Redfern 2002; Pinjnappels et al. 2001). Exploring implies the prehistoric cavers were unfamiliar with their surroundings and would have stopped more often to become familiar with the passage as they entered. Thus, if Watson et al. (2005) are correct and these prehistoric cavers explored as they entered Aborigine Avenue and made an expedient exit, inbound step lengths should be shorter and have greater variability than outbound step lengths.
Materials

This thesis used Louise Robbins’s and Patty Jo Watson’s Aborigine Avenue, Jaguar Cave, research materials currently curated at the William S. Webb Museum of Anthropology, University of Kentucky, Lexington. Materials employed in this thesis included personal correspondence, field notes and survey station area maps of 274 foot impressions.

These foot impressions were drawn on eight maps from eight survey stations (Watson et al. 2005:29). Survey stations were established by National Speleological Society members as they mapped Aborigine Avenue (Watson et al. 2005:27, 31). Each map was assigned the number of the survey station used to create it. At these survey stations, at least four people documented the foot impressions. Using a plane table, one person mapped the impressions using an alidade and measuring tape; one person sighted and measured the most posterior and anterior points of foot impressions; one person kept records; and one person was in charge of lighting (Watson et al. 2005:31). A carbide lamp was held obliquely over the foot impressions so the mapper could sight on impressions through the alidade (Watson et al. 2005:31). This distance (survey station to foot impression) was measured using a measuring tape and a line with corresponding angle was drawn on the field map (Watson et al. 2005:31). These field maps were labeled Survey Station (SS) 10, 12, 13, 15, 16, 17, 18, and 22, corresponding to the area surrounding the SS. Some of these areas, such as SS 16, were too large to be drawn as one map. These areas were drawn as two maps and labeled A and B, with area A closer to the entrance of the passage. After a number was assigned to each print, a Mylar tag with the impression number was placed in the foot impression (Watson, unpublished notes).
Flagging tape was used as a barrier to separate foot impressions from present-day trails and to preserve the impressions from accidental destruction by modern cavers (Watson, unpublished notes). Foot impressions were documented (mapping, photography, and impression casting) on 21 trips by different crewmembers between October 1976 and August 1993 (Table 2).

Table 2. Dates of Jaguar Cave foot impression documentation trips.

<table>
<thead>
<tr>
<th>Trip Number</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>October 15-16, 1976</td>
</tr>
<tr>
<td>2</td>
<td>November 25-27, 1976</td>
</tr>
<tr>
<td>3</td>
<td>February 10-13, 1977</td>
</tr>
<tr>
<td>4</td>
<td>February 18-20, 1977</td>
</tr>
<tr>
<td>5</td>
<td>May 28-June 21, 1977</td>
</tr>
<tr>
<td>6</td>
<td>September 16-19, 1977</td>
</tr>
<tr>
<td>7</td>
<td>November 1978</td>
</tr>
<tr>
<td>8</td>
<td>September 21-23, 1979</td>
</tr>
<tr>
<td>9</td>
<td>November 21-22, 1979</td>
</tr>
<tr>
<td>10</td>
<td>October 10-12, 1980</td>
</tr>
<tr>
<td>11</td>
<td>November 26-30, 1980</td>
</tr>
<tr>
<td>12</td>
<td>June 25, 1982</td>
</tr>
<tr>
<td>13</td>
<td>June 10, 1983</td>
</tr>
<tr>
<td>14</td>
<td>August 9-11, 1983</td>
</tr>
<tr>
<td>15</td>
<td>March 3-4, 1984</td>
</tr>
<tr>
<td>16</td>
<td>June 22, 1984</td>
</tr>
<tr>
<td>17</td>
<td>June 21, 1985</td>
</tr>
<tr>
<td>18</td>
<td>June 13, 1986</td>
</tr>
<tr>
<td>19</td>
<td>June 4, 1987</td>
</tr>
<tr>
<td>20</td>
<td>June 26, 1993</td>
</tr>
<tr>
<td>21</td>
<td>August 16, 1993</td>
</tr>
</tbody>
</table>

Source: Adapted from Watson, P. J., Unpublished field notes on a visit to Fisher Ridge Cave (June 27, 1982); Unpublished field notes on a visit to Upper Crouchway in Unknown Cave, Mammoth Cave National Park, Kentucky (July 7, 1996).
Not all areas of Aborigine Avenue have foot impressions and not all areas containing foot impressions are appropriate for step length analysis. Areas with tracks in the same general direction with minimal confounding factors, such as overlapping and partial impressions, are the most appropriate for analysis. SS areas 12, 13, 15, 16A, 16B, and 18 have the fewest confounding factors and are examined in the present study. SS Area 10 has a limited number of foot impressions \( n = 12 \), and no trackways are identified from this area. SS areas 17 and 22 are also problematic for step length analysis. These SS areas are near Aborigine Avenue’s dead end and have numerous overlapping impressions \( n \geq 52, n \geq 50 \) for SS areas 17 and 22, respectively. In many cases, the orientation of the foot impressions from these areas, either inbound or outbound, is unclear. Due to these issues, SS areas 10, 17, and 22 are excluded from step length analysis.

Methods for Identifying Trackways

To identify trackways of the prehistoric cavers, the results of Jasuja (1993) are used to estimate the most likely next step location. Participants in the Jasuja (1993) study, including 283 adult Jat Sikh males from India, were asked to walk at their preferred walking speed with ink-soaked feet across white paper on an even surface. Four to five foot prints, equivalent to three or four step lengths, were recorded for each individual. Descriptive statistics included minimum and maximum step length, and mean and standard deviation of step length as well as height. Statistics for the Jat Sikh sample (Table 3) make it possible to estimate a location where the next step of a trackway may be located.
Table 3. Descriptive statistics of step length and stature (in cm) of the Jat Sikh sample.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step Length</td>
<td>43.1</td>
<td>81.2</td>
<td>60.7</td>
<td>6.6</td>
</tr>
<tr>
<td>Stature</td>
<td>158.5</td>
<td>188.8</td>
<td>170.1</td>
<td>6.1</td>
</tr>
</tbody>
</table>


To identify the next most likely foot impression in a trackway, the Jaguar Cave maps were examined. Foot impressions were chosen, and were conspicuous and near one edge of the field map, pointing toward the opposite side of the map to be considered. After this first foot impression was selected, three arcs were drawn from that foot impression, using the most posterior point of the heel as the center of the arc. The middle arc represented the average expected step length of the prehistoric cavers based on the average Jat Sikh step length; the shortest and longest radii represented two standard deviations from this average step length. The next footstep was expected to fall between the shortest and longest radii 95 percent of the time. Any portion of a foot impression in this area was considered a possible next step.

Next, data concerning side (left or right), orientation (inbound or outbound), size of the foot impression, and gait angle were used to eliminate foot impressions in the next step area. It is unlikely that the next foot impression of a trackway would have the opposite orientation of the previous step. It is also unlikely that two sequential foot impressions of a trackway would be the same side. Therefore, foot impressions of the same side or opposite orientation as the starting foot impression were eliminated from
further consideration. If more than one foot impression that were possible next steps remained, foot impression measurements and gait angle were examined.

Foot impression measurements from Watson et al. (2005:32-33, Table 1) are used to compare the first step and potential next steps. It is likely the next foot impression in a trackway is similar in size to others in that trackway, although foot impression measurements have limitations. Substrate has an effect on the dimensions of foot impressions (Robbins 1985:143). If a substrate is less malleable, only the plantar surface of the foot deforms the surface. Thus, the size of the foot impression underestimates the size of the actual foot. If a substrate is more malleable, adhesion, suction and lateral inflow distort the foot impression, resulting in spurious measurements (Allen et al. 2003:60). Also, fatigue of the recorders and conditions of the cave, such as dim lighting, low ceiling height and irregular terrain, could introduce error in the measurements. Because of the nature of foot impressions and the difficult working conditions of the cave, foot impression measurements are used as a supplementary line of evidence to identify trackways.

The next observation, gait angle, was determined from the field maps by drawing a straight line extending through the most posterior point and the most anterior point of the previous foot impression assigned to the trackway. A corresponding line was drawn through the possible next step. The angle where these lines intersect is the gait angle.

Based on the studies by Dougan (1924), Patek (1926), and Morton (1932), the range of gait angle is $35^\circ$, varying between $-10^\circ$ and $25^\circ$. This interval indicates the most
likely angles of possible next steps. Gait angles outside this interval cannot be eliminated, but are unlikely to be the next step.

There are several reasons why foot impressions cannot be excluded based on gait angle. First, all studies on gait angle are based on people walking in a straight line. It cannot be assumed the prehistoric cavers walked in a straight line through Aborigine Avenue, especially if they were wandering. Inaccuracy associated with mapping and drawing the foot impressions may add error to gait angle estimates. Finally, other extrinsic factors, such as irregular terrain and slippery surfaces, influence gait angle in unpredictable ways. Because of these limitations, angle of gait is used only as a supplementary line of evidence to identify trackways.

Side, orientation and measurements of the foot impressions, gait angle and step length are compared to determine which impression represents the most likely next step. Of these criteria, side and orientation of foot are the most reliable. These criteria are the most reliable because they are clear-cut traits that have been observed directly from the foot impressions. Foot measurements are more reliable than gait angle, but less reliable than side and orientation of the foot. Foot measurements have been measured directly from the foot impressions. Gait angle is the least reliable of the criteria. This criterion is the only one that was not observed or measured directly from the foot impressions and instead was estimated solely from the field maps. These criteria are applied to the foot impressions on the field maps until a trackway could no longer be identified.

After trackways are identified, trackway characteristics are analyzed. Trackways are separated into inbound and outbound trackways. The assertion by Watson
et al. (2005) that these prehistoric cavers explored as they entered the cave passage and
exited using the most direct route is tested by comparing average step length and
variation in step length between the two trackway types.

Step length is measured on the field maps. These field maps are drawn with a
1:20 scale; thus actual distances are 20 times the map distances. A subsample of step
length measurements taken directly from the foot impressions are compared to the step
length measurements estimated from the field maps. This comparison is presented in the
discussion chapter.

Statistical Analyses

Statistical analyses were performed using SPSS 16.0. Descriptive statistics for
inbound and outbound trackways and foot impressions included minimum and maximum
lengths, mean lengths, and standard deviations. Independent sample t-tests were used to
examine differences in average step length and foot length of inbound and outbound
trackways and the effect of ceiling height on step length. A t-test assumes data are
normally distributed and the variances of samples are comparable. To test whether the
trackway samples met these assumptions, Levene’s test for equality of variance was used.

To assess if a relationship between step length and foot length exists,
regression and correlation analyses are used. Pearson’s $r$ indicates the relationship
between these two variables. A Pearson’s $r$ value of 0.3 and less is considered a weak
relationship, values between 0.3 and 0.6 are moderate, and values greater than 0.6
indicate a strong relationship. The $r^2$ value defines the amount of variation in step length
that is explained by foot length. The linear regression equation is calculated from the data
using the equation \( y = a + bx \), where \( b \) is the slope of the line and \( a \) is the y-intercept. The relationship between step length and foot length is examined for the total trackway sample, for inbound and outbound trackways separately, and trackways with high and low ceilings.

A limitation of all statistical comparisons is the chance of spurious results. Statistical error occurs in two ways: Type 1 and Type 2 errors. Type 1 statistical error rejects the null hypothesis when it is true. Type 2 error, on the other hand, accepts the null hypothesis when it is false. The probability of statistical error depends on the alpha level employed. A smaller alpha level increases the chance of Type 2 error and a larger alpha level increases the chance of Type 1 error. Following convention of social scientists, an alpha level of 0.05 is employed for all statistical comparisons.

Summary

This study evaluates the hypothesis that prehistoric cavers explored as they entered Aborigine Avenue and then made an expedient, direct exit. This assertion is tested by identifying trackways and analyzing step lengths of these trackways. First, inbound and outbound trackways are identified using the average step length of a contemporary sample, and impression side, orientation, size and gait angle. Second, step lengths for each trackway are measured. Comparisons of inbound and outbound step lengths are made using independent sample t-test, and regression and correlation.
CHAPTER IV

RESULTS

The results of trackway identification and analyses are reported in this chapter. First, the location, direction, number of impressions and length of each trackway are described, starting near the front of Aborigine Avenue and progressing toward the end of the passage. Foot impressions in each trackway are presented in sequential order, proceeding through the trackway, rather than numerically. Assigning foot impressions to Trackways 4-7 required examination of foot impression measurements and gait angles. This process is discussed in further detail when these trackways are described. Then descriptive statistics of step lengths and foot impression lengths are presented, followed by the results of inferential statistical comparisons.

Trackway Descriptions

Using methods outlined in the previous chapter, 16 trackways are identified from Survey Station (SS) areas within Aborigine Avenue (Table 4). These trackways consist of 2 to 6 foot impressions per trackway, totaling 42 impressions. There are eight inbound trackways and eight outbound trackways. On average, inbound trackways have more impressions than outbound trackways, with a total of ten more inbound than outbound impressions. Trackways 12 and 14 contain partial impressions without assigned numbers; these partial prints have heel impressions, making step length measurements
Table 4. Descriptive data of Aborigine Avenue trackways.

<table>
<thead>
<tr>
<th>Trackway</th>
<th>SS area</th>
<th>Impression Number</th>
<th>Foot Length</th>
<th>Ball Width</th>
<th>Heel Width</th>
<th>Side*</th>
<th>Direction**</th>
<th>Step Length</th>
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<td>TW1</td>
<td>12</td>
<td>77</td>
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<td></td>
<td></td>
<td>78</td>
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<td></td>
<td>L</td>
<td>I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TW14</td>
<td>16B</td>
<td>38</td>
<td>25.5</td>
<td>6</td>
<td>6</td>
<td>L</td>
<td>I</td>
<td>54.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>156</td>
<td>24</td>
<td>7</td>
<td></td>
<td>R</td>
<td>I</td>
<td>68.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>L?</td>
<td>I</td>
<td></td>
<td>45.1</td>
</tr>
<tr>
<td>TW15</td>
<td>16B</td>
<td>39</td>
<td>26</td>
<td>7.5</td>
<td>7</td>
<td>L</td>
<td>I</td>
<td>48.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>158</td>
<td>25</td>
<td>10</td>
<td>7</td>
<td>R</td>
<td>I</td>
<td></td>
</tr>
</tbody>
</table>
Table 4 (Continued)

<table>
<thead>
<tr>
<th>Trackway</th>
<th>SS area Number</th>
<th>Impression Number</th>
<th>Foot Length</th>
<th>Ball Width</th>
<th>Heel Width</th>
<th>Side*</th>
<th>Direction**</th>
<th>Step Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>TW16</td>
<td>18</td>
<td>215</td>
<td>22</td>
<td>8.5</td>
<td>6.5</td>
<td>L</td>
<td>I</td>
<td>49.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>217</td>
<td>22</td>
<td>8.0</td>
<td>7.0</td>
<td>R</td>
<td>I</td>
<td>47.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>218</td>
<td>22</td>
<td>8.5</td>
<td>6.0</td>
<td>L</td>
<td>I</td>
<td></td>
</tr>
</tbody>
</table>

*L left, R right **I inbound, O outbound


possible for this analysis. No measurements of the impression dimensions, however, are provided for partial impressions.

SS 12 Trackways

Trackways 1-3 are northwest of SS 12 (Figure 2). All three trackways are outbound and located close to each other and near the northern edge of an ancient

![Figure 2](image)

**Figure 2.** The location of foot impressions and survey stations in Aborigine Avenue. Triangles represent the location of survey stations and dots are the location of foot impressions.

streambed. These trackways are in a portion of the cave passage that is relatively wide and has a ceiling height greater than 2 m. Foot impressions from Trackway 3 and Trackway 1 are adjacent to one another. The first impression of Trackway 3 (Impression 76) is between the second (Impression 78) and third (Impression 75) impressions of Trackway 1. Being 1.13 m in length, Trackway 1 is the longest of the three trackways and is composed of Foot Impressions 77, 78, and 75. Trackway 2, located immediately north of Trackway 1, is 50.9 cm in length and is composed of Foot Impressions 79 and 70. Trackway 3 is 50.8 cm long and is comprised of Foot Impressions 76 and 82.

**SS 13 Trackways**

Trackways 4-8 are located near SS 13 (Figure 2) and consist of two concentrations of foot impressions (one southwest and one west of SS 13). These concentrations are separated by an area of disturbed sand where no impressions are present. The prehistoric cavers were forced to crouch as they walked through this area because the ceiling height where the foot impressions are located decreases from over 2 m to approximately 1 m. While the ceiling height immediately north of these trackways is roughly half a meter higher, the ceiling height there is also too low for erect walking.

Trackways 4-7 are close to one another in the southwestern concentration of SS 13, and Trackway 8 is located in the western concentration of SS 13. Trackways 4-8 are south of the ancient streambed, close to a ridge separating a sand bed and flowstone crust. Trackways 4, 5, and 8 are inbound, and Trackways 6 and 7 are outbound. Each trackway consists of two foot impressions. Trackway 4 is 64.4 cm long and consists of Foot Impressions 116 and 123. Trackway 5 is 72.2 cm long and is composed of Foot Impressions 119 and 4. Trackway 6 is 41.3 cm long and is composed of Foot Impressions
Trackway 7 is 40.6 cm long and consists of Foot Impressions 118 and 2. And Trackway 8 is 66.2 cm long and is composed of Foot Impressions 108 and 8.

Trackways are difficult to identify because other surrounding foot impressions could be part of the trackways. In most cases, these surrounding foot impressions are eliminated by using step length, side, and orientation of foot impressions. In the cases of Trackways 4-7, however, additional criteria, examination of foot impression measurements and gait angle, are required to assign foot impressions to a trackway.

Trackways 4 and 5, and Trackways 6 and 7 are adjacent to each other. In these cases, the second impression of each trackway could belong to the first impression of the trackway adjacent to it. Comparing foot impression measurements and gait angle help identify which foot impression is associated with each trackway.

The first impressions of Trackways 4 and 5 are left-foot impressions that overlap. The second impressions of each trackway are right-foot impressions that are close to one another. Because these two trackways coincide with each other, it is difficult to distinguish which second foot impression belongs to which trackway. The sizes of these foot impressions are different and permit identification to trackways (Table 5). The first (Impression 116) and second impression (Impression 123) of Trackway 4 have smaller foot length and heel width measurements than either impression of Trackway 5 (Impression 119 and Impression 4; Table 5). Based on similarities in the size of the foot impressions, Foot Impression 116 is assigned to Trackway 4 and Foot Impression 4 is assigned to Trackway 5.

The first and second impressions of Trackways 6 and 7 are from the same side and are adjacent to each other. Unlike Trackways 4 and 5 that had different foot
Table 5. Foot impression sides, directions and measurements (in cm) for Trackways 4 and 5.

<table>
<thead>
<tr>
<th>Trackway Number</th>
<th>Impression Number</th>
<th>Foot Length</th>
<th>Ball Width</th>
<th>Heel Width</th>
<th>Side*</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>116</td>
<td>24.0</td>
<td>NA</td>
<td>6.0</td>
<td>L</td>
<td>Inbound</td>
</tr>
<tr>
<td>4</td>
<td>123</td>
<td>24.0</td>
<td>NA</td>
<td>5.5</td>
<td>R</td>
<td>Inbound</td>
</tr>
<tr>
<td>5</td>
<td>119</td>
<td>29.0</td>
<td>NA</td>
<td>7.0</td>
<td>L</td>
<td>Inbound</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>28.5</td>
<td>5.5</td>
<td>8.0</td>
<td>R</td>
<td>Inbound</td>
</tr>
</tbody>
</table>

*L left, R right


impression sizes, the impressions of Trackways 6 and 7 are similar in size (Table 6). The largest difference in the measurements of these foot impressions is a 3 cm difference in ball width between the first impression of Trackway 7 (Impression 118) and the second impression of Trackway 6 (Impression 3). All other measurements are within 1 cm, suggesting two individuals with comparable foot dimensions made these trackways.

Table 6. Foot impression sides, directions and measurements (in cm) for Trackways 6 and 7.

<table>
<thead>
<tr>
<th>Trackway Number</th>
<th>Impression Number</th>
<th>Foot Length</th>
<th>Ball Width</th>
<th>Heel Width</th>
<th>Side*</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>117</td>
<td>23.5</td>
<td>NA</td>
<td>5.5</td>
<td>L</td>
<td>Outbound</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>23.0</td>
<td>5.0</td>
<td>6.0</td>
<td>R</td>
<td>Outbound</td>
</tr>
<tr>
<td>7</td>
<td>118</td>
<td>24.0</td>
<td>8.0</td>
<td>6.0</td>
<td>L</td>
<td>Outbound</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>24.0</td>
<td>6.0</td>
<td>6.0</td>
<td>R</td>
<td>Outbound</td>
</tr>
</tbody>
</table>

*L= left, R= right

Because the measurements of these foot impressions are similar, gait angle is examined to assign Foot Impressions 2 and 3 to Trackway 6 or 7.

The gait angles of Foot Impression 117 with Impressions 3 and 2, and the gait angle of Foot Impressions 118 and 2 are in the normal range of variation (Table 7). The gait angle of Foot Impressions 118 and 3, however, is beyond normal gait angle variation. Because the gait angle of Impressions 118 and 3 are beyond the normal interval, it is unlikely that these impressions form a trackway. Thus, Foot Impressions 117 and 3 make up Trackway 6, and Foot Impressions 118 and 2 form Trackway 7.

### Table 7. Gait angles for foot impressions in Trackways 6 and 7.
Gait angles are in degrees.

<table>
<thead>
<tr>
<th>Impression Numbers</th>
<th>Gait Angle</th>
<th>Normal Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>117 and 3</td>
<td>22.5</td>
<td>Yes</td>
</tr>
<tr>
<td>117 and 2</td>
<td>4.5</td>
<td>Yes</td>
</tr>
<tr>
<td>118 and 3</td>
<td>33.5</td>
<td>No</td>
</tr>
<tr>
<td>118 and 2</td>
<td>14</td>
<td>Yes</td>
</tr>
</tbody>
</table>

SS 15 Trackways

Trackways 9-11 are located near SS 15 (Figure 2). Trackways 9 and 10 are outbound and are west of SS 15 in laminated brown clay near the northern edge of the ancient streambed. Trackway 9 is 89.5 cm long and consists of Foot Impressions 127, 126, and 32. Trackway 9 is closer to SS 15 and the front of Aborigine Avenue than Trackway 10; it is 42.9 cm long and consists of Foot Impressions 103 and 100. Trackway 11 is inbound east of SS 15, also in laminated brown clay near the northern edge of the ancient streambed, and is 62.1 cm long and composed of Foot Impressions 19 and 23.
SS 16A Trackways

Trackways 12 and 13 are inbound trackways covering the length of the SS 16A area (Figures 2 and 3). A group of stalactites separate Trackways 12 and 13, with Trackway 12 closer to the entrance and Trackway 13 closer to the rear of the passage. Trackway 12 is the longest of all trackways, measuring 2.72 m in length and is composed of Foot Impressions 138, 147, 92, a partial impression, then 154, and 89. Trackway 13 is 47.3 cm long and is composed of Foot Impressions 152 and 153.

It is possible that Trackways 12 and 13 represent one individual walking in a straight line. The foot impression measurements of Trackway 13 are comparable to those of Trackway 12. Trackways 12 and 13 are separated by two average step lengths, suggesting that there is a missing foot impression between the last impression of Trackway 12 and the first impression of Trackway 13.

SS 16B Trackways

Trackways 14 and 15 are inbound in the SS 16B area along the edge of a pit (Figures 2 and 3). Trackway 14 is the second longest of all trackways, measuring 1.68 m in length, and is composed of Foot Impressions 38, 156, a partial impression, and 161. Trackway 15 is 48.9 cm long and is composed of Foot Impressions 39 and 158. Trackways 14 and 15 are adjacent to each other (Figure 3). The first foot impression of Trackway 15 (Impression 39) is located directly in front of the second foot impression of Trackway 14 (Impression 38). The second foot impression of Trackway 15 (Impression 158) is located directly in front of the third foot impression of Trackway 14 (Impression 156).
Figure 3. Four inbound trackways near SS 16 (Trackways 12-15) in Aborigine Avenue. Foot impressions are numbered and darkened foot impressions indicate impressions in each trackway; outlined foot impressions are unassociated with depicted trackway.

SS 18 Trackway

Trackway 16 is inbound, near SS 18, west of the ancient streambed and approaches an area disturbed by water (Figure 2). This location may have been a point of
interest for this prehistoric caver, although no cave features are in this area. Trackway 16 is 97.2 cm long and is composed of Foot Impressions 215, 217, and 218.

Statistics

Having identified and described trackways in Aborigine Avenue, this section analyzes these trackways statistically. Overall, inbound steps are longer and more variable than outbound steps (Table 8). The average step length for the entire sample is 53.3±10.8 cm, with inbound being 56.5±11.59 cm and outbound 47.6±6.6 cm. As found with step length, inbound foot impression lengths are longer and more variable than outbound impression lengths (Table 8). The average foot impression length for the total sample is 24.1±2 cm, with inbound being 24.7±2.1 cm and outbound 22.9±1.1 cm. The next section examines if these differences are statistically significant.

Table 8. Mean step and impression lengths (in cm) for the Jaguar Cave sample.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>s.d.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Step Length</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>25</td>
<td>53.3</td>
<td>33.8</td>
<td>76.5</td>
<td>10.8</td>
</tr>
<tr>
<td>Inbound</td>
<td>16</td>
<td>56.5</td>
<td>33.8</td>
<td>76.5</td>
<td>11.6</td>
</tr>
<tr>
<td>Outbound</td>
<td>9</td>
<td>47.6</td>
<td>40.6</td>
<td>60.5</td>
<td>6.6</td>
</tr>
<tr>
<td><strong>Impression Length</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>25</td>
<td>24.1</td>
<td>21.0</td>
<td>29.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Inbound</td>
<td>16</td>
<td>24.7</td>
<td>21.5</td>
<td>29.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Outbound</td>
<td>9</td>
<td>22.9</td>
<td>21.0</td>
<td>24.3</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Step Length and Foot Impression Length Comparisons

In this section, independent sample t-tests compare step length and foot impression length by orientation (inbound and outbound) and ceiling height. Comparisons of step length for inbound and outbound trackways are presented. Then, the effect of low ceiling height on step length is assessed, followed by comparisons of foot length for inbound and outbound trackways.

There is a statistically significant difference between inbound and outbound step lengths (Table 9; $t = 2.437$, $df = 22.961$, $p = 0.023$; Levene’s Test not assuming equal variance). Inbound step lengths are longer and more variable than outbound step lengths. There is no difference, however, between step lengths in low and high ceiling areas (Table 10; $t = -.833$, $df = 23$, $p = .413$). These results suggest that the prehistoric cavers used different walking patterns when entering than when exiting the cave passage, and these patterns were not affected by ceiling height.

There is a statistically significant difference between inbound and outbound foot lengths (Table 11; $t = 2.287$, $df = 23$, $p = 0.032$). Inbound trackways represent taller (at least longer footed) individuals than outbound trackways.

<table>
<thead>
<tr>
<th>Step Length</th>
<th>$N$</th>
<th>T-Value</th>
<th>Degrees of Freedom</th>
<th>$P$-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>25</td>
<td>2.437</td>
<td>22.961</td>
<td>0.023</td>
</tr>
<tr>
<td>Inbound</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outbound</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 10. Independent samples t-test results for step lengths in low and high ceiling areas.

<table>
<thead>
<tr>
<th>Step Length</th>
<th>N</th>
<th>T-Value</th>
<th>Degrees of Freedom</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>25</td>
<td>-.833</td>
<td>23</td>
<td>0.413</td>
</tr>
<tr>
<td>Low Ceiling</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Ceiling</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 11. Independent samples t-test results for inbound and outbound foot impression lengths.

<table>
<thead>
<tr>
<th>Foot Impression Length</th>
<th>N</th>
<th>T-Value</th>
<th>Degrees of Freedom</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>25</td>
<td>2.287</td>
<td>23</td>
<td>0.032</td>
</tr>
<tr>
<td>Inbound</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outbound</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Regression and Correlation of Step Length and Foot Impression Length**

Previous research has shown positive correlations between step length and height (Jasuja 1993; Jasuja et al. 1997), and foot length and height (Robbins 1986). This model is applied to the Jaguar Cave foot impressions, assuming taller individuals have longer feet and step lengths. Foot impression length is treated as the independent variable and step length is treated as the dependent variable.

As expected, there is a positive relationship between these two variables for inbound trackways ($r = 0.420, p = 0.105$) and the total sample ($r = 0.426, p = 0.034$), although this relationship is significant only for the total sample (Figure 4; Table 12).
Figure 4. Scatter plot of step length and foot impression length (in cm) by trackway type.

Table 12. Regression and correlation of foot impression length and step length for the Jaguar Cave sample.

<table>
<thead>
<tr>
<th>Trackway</th>
<th>$R$</th>
<th>$r^2$</th>
<th>$P$-Value</th>
<th>Linear Regression $(v =)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>0.426</td>
<td>0.181</td>
<td>0.034</td>
<td>-3.183+2.349(FIL*)</td>
</tr>
<tr>
<td>Inbound</td>
<td>0.420</td>
<td>0.176</td>
<td>0.105</td>
<td>Not Significant</td>
</tr>
<tr>
<td>Outbound</td>
<td>-0.407</td>
<td>0.166</td>
<td>0.277</td>
<td>Not Significant</td>
</tr>
</tbody>
</table>

$FIL =$ foot impression length.
Unexpectedly, however, outbound trackways have the opposite relationship between the two variables, with a moderate negative relationship ($r = -0.407, p = 0.277$). This relationship, however, is not statistically significant (Table 12). Non-significant inbound and outbound samples could result from small sample sizes ($n=16$ and $n=9$, respectively).

As mentioned earlier, an independent sample t-test suggests ceiling height did not affect step length. Regression and correlation analysis can further examine the affect of ceiling height on step length. When trackways with low ceilings (Trackways 5-9) are excluded from analysis and statistics recalculated, the direction of the relationship of step length to foot length remains the same for inbound and outbound trackways and the total sample. However, the change in step length with foot impression length is less pronounced and the relationships are no longer significant (Figure 5; Table 13).

**Summary**

These findings suggested that the prehistoric cavers in Aborigine Avenue took longer and more variable steps when entering the cave passage than when exiting. Ceiling height did not affect step length. On average, longer-footed individuals created inbound trackways. The expected moderate positive relationship of foot impression length and step length was found for inbound trackways and the total sample; outbound trackways, however, showed a negative relationship between these two variables. These relationships remained the same when trackways with low ceiling height were eliminated from analysis, although the strength of these relationships was weaker. The only significant relationship of foot impression length and step length was for the total sample, suggesting other relationships of foot impression length to step length may be due to
**Figure 5.** Scatter plot of step length and foot impression length (in cm) by ceiling height.

**Table 13.** Regression and correlation of foot impression length and step length from high ceiling areas for the Jaguar Cave sample.

<table>
<thead>
<tr>
<th>Trackway</th>
<th>$R$</th>
<th>$r^2$</th>
<th>$P$-Value</th>
<th>Linear Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>0.191</td>
<td>0.037</td>
<td>0.419</td>
<td>Not Significant</td>
</tr>
<tr>
<td>Inbound</td>
<td>0.208</td>
<td>0.043</td>
<td>0.495</td>
<td>Not Significant</td>
</tr>
<tr>
<td>Outbound</td>
<td>-0.348</td>
<td>0.121</td>
<td>0.444</td>
<td>Not Significant</td>
</tr>
</tbody>
</table>
chance. The implications of these results and explanations for differences in trackway types are discussed in the Chapter V.
CHAPTER V

DISCUSSION

Chapter IV presented the results of the Jaguar Cave trackway analysis. This chapter discusses the behavioral implications of those results. First, possible reasons for differences in inbound and outbound walking patterns are discussed. Then, limitations of this study are presented. Finally, the Jaguar Cave Trackways are compared to other prehistoric trackway sites, followed by issues pertaining to the protection and preservation of the Jaguar Cave foot impressions.

Interpretation of Walking Patterns

There are three possible explanations for differences between inbound and outbound walking patterns. The first explanation is that prehistoric cavers walked faster when they entered Aborigine Avenue than when they exited. The second explanation is that prehistoric cavers walked over a more slippery, level surface exiting the cave passage than entering. After surface properties are examined, possibilities for the different number of inbound and outbound foot impressions are discussed, followed by the third explanation, that different individuals created the inbound and outbound trackways. A factor that should influence walking patterns, ceiling height, had no affect on inbound or outbound step length. This interesting finding is discussed at the end of the section.
Speed

A faster walking speed for inbound trackways and longer strides is counterintuitive. Whether these prehistoric cavers were exploring Aborigine Avenue or using it for some other purpose, they were more familiar with the passage when leaving by virtue of having recently walked through the passage. A lack of familiarity with the cave passage does not necessarily exclude the possibility that the prehistoric cavers walked faster as they entered the passage. Speed-limiting factors, such as fatigue and lighting from cane torches, may have slowed the prehistoric cavers more on exiting the passage than on entering it. For this explanation to be plausible, however, differences in outbound and inbound trackways should be consistent with differences between slow and fast walking.

As walking speed increases, step frequency remains constant, and step length increases and becomes less variable. If the prehistoric cavers walked faster entering the cave passage, inbound trackways should be longer and less variable than outbound. Step lengths are longer than outbound, but more variable. A faster walking speed for inbound trackways is only partially consistent with these data and is rejected as an explanation for longer inbound step lengths.

Surface Properties

Next, the possibility that the prehistoric cavers walked over different surfaces entering than exiting the cave passage is examined. The fact that the prehistoric cavers left foot impressions indicates they walked over pliable and slippery surfaces. Pliable surfaces produce less friction between the foot and surface than rough surfaces. On slippery surfaces, individuals change their walking pattern to produce more friction by
increasing the angle of contact between the foot and surface, thus decreasing step length. If outbound trackways are on slipperier surfaces than inbound trackways, this walking adjustment could explain the shorter outbound step lengths. If inbound and outbound trackways are located on similar surfaces, however, walking patterns differences could result from adjustments to a more uneven surface when the prehistoric cavers entered the passage.

Longer step length increases the time the foot is suspended and provides individuals more time to decide where to place the foot when terrain is uneven (Menz et al. 2003). Longer and more variable step length is consistent with walking pattern adjustments for an uneven surface and is the walking pattern observed in inbound trackways. Slipperier outbound and more uneven inbound surfaces are possible explanations based on differences in inbound and outbound walking patterns. Observations of the surface properties of Aborigine Avenue can further assess these explanations.

Observations of the surface properties of Aborigine Avenue do not support these explanations. The surface consistency of Aborigine Avenue shows dramatic differences only between the front and back of the passage; the front of the passage is drier than the back. The middle of the passage, where a majority of trackways are found, has a uniform surface grade and consistency.

Number of Inbound and Outbound Foot Impressions

Having eliminated surface property differences as a reason for inbound and outbound walking pattern differences, another way to evaluate differences in step length
is the number of inbound and outbound foot impressions. If the prehistoric cavers exited Aborigine Avenue using the same route they entered, inbound foot impressions were subject to damage by the foot impressions of the exiting prehistoric cavers, resulting in fewer inbound than outbound foot impressions (Watson et al. 2005). In most cases, inbound and outbound trackways were close to each other, suggesting outbound foot impressions probably destroyed some inbound foot impressions. Despite being subject to damage by outbound foot impressions, however, there were 27 more inbound than outbound foot impressions in Aborigine Avenue (150 inbound and 123 outbound; Watson et al. 2005:35).

Similarities in the location and surface properties of inbound and outbound trackways refute the explanation that differences in walking patterns are caused by differences in surface properties. Because surface properties for inbound and outbound trackways are similar, the greater number of inbound than outbound foot impressions is because the prehistoric cavers took more steps as they entered the passage, which is consistent with exploring. Also, inbound step lengths are more variable than outbound step lengths. This pattern for inbound trackways is consistent with repeated starts and stops during walking, because the first few steps are the most variable.

Different Individuals

Walking pattern differences for inbound and outbound trackways may not be caused by different behavior by the same individuals, but by interpersonal differences in the walking patterns. Individuals have preferred walking patterns, and differences in inbound and outbound walking patterns could simply be interpersonal differences in the
walking patterns. This explanation can be evaluated by comparing the foot size of inbound and outbound trackways.

Recall that inbound foot impressions average 1.8 cm longer than outbound (24.7 cm and 22.9 cm for inbound and outbound trackways, respectively). This difference suggests taller individuals created inbound trackways. It should be noted, however, that this difference is less than the difference between foot impressions from the same trackway. For example, Trackway 12 has a 6 cm difference in length between the shortest and longest foot impressions in the trackway. Assuming one individual created Trackway 12, the same foot can produce impressions with a length difference greater than two times greater than the average difference between inbound and outbound trackways. More than one person, however, may be represented by Trackway 12. Thus, the variation in foot impression dimensions in Trackway 12 may overestimate the variability in foot impression dimensions that one foot may produce. This limitation, that trackways may represent more than one individual, is examined further in the next section.

Because inbound and outbound trackways were created on similar surfaces, variability in foot impression dimensions from the same foot should have a similar effect for inbound and outbound trackways. If the difference in average foot impression length is a real difference in the size of the feet that created them, then average foot impression length supports the explanation that different individuals are responsible for inbound and outbound trackways. This explanation is assessed by comparing trackway foot impressions with cluster groups from Watson et al. (2005).

Based on measurements and qualitative observations of the foot impressions, an estimated nine people created the Jaguar Cave foot impressions (Robbins et al. 1981).
Foot impressions were assigned to one of nine clusters based on cluster analysis of foot impression length, ball width, and heel width measurements (Watson et al. 2005:35-36).

Six of nine clusters have foot impressions in trackways (Table 14). Cluster 9 has the greatest number of foot impressions. Clusters 9 and 3 are the only clusters with impressions in both inbound and outbound trackways. Cluster 9 has impressions evenly distributed between inbound and outbound trackways (Table 14). Cluster 3, however, has three inbound foot impressions and only one outbound. Cluster 7 and 8 impressions are only present in outbound trackways, and Cluster 1 and 2 impressions are only represented in inbound trackways. With the exception of Cluster 9 and to a lesser degree Cluster 3, comparisons of foot impression clusters to inbound and outbound trackways support the explanation that different individuals created inbound and outbound trackways.

Beyond examining whether inbound and outbound trackways were created by different individuals, comparisons of cluster individuals within trackways can also assess the likelihood that a trackway represents one individual. Of the 14 trackways that contain

<table>
<thead>
<tr>
<th>Cluster Number</th>
<th>Number of Foot Impressions in Trackways</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outbound</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>12</td>
</tr>
</tbody>
</table>
foot impressions from clusters, nine have two or more impressions from clusters. In only two cases (Trackways 10 and 16) do the cluster groups support the trackway determinations however (Table 15). Half of the trackways that contain foot impressions

<table>
<thead>
<tr>
<th>Trackway</th>
<th>Foot Impression Number</th>
<th>Cluster Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>77</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>70</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>76</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>82</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>7</td>
<td>118</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>127</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>126</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>103</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>9</td>
</tr>
<tr>
<td>11</td>
<td>19</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>138</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>147</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>92</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>152</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td>135</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>161</td>
<td>2</td>
</tr>
<tr>
<td>15</td>
<td>158</td>
<td>9</td>
</tr>
<tr>
<td>16</td>
<td>215</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>217</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>218</td>
<td>9</td>
</tr>
</tbody>
</table>
from a cluster group have foot impressions from different clusters (7 of 14 trackways), suggesting that some trackways represent more than one individual. While comparisons of trackways with cluster groups support the assertion that different individuals are represented by inbound and outbound trackways, this comparison also suggests that some trackways may represent more than one individual.

Ceiling Height

As mentioned in the description of Aborigine Avenue, this passage has two areas where the ceiling height is approximately 1 m high, making normal walking impossible. Trackways 4-8 are from the first of these two areas. Trackways from low ceiling areas should be shorter than step lengths from high ceiling areas. However, the step lengths of these trackways were not affected by the low ceiling height. The association of foot impression length and step length is similar for low and high ceiling areas. If low ceiling height did affect the walking patterns of the prehistoric cavers, it was not responsible for inbound and outbound walking pattern differences because the number of inbound and outbound trackways from low-ceiling areas is similar. Three of these trackways (Trackways 4, 5, and 8) are inbound and two (Trackways 6 and 7) are outbound. Because step length is not affected by ceiling height, some trackways may not represent the actual routes of these prehistoric cavers. This is one of several limitations of this study that discussed in the following section.

Limitations

This study had four limitations. The first limitation was the use of the step length sample in identifying Jaguar Cave trackways. Second, there have been questions
about the accuracy of the Aborigine Avenue maps and foot impression measurements.

Third, foot impressions were artificially placed into trackways, which may not represent the actual paths of the prehistoric cavers. Fourth, many foot impressions were excluded from this analysis. Only a small subset of foot impressions were assigned to trackways and these were from the front and middle of Aborigine Avenue.

Differences between the Jaguar Cave and Jak Sikh Samples

The sample used to identify the Jaguar Cave trackways is based on the average step length and standard deviation of 283 adult Jat Sikh males from India. The Jat Sikh sample is all male, taller than the estimated heights of the prehistoric cavers by an average of 4.5 cm, removed from the prehistoric cavers by more than 4,000 years, and many thousand miles.

Despite all of those differences, the step length of the Jat Sikh sample probably compares well with the step lengths of the prehistoric cavers. Height, as other anthropometric variables, is only weakly correlated with step length. Speed affects step length more than body size and proportions. These prehistoric cavers almost certainly walked, not ran, when in Aborigine Avenue. Conditions present in the cave would have made traveling at speeds faster than walking difficult and perilous. Step lengths from the Jat Sikh sample were also based on walking. Table 16 compares the mean step length for Jaguar Cave trackways to people walking at a preferred speed and running. The average step length of the Jaguar Cave trackways is shorter than preferred walking and running step lengths, which suggests the prehistoric cavers walked slower than their preferred walking speed in Aborigine Avenue. This logic, however, is circular. The similarity in
Table 16. Comparison of average step length (in cm) for Jaguar Cave, and preferred walking (Jasuja 1993) and running (Cavanagh and Kram 1989) step lengths of modern samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Average Step Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jaguar Cave</td>
<td>53.3</td>
</tr>
<tr>
<td>Preferred Walking</td>
<td>60.7</td>
</tr>
<tr>
<td>Running (3.15 m/s)</td>
<td>113.5</td>
</tr>
</tbody>
</table>


Step length between the Jaguar Cave and Jat Sikh samples may be because the Jat Sikh sample is used to identify the Jaguar Cave trackways.

Map Accuracy

Step lengths in Aborigine Avenue were measured by the author with electronic sliding calipers (accurate to 0.001 of a cm) on field maps of the foot impressions and not directly from the foot impressions themselves. However, step lengths measured from these field maps may vary from the actual step lengths because of mapping errors.

It is assumed that these maps are accurate, but there are several reasons to question their accuracy. Conditions of Aborigine Avenue, including lighting and ceiling height, make it a difficult working environment. Factors, such as the angle of the alidade and the foot impression, distance of the foot impression from the survey station, the access to the impression for measurement, and different mapping teams may diminish the accuracy of field maps.
To examine differences between actual step length measurements and step lengths measured from the field maps, a sample of step lengths measured directly from the foot impressions was compared to their field map counterparts (Table 17). These step lengths were measured from the most posterior point of the impression to the most posterior point of the next impression in the trackway by two people using oblique lighting and a measuring tape (author’s unpublished field notes on a visit to Jaguar Cave, August 30, 2008).

**Table 17.** Step lengths measured from Jaguar Cave field maps and lengths (in cm) measured directly from the foot impressions.

<table>
<thead>
<tr>
<th>Trackway</th>
<th>Step Length from Maps</th>
<th>Actual Step Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60.5</td>
<td>58</td>
</tr>
<tr>
<td>2</td>
<td>50.9</td>
<td>53</td>
</tr>
<tr>
<td>3</td>
<td>50.8</td>
<td>66</td>
</tr>
<tr>
<td>7</td>
<td>40.6</td>
<td>41</td>
</tr>
<tr>
<td>8</td>
<td>66.2</td>
<td>66</td>
</tr>
<tr>
<td>13</td>
<td>47.3</td>
<td>49</td>
</tr>
</tbody>
</table>

For the most part, step lengths measured from the field maps were close to those measured directly from the foot impressions (Table 17). The only exception was Trackway 3; there was a 15.2 cm difference between the step length measured from the field map and the actual step length measured from the foot impressions. This step length was re-measured from the field maps and that measurement did not change. This difference in step length for Trackway 3 could be from an inaccurate field map or erroneous measurement taken in Aborigine Avenue. A majority of step lengths measured from the field maps corresponded well with their directly measured counterpart,
suggesting the field maps accurately represent the actual foot impressions, for the most part.

**Artificial Trackways**

Trackways identified in the present study may or may not represent the actual trackways created by the prehistoric cavers. Although the method used in the present study attempts to provide a quantitative means for identifying trackways, foot impressions are “fit” into trackways. Interpretations of walking patterns based on these assumed trackways may not reflect the actual walking patterns and routes.

As demonstrated above, comparison of trackway foot impressions with the cluster groups and examination of the effect of low ceiling height on step length provides a means of assessing the validity of trackways. Half of the trackways that contain foot impressions from a cluster group have foot impressions from multiple clusters (7 of 14 trackways), and low ceiling height did not affect step length. These problems suggest that some trackways may not be the trails left by the prehistoric cavers. Morphological analysis of the foot impressions would be useful in assessing the likelihood that the identified trackways are the paths of the prehistoric cavers. Trackway 1, for example, has foot impressions with similar measurements, although the morphology of these foot impressions differs (McCormick, unpublished notes). The morphology of Foot Impression 77, the first impression in Trackway 1, has a larger and more pronounced big toe than the second and third foot impressions in Trackway 1 (Foot Impressions 78 and 75, respectively; McCormick, unpublished notes). All of these lines of evidence suggest that some trackways may not be the trails left by specific individual prehistoric cavers.
Trackway Distribution

Only Survey Station (SS) areas from near the front and middle of Aborigine Avenue produced trackways. Other SS areas had foot impressions but had no identified trackways; SS areas 10, 17, and 22 were excluded from this study. SS Area 10 was nearest the entrance of Aborigine Avenue. This SS area contained few foot impressions \( (n = 12) \) and no identifiable trackways. SS Areas 17 and 22 were near Aborigine Avenue’s dead end and had numerous overlapping impressions \( (n \geq 52, n \geq 50 \text{ for SS Areas 17 and 22, respectively}) \). In many cases, the orientation of the foot impression from these areas, either inbound or outbound, was unclear. Also, SS Area 12 only had outbound trackways and SS Area 16A had only inbound trackways. SS Areas 13 and 15 had both inbound and outbound trackways. Because trackways were only identified from the front and middle of Aborigine Avenue, this study only addressed walking pattern differences in those areas. Finally, only a small subset of all foot impressions was included in trackways. The results of this study were based on a small number of foot impressions and from limited areas of Aborigine Avenue. Thus, this study only addresses behavioral differences from those areas and not the entire passage.

Other Prehistoric Trackway Sites

The Jaguar Cave trackways are one of several sites where human trackways have been identified. Other prehistoric trackway sites provide a comparison of prehistoric behavior from a variety of contexts. Other sites include Cuatro Cienegas, Coahuila, Mexico; El Cauce, Nicaragua; Devil's Trail, southern Italy; Formby Point, England; and
Willandra Lakes, New South Wales, Australia. This section compares the locomotory pattern of Jaguar Cave with those other trackway sites.

The Jaguar Cave trackways are on relatively flat and level surfaces. With the exception of the Devil’s Trail trackways, which are on an irregular and inclined surface, trackways from the other sites are also on a flat level surface (Table 18). Unlike Jaguar Cave, all of these other trackway sites are in open environments, which may have resulted in locomotory differences between the two environments.

**Table 18.** Comparison of prehistoric trackways by step length (in cm), surface type and environment.

<table>
<thead>
<tr>
<th>Site</th>
<th>Average Step Length</th>
<th>Surface Type</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jaguar Cave</td>
<td>53.3</td>
<td>Flat and level mud</td>
<td>Cave</td>
</tr>
<tr>
<td>El Cauce</td>
<td>53.7</td>
<td>Flat and level mud</td>
<td>Open</td>
</tr>
<tr>
<td>Formby Point</td>
<td>56.0*</td>
<td>Flat and level mud</td>
<td>Open</td>
</tr>
<tr>
<td>Devil's Trail</td>
<td>60.0</td>
<td>Irregular inclined mud</td>
<td>Open</td>
</tr>
<tr>
<td>Cuatro Cienegas</td>
<td>75.0</td>
<td>Flat and level wet tufa</td>
<td>Open</td>
</tr>
<tr>
<td>Willandra Lakes</td>
<td>136.8**</td>
<td>Flat and level wet hardpan</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td>62.0***</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Average step length based on one trackway from site Gamma U1-XXVII  
**Average step length of tall, running males  
***Average step length of walking women and child

Of these trackway sites, Jaguar Cave has the shortest average step length, suggesting that the cave environment caused the prehistoric cavers to walk slower than usual (Table 18). Conditions of the cave, such as low ceiling height and dim lighting from cane torches, could have caused the prehistoric cavers to walk slower than their preferred speed. Surface conditions may have also influenced step length. The Jaguar Cave average step length is comparable to Formby Point and El Cauce, which are also trackways in slippery mud. These comparable average step lengths suggest that the slipperiness of the surfaces shortened the step lengths.

On the other hand, the trackways at Cuarto Cienegas and Willandra Lakes have much longer average step lengths (Table 18). These trackways are in wet tufa and hardpan, respectively, which are less slippery substrates than the mud of Jaguar Cave. These increased step lengths suggest these people traveled faster because they were not under the same surface property constraints that mud presented.

As mentioned above, the Devil’s Trails trackways are the only trackways not on a flat and level surface. These trackways are on an irregular and inclined surface, causing the prehistoric people to use different locomotory strategies to navigate the difficult surface. Of the three Devil’s Trails trackways, the first walked down the slope in a “Z” pattern. The three changes in direction of this trackway correspond with the most pronounced slope breaks, suggesting this prehistoric person chose to descend along the less pronounced grade (Avanzini et al. 2008:182). The second trackway descends across the slope at a 45° angle. And similar to the first trackway, the second trackway changed direction to follow the least pronounced grade when confronted by a steep slope. The
third trackway negotiates the least irregular terrain of the three trackways, is in a straight line and has the most regular step lengths (Avanzini et al. 2008:183).

Some general trends in human locomotion are apparent from the trackway sites discussed above. Most trackways are in a straight line. The exception to this generality is the Devil’s Trails trackways. These trackways are on a steep and irregular slope and the prehistoric people who navigated this descent deviated from a straight line to follow the least extreme slope. Interestingly, the third Devil’s Trails trackway, which followed the more even and level terrain than the other two trackways, is the straightest of the three trackways and has the most regular step length. Also, the trackways on slippery mud have shorter step lengths than trackways on less slippery substrates. This trend suggests that people tend to take the easiest route across terrain at a preferred speed that is influenced by the consistency of the substrate.

Preservation

Until the gating of the cave entrance in the summer of 2000, Jaguar Cave was a popular and frequently visited cave (Bobo and Greene 2000). In addition to vandalism in the front areas of the cave and the killing of endangered bats hibernating there, boot prints from modern cavers modified and partially destroyed some of the Jaguar Cave foot impressions (Bobo and Greene 2000:284).

Damage to foot impressions was not limited to careless cavers. Damage also occurred during data collection (Willey et al. 2005). Type foot impressions, representing the nine individuals identified during archaeological fieldwork, were cast to preserve permanent models of the foot impressions (Willey et al. 2005:64). The nature of the
casting process, however, destroyed or severely damaged those impressions (3.3 percent of the total 274 mapped prints; Robbins et al. 1981:377; Willey et al. 2005:64). Efforts taken to preserve the Jaguar Cave foot impressions included flagging and sectioning off the foot impressions with yellow tape.

Gating the cave entrance drastically decreased the number of people visiting the cave and diminished the exposure of the foot impressions to modern cavers. The 2002 purchase of Jaguar Cave by the Southeastern Cave Conservatory (SCCi) with donations from the Nature Conservancy (Tennessee Chapter) and the Bat Conservation International was another action that protected the endangered bats and foot impressions (Southeastern Cave Conservancy 2002). After the purchase, the SCCi adopted policies limiting access to the cave. These policies included closing the cave after September 16 for the endangered bat’s hibernating season and limiting access during other times to researchers and cavers approved by the SCCi (Southeastern Cave Conservancy 2002).

The foot impressions at Jaguar Cave are a rare and valuable source of information about the behavior of past people. The recent attempts to protect and preserve the foot impressions, such as gating the entrance to Jaguar Cave and flagging the foot impressions areas, have lessened their exposure to modern cavers. These steps will help maintain the integrity of the foot impressions and allow for future research.

Summary

Walking pattern differences were observed between inbound and outbound trackways in Jaguar Cave. Different average foot impression lengths and comparisons of trackway foot impressions with cluster groups suggested differences in the walking
patterns between inbound and outbound trackways could be due, in part, to different individuals. Other possibilities for walking pattern differences, such as variation in surface properties or speed of walking, were not supported by the contextual evidence of Aborigine Avenue or trackway walking patterns. Because of more variability in inbound steps lengths, inbound trackways were closer to expected walking patterns while exploring than outbound, although this study had several limitations.

These inferences had limitations. The first limitation was possible differences between the step lengths of the prehistoric cavers and those of the Jat Sikh sample, which were used to identify Jaguar Cave trackways. Although there were temporal, spatial, and genetic differences between the Jat Sikh males and the Jaguar Cave prehistoric cavers, both groups walked, making their step lengths broadly comparable.

Another limitation included the accuracy of the field maps. Overall, step length measured from the field maps for this research was comparable to those from Aborigine Avenue, suggesting the maps were accurate.

There was also reason to question the validity of the trackways. Low ceiling areas did not affect step length, which was unexpected. Additionally, most trackways with more than one foot impression from a cluster group had foot impressions from multiple clusters. Finally, morphological examination of foot impressions in Trackway 1 suggested that despite similar measurements, these impressions were from more than one individual.

The last limitation was the distribution of trackways in Aborigine Avenue. Most of the trackways were from the middle of Aborigine Avenue. Thus, this study only addressed walking pattern differences from this area.
Despite the limitations of this study, the behavior inferred from the Jaguar Cave trackways was compared to other prehistoric trackway sites. As the Jaguar Cave trackways, trackways from El Cauce and Formby Point were in slippery mud. These trackways had shorter average step lengths than trackways in less slippery surfaces, such as Cuarto Cienegas and Willandra Lakes, suggesting that the slipperiness of a surface limited the speed that human can safely travel. Also, all trackways on a flat, level surface were in a straight line. The only trackways that were not in a straight line were the Devil’s Trails trackways, which were on an irregular declined surface.

Jaguar Cave is a valuable example of past locomotory patterns and behavior that requires protection. Jaguar Cave was gated in the summer of 2000. This action, along with the policies of the SCCi, drastically decreases the number of people visiting Jaguar Cave, which helps protect the cave from vandalism, the endangered bats that hibernate in the cave, and the foot impressions in Aborigine Avenue from modern cavers. Besides damage from modern cavers, certain “type” foot impressions were destroyed during casting.
CHAPTER VI

SUMMARY

Sixteen trackways are identified from the Jaguar Cave foot impressions. Step length analysis demonstrates that these prehistoric cavers used different walking patterns entering Aborigine Avenue than exiting the passage. The inbound trackways have more variable step lengths than outbound trackways. Furthermore, there are 27 more inbound foot impressions than outbound altogether. These differences suggest that the prehistoric cavers took more steps and stopped walking more often entering Aborigine Avenue than exiting the passage. Thus, inbound walking patterns are more consistent with exploring than outbound, which supports the assertion of Watson et al. (2005) that the prehistoric cavers explored as they entered Aborigine Avenue and made a direct and expedient exit from the passage. This chapter summarizes the study and makes suggestions for future research.

This thesis begins with an introduction of foot impressions, trackways, and an explanation of the rare circumstances that lead to the preservation of foot impressions in the archaeological record. Foot impressions most frequently preserve in locations where fine and course sediments are interlaminated, such as estuarine, flood plain and coastal environments, and where erosion and weather have a minimal effect on preservation, such as caves.
In previous studies, foot impressions are analyzed metrically and morphologically as well as in situ. Foot impressions are analyzed in situ by examining the relationship of foot impressions to each other and the substrate. In some instances, it is possible to follow the route of individuals by identifying trackways. The step lengths (the distance between two consecutive foot impressions) of a trackway provide information regarding the individual’s locomotory pattern.

After introducing foot impressions and trackways, Jaguar Cave, a complex cave system in north-central Tennessee, is systematically described, followed by presenting the purpose of this study. This study examines the relationship between the prehistoric foot impressions from Aborigine Avenue, a passage in this cave. Trackways of these prehistoric cavers are identified to investigate further the assertion of Watson et al. (2005) that the prehistoric cavers explored entering the passage and made a direct and expedient exit.

The literature review provides a background for this examination by describing research on variables that affect locomotory patterns in humans and previous research on archaeological foot impressions. Human locomotory patterns are affected by two types of variables: intrinsic and extrinsic variables. Intrinsic factors are inherent to the individual and independent of the individual’s control. Extrinsic factors, on the other hand, derive outside the individual. Other factors, such as velocity and fatigue, did not fit into either category, therefore they are discussed separately.

Two variables that may have influenced walking patterns in Aborigine Avenue are surface grade and properties, and walking velocity. Changes in surface grade affect the influence of gravity on the body. On an incline, the body must overcome
gravity as it moves vertically as well as horizontally. To maintain balance on inclines, step length is increased. On a decline, however, gravity provides kinetic energy to move the body downward, which decreases step length.

Step length also decreases when individuals walk across a slippery surface. This decreased step length is due to an increase in the horizontal angle of foot contact, which increases friction between the foot and surface. In contrast with slippery surfaces, step length is increased and step frequency is reduced as individuals walk over an irregular surface. This adjustment increases the time the foot is in the air and allows individuals extra time to react to surface irregularities.

Velocity is influenced by the physical ability and choice of the individual and the environment. At walking speeds, which are typically slower than 2.0 m/s, step length increases with velocity and step frequency remains constant. At running speeds (> 2.5 m/s), however, step frequency increases with velocity.

After a review of variables that affect locomotory patterns, past research on foot impressions is discussed. This research is separated into two sections: cave sites from the southeastern U.S. and other sites that contain foot impressions. The research on foot impressions from cave sites in the southeastern U.S. includes metric and morphological examination. Research from other sites containing foot impressions, on the other hand, has been metric and morphological as well as in situ examination.

The materials and methods chapter further develops the purpose of this study by presenting the research hypothesis and the walking pattern expectations for this hypothesis. The purpose of this thesis is to investigate further the assertion of Watson et al. (2005) that the prehistoric cavers explored Aborigine Avenue as they entered the
passage and made a direct and expedient exit from the passage. This investigation is done by identifying trackways from the Jaguar Cave foot impressions and analyzing inbound and outbound walking patterns. Certain walking patterns are expected while exploring. If prehistoric cavers explored as they entered and made an expedient exit, inbound step lengths should be shorter and have greater variability than outbound step lengths.

After detailing the expectations and materials of this study, a method for identifying trackways is developed. Jaguar Cave trackways are identified using side, orientation, measurements and gait angle of the foot impressions. These criteria are applied to the field maps until a trackway could no longer be identified.

Using the outlined methods, 16 trackways are identified from areas in Aborigine Avenue. These trackways consist of two to six foot impressions per trackway for a total of 42 impressions. There are eight inbound trackways and eight outbound trackways. On average, inbound trackways have more impressions than outbound trackways with ten more inbound than outbound impressions.

Statistical analyses of these trackways indicate that the prehistoric cavers walked differently into Aborigine Avenue than when leaving the cave passage. Overall, inbound steps are longer and are more variable than outbound steps. As step length, inbound foot lengths are longer and more variable than outbound foot lengths.

A moderate positive relationship of foot impression length and step length is found for inbound trackways and the total sample. Outbound trackways, however, show a negative relationship between these two variables. These relationships remain the same when trackways with low ceiling height are eliminated from analysis, although the strength of these relationships is weaker. The only significant relationship of foot
impression length and step length is for the total sample, which suggests that other relationships of foot impression length to step length might be due to chance. These findings establish that the prehistoric cavers in Aborigine Avenue took longer and more variable steps when entering the cave passage than when exiting.

Morphological analysis of foot impressions, comparisons of trackways with cluster groups from Watson et al. (2005), and modern observations of Aborigine Avenue provide evidence for interpreting differences in inbound and outbound trackways. Comparisons of trackway foot impressions with cluster groups and morphological analysis of foot impressions suggest that different individuals are represented with each trackway.

Other possibilities for walking pattern differences, such as differences in surface properties or speed of walking, are not supported by the contextual evidence of Aborigine Avenue or trackway walking patterns. The relative uniformity of surface consistency and grade, and the close proximity of inbound and outbound trackways to each other lessen the possibility that walking pattern differences result from differences in surface properties.

It is likely different individuals created inbound and outbound trackways, which may have contributed to differences in walking patterns. Although it is impossible to control for interpersonal differences in walking that may contribute to differences in inbound and outbound walking patterns, it is possible to demonstrate which walking pattern (inbound or outbound) is more consistent with exploring.

Step length has low variability when an individual walks quickly and uninterrupted. Inbound step lengths are more variable than outbound step lengths,
suggesting that those who created inbound trackways started and stopped more often than those who created outbound trackways. This behavior is consistent with exploring. In addition, despite possible damage from outbound foot impressions, there are 27 more inbound than outbound foot impressions in the total assemblage. This greater number of inbound foot impressions suggests that the greater number of inbound foot impressions is because the prehistoric cavers took more steps as they entered Aborigine Avenue, which is also consistent with exploring. These findings show that inbound walking patterns are more consistent with exploring than outbound.

There are several limitations to this study. The first limitation is the differences between the step lengths of the prehistoric cavers and those of the base sample used to identify Jaguar Cave trackways. Although there are temporal, spatial and genetic differences between the Jat Singh males and the Jaguar Cave prehistoric cavers, both groups walked, rather than ran, making their step lengths broadly comparable. Another limitation of this study is the accuracy of the field maps. Overall, step lengths measured from field maps are comparable to measurements taken in Aborigine Avenue, suggesting that the maps are accurate. There is also reason to question the validity of the trackways. Low ceiling areas did not affect step length, which is unexpected. Additionally, most trackways with more than one foot impression from a cluster group have foot impressions from multiple clusters. Finally, morphological examination of foot impressions in Trackway 1 suggests, despite similar measurements, that these impressions are from more than one individual. A final limitation is the distribution of trackways in Aborigine Avenue. Most of the trackways are from the middle of Aborigine
Avenue. Thus, this study only assesses walking pattern differences from the middle of the passage, not the entire route.

Jaguar Cave is only one site with trackways. As the Jaguar Cave trackways, trackways from El Cauce and Formby Point are on slippery mud. These trackways have shorter average step lengths than trackways on less slippery surfaces, such as Cuarto Cienegas and Willandra Lakes, suggesting that the slipperiness of a surface limits the speed that human can safely travel. Also, all trackways on flat, level surfaces are in a straight line. The only trackways that are not in a straight line are the Devil’s Trails trackways. These trackways are on an irregular inclined surface. This finding suggests that people prefer to travel the easiest route, which is a straight line, unless obstacles such terrain irregularities cause people to change their route.

Protecting prehistoric foot impressions, such as the ones at Jaguar Cave, is important for future research. Jaguar Cave was gated in the summer of 2000. This action has drastically decreased visits made to Jaguar Cave and helped to protect the cave from vandalism, the endangered bats that hibernate in the cave, and the foot impressions in Aborigine Avenue from modern cavers. Besides damage from modern cavers, certain “type” foot impressions were destroyed during casting.

Suggestions for Future Research

Archaeological analysis of locomotory patterns is a recent extension of foot impression research. These analyses are limited to inferences of speed from step length and qualitative observations of behavior based on the distribution of foot impressions. Speed estimations are based on the average step length of trackways. While average step
length is informative, step variability, which has been widely overlooked by archaeologists, provides detail about locomotory adjustments that are lost when step lengths are averaged. The longer average inbound than outbound step lengths of the Jaguar Cave trackways, for example, suggest that these prehistoric cavers walked faster as they entered the passage. However, experimental research shows that variability in step length decreases as speed increases. For the Jaguar Cave trackways, inbound step lengths are more variable than outbound, suggesting that a faster walking speed is unlikely. Step length variability and average step length are both important aspects of locomotory patterns and both need to be considered when inferring locomotory patterns from trackways.

As with step length variability, gait angle is another part of locomotory patterns that has received little attention. Gait angle remains poorly understood and research on the subject is limited to a few studies conducted over 70 years ago. Those studies only examine gait angle of individuals walking in a straight line. Experimental studies should investigate how gait angle is affected when individuals deviate from a straight line. With other experimental studies on locomotory aspects such as the affect on step length as locomotion deviates from a straight line, this research could help archaeologists identify trackways that are not obvious.

In some situations, trackways are evident from foot impressions. For example, the Upper Crouchway trackways were created by two prehistoric cavers with distinct foot morphology walking straight without other foot impressions to obscure their trails. In these situations a method for identifying trackways is unnecessary. The process of identifying trackways employed in the current study is an attempt to identify trackways
when other foot impressions obscure trackways, although this process may identify spurious trackways. Examination of foot impression morphology and measurements, and gait angles of trackways that are not obvious are ways to verify these trackways.

Further experimental research on locomotory patterns would help create a method to identify trackways when they are not obvious. Trackways identified using this method could be validated by examining foot impression morphology and measurements as well as gait angle. This method could be employed on foot impressions at sites such as Oro Grande and Monte Hermoso 1, where trackways maybe obscured by other foot impressions.
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