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Infant Carrying: The Role of Increased Locomotory Costs in Early Tool Development

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ABSTRACT Among the costs of reproduction, carrying one's infant incurs one of the greatest drains on maternal energy, simply because of the added mass alone. Because of the dearth of archaeological evidence, however, how early bipeds dealt with the additional cost of having to carry infants who were less able to support their body weight against gravity is not particularly well understood. This article presents evidence on the caloric drain of carrying an infant in one's arms versus having a tool with which to sling the infant and carry her passively. The burden of carrying an infant in one's arms is on average 16% greater than having a tool to support the baby's mass and seems to have the potential to be a greater energetic burden even than lactation. In addition, carrying a baby in one's arms shortens and quickens the stride. An anthropometric trait that seems to offset some of the increased cost of carrying a baby in the arms is a wider bi-trochanteric width. Am J Phys Anthropol 133:841–846, 2007. ©2007 Wiley-Liss, Inc.

With the advent of bipedalism, early hominin mothers with pre-weaned infants would have been unable to remain mobile in the same manner as their quadrupedal ancestors. While the clinging ability inherent among infant chimpanzees allows them hang to their mothers for short-term bipedal activities (Hunt, 1998), it is likely that holding their body weight against gravity for long-term bipedal walking would be extremely challenging. Further evidence from DIK-1-1 suggests that, when compared with chimpanzees, early bipeds had slower development and more rigid feet, both of which would have much reduced grasping ability early in life (Alemseged et al., 2006). A childbearing female would thus have either had to carry (or strongly brace) her baby in her arms, use a tool such as a sling, or risk falling behind her tribe in the search for food or in an escape from predators. There is little evidence that primates park their infants, (Lee, 1989; Altmann and Samuels, 1992; Ross, 2001; Rosenberg et al., 2004, though see Falk, 2004) especially among the African apes (Reynolds, 1979), so setting the baby down was not likely a strategy utilized by early hominins. Evidence from milk composition (humans and other primate carriers have reduced fat and increased carbohydrate contents of their milk, whereas parkers have high fat and protein contents) (Tilden and Oftedal, 1997), and the infant carrying habits of many modern human populations (Konner, 1972; Brazelton, 1977; Goldberg, 1977; Konner, 1977; Blurton Jones et al., 1989; Hawkes et al., 1989; Tracer, 2002; Marlowe, 2005) further support the likelihood that all hominin populations expended some amount of energy carrying their infants.

The modern human model of long distance transport, including that of infants, is generally agreed to have occurred by the time of *Homo erectus*–around 1.7 million years before the present (Antón, 2003). Among the Australopithecines, relatively smaller daily movement distances (Kramer, 2004 and references therein) may have offset increased baby-carrying costs. Nonetheless, despite smaller movement distances than *Homo*, early bipeds had relatively expanded day- and home-ranges in comparison with earlier primates (Foley, 1992, 1999), and this expanded movement between resources would have required the ability to transport an infant in an economic manner. Thus, a better understanding of infant carrying strategies is of evolutionary significance for all the hominins.

It remains difficult to make direct inferences as to the role of infant carrying in the daily energetic expenditure of early hominin populations because of scarce evidence that infant carrying tools existed before 15,000 years before the present (bp); this is hardly surprising as modern infant carrying tools do not readily withstand periods of exposure. Modern hunter-gatherers use various methods to carry their infants but most commonly utilize slings which can be moved to different locations on the torso (Becker, 1956: 29; Quilici, 1972; Harris, 1975; McElroy and Townsend, 1996) and inside or out of the clothing (Rosenberg et al., 2004). Nonetheless, the gap in the archaeological record leaves us without a clear understanding of when carrying or other organic tool types were possibly developed. We therefore want to evaluate the energetic cost of carrying an infant in one's arms as compared to having a tool to carry the infant. We suspect that the energetic drain of carrying an infant would be such that some sort of carrying device would have been required soon after the development of bipedalism and definitely to allow long distance travel, especially that out of Africa and across Asia.

Here, we determine the cost to carry an infant in one's arms (Baby with No Arm Swing, abbreviated as BNAS)

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versus having a tool to carry the infant (Baby with Arm Swing, BAS). We designed the protocol to include controls both for the additional mass of the infant (Mass with Arm Swing, MAS) as well as for the removal of arm swing capabilities while carrying (Mass with No Arm Swing, MNAS).

MATERIALS AND METHODS

Six females participated (average age = 20.5 years, standard deviation = 0.8; average mass = 74.8 kg, standard deviation = 5.6), all of whom signed written informed consent papers approved by the University of Wisconsin-Madison Human Subjects' Committee within the Social and Behavioral Science Institutional Review Board, and walked on a treadmill under the four conditions. While 74.8 kg may be higher than some populations' averages for reproductive aged females (World Health Organization Global Database), none were clinically obese. Each female came into the lab on five different occasions and performed a randomized without replacement set of each of the four conditions while her oxygen consumption was measured using a SensorMedics Vmax 29c respiratory gas analysis system. The order of conditions was different for each day the participant came and the same set of orders was used across subjects. The first day was not included in the analysis and was considered a training day. Each condition lasted for 12 min and the final 4 min of the condition were averaged to get the steady state value for that day under that condition. The speed of the treadmill was held constant under all days and conditions at 1.16 m s^{-1} (2.6 mph). This speed was chosen as it is near energetic optimality (Steudel-Numbers and Tilkens, 2004), but on the low end as appropriate for subjects carrying a load.

We simulated a "baby" by determining the mass and the length of a typical infant using the 50th percentile value for a 6 month, unweaned child as developed by the National Center for Health Statistics in collaboration with the National Center for Chronic Disease Prevention and Health Promotion (CDC). We took an average of the values for both males and females which resulted in a mass of 7.7 kg (17 pounds) and a length of 66 cm (26 inches). We then created an infant-shaped, cloth model to these specifications. Infant-shaped implies that this "infant model" was the length, mass, and had the head/arms/legs proportions of a child and was filled with sand, so was malleable. This amount of mass was 9.7–12.5% of the subjects' body mass. As a control for the additional cost of the mass, one condition included strapping 7.7 kg around the waist (approximating the center of mass) while maintaining a normal stride in all other ways. For the MAS condition, the mass was evenly distributed around the entire waist by using a diving belt. The second control condition (MNAS) included the additional mass at the center of mass, with no armswing (each person was instructed to fold her arms at her weight belt). The third and fourth conditions were used to determine the cost of actually carrying the infant. In the BNAS condition, the infant-model (IM) was carried in the arms of the participant. Generally each person carried the IM towards one side and did not move it from side to side during the condition. While we acknowledge all infants are different, our own experiences suggested that 6-month-olds carried in the arms still needed support of both body and very heavy head, and thus the carrying of the IM with one arm only did not seem as reasonable as carrying it in two.

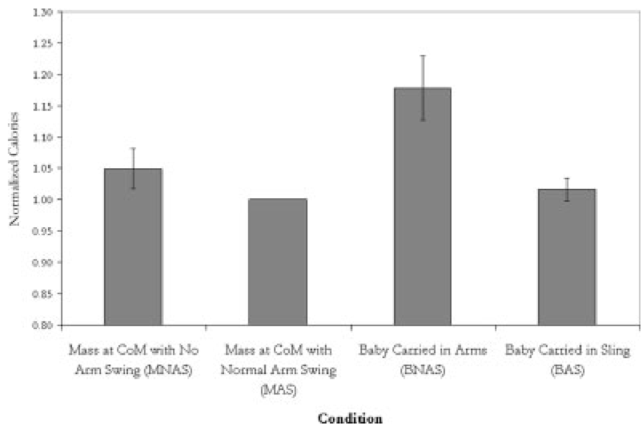


Fig. 1. Each column represents the average normalized calories across subjects at each condition. The error bars represent one standard deviation above and below the mean; there are no error bars for the MAS condition because the other conditions were normalized to it. MAS is included in this figure, despite that it acts as a constant, so that the patterns of increase above this control are more visually accessible. The only conditions not significantly different from one another are BAS and MNAS ($P = 0.108$) and BAS and MAS ($P = 0.107$). All other conditions are significantly different from one another ($P \leq 0.01$). Most importantly, carrying a baby in a sling demands significantly fewer calories than carrying a baby in one's arms.

In the BAS condition the IM was carried in a sling (folded shawl which crossed and tied over the chest) on the back.

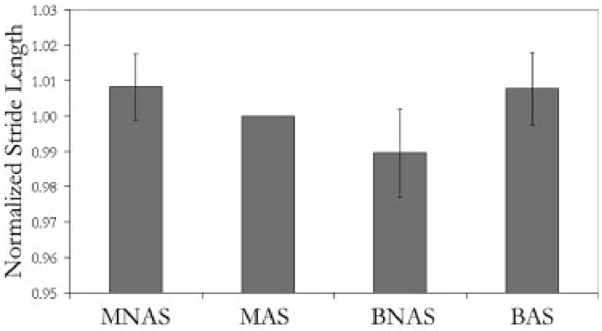
On the final day of VO_2 collection, kinematic information was also collected, including stride length (speed divided by stride frequency) and contact time (time in seconds the foot remained on the ground during a stride), at each of the conditions. Standard anthropometrics were also gathered including lower limb length (from greater trochanter to lateral malleolus), mass, and stature. In addition, bi-iliac width and bi-trochanteric width were measured by pressing the anthropometer very tightly against the top of the ilia and the most lateral projections of the greater trochanters respectively to get as close to the bone as possible.

The analysis included paired t-tests to test the overall differences between the cost of baby carrying and the controls (in the t-tests, an average of all 4 days was used at each condition). In addition, because we were able to measure both oxygen consumed and carbon dioxide produced, VO_2 and VCO_2 values were used to calculate calories using Weir's standard equation: Cal/min = (1.1RQ +3.9) VO_2 (Weir, 1949; McArdle et al., 2001). Because the main interest is in looking at change above a control condition, all results presented will be normalized as multiples to the MAS condition. To obtain such normalization, each condition was divided by MAS: MNAS/MAS, BAS/MAS, and BNAS/MAS. When shown in graphic form, MAS/MAS (= 1) will also be shown to give a sense of the level of the control condition.

RESULTS

The results of all days and subjects are summarized in Figure 1. The results have been averaged and normalized to the MAS condition to minimize differences between days and subjects; however, the results are similar using the raw data. Significant differences (using a paired t-test) between the calories needed at each of the

(a)



(b)

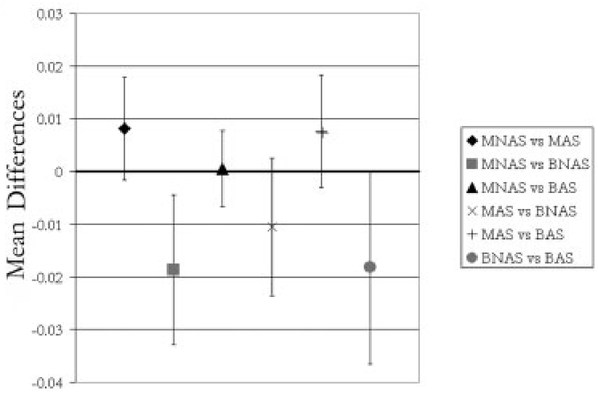


Fig. 2. (**a**) Each column represents the average changes in stride length, normalized to MAS (control condition). This graph illustrates the much shorter strides when carrying the baby in one's arms; significantly different from carrying the baby in a sling at $P = 0.05$. The error bars represent one standard deviation away from the mean. (**b**) This plot illustrates that even when the standard deviations of the condition overlap, the mean "between subject differences" are such that differences between the conditions are significant. As the null hypothesis is that there is 0 difference, if the 95% confidence intervals of the mean "between subject differences" cross 0, then the null hypothesis cannot be rejected. In fact, the advantage of using the same subjects for all conditions is that the differences between the conditions are going to be much smaller than the differences between subjects.

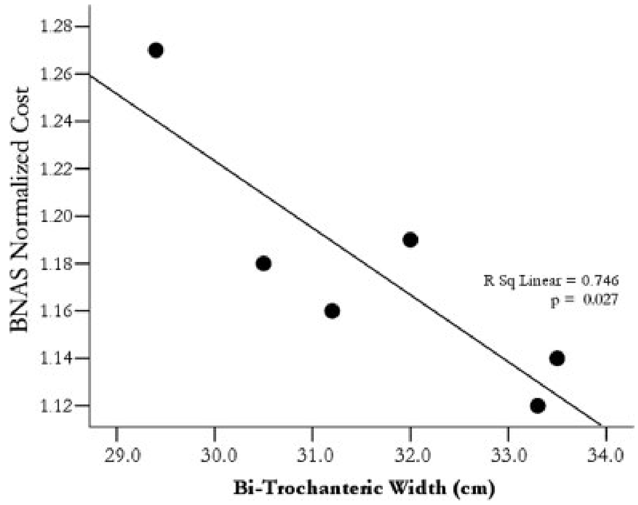


Fig. 3. The significant, negative relationship between bi-trochanteric width and the increase in cost of carrying the baby in the arms.

conditions exist between MAS and MNAS ($P = 0.014$), MNAS and BNAS ($P = 0.001$), MAS and BNAS ($P < 0.001$), and BNAS and BAS ($P < 0.001$). Most interestingly, the average increase in cost by carrying a baby in one's arms versus carrying it in a sling is 16% (ranging from 13% up to 25% of an increase). The individual variation of increased cost is correlated neither with a subject's total body mass ($P = 0.557$), nor the percentage of the IM's mass to the subject's body mass ($P = 0.599$). Lack of arm swing (MNAS) only accounts for 5% of the increase in cost above the control condition (MAS) (see Umberger, 2006 for a similar finding) and only 3% of the increase in cost above carrying the IM in a sling (BAS). This leaves approximately 13% of the cost of carrying the IM in the arms to be explained; likely contributing factors are the muscular force required to carry the extra mass in the arms and changes in kinematics.

Normalized stride lengths are shorter during BNAS than during the other experimental conditions. BNAS is significantly different from MNAS ($P = 0.020$) and BAS ($P = 0.052$) (see Fig. 2). Normalized contact time during BNAS shows the exact same pattern as stride lengths—BNAS had the shortest contact time in comparison with all the other conditions—but the size of the effect did not reach significance between MNAS (the longest contact time) ($P = 0.061$). Essentially, however, during BNAS individuals are taking shorter, more rapid strides.

The only anthropometric measure that has any correlation with the stride parameters is bi-trochanteric width. Bi-trochanteric width is significantly correlated with stride length ($P = 0.036$, Pearson Correlation = 0.840) and contact time ($P = 0.017$, Pearson Correlation = 0.891) under the most "normal" condition, MAS. The positive nature of the correlations indicates that as bi-trochanteric width increases, contact time and stride length also increase when arm swing is not restricted and added mass is simply distributed around the CoM. This trend exists for carrying the IM in the arms (BNAS), but is not significantly correlated ($P = 0.108$ for contact time, Pearson Correlation = 0.718; $P = 0.109$ for stride length, Pearson Correlation = 0.716). Bi-trochanteric width does not seem to have any relationship with non-normalized caloric usage under any of the conditions, but because of the strength of the relationship between mass and cost ($P < 0.01$, Pearson Correlation > 0.900), this is hardly surprising (mass and bi-trochanteric width are not significantly correlated). Bi-trochanteric width is in fact significantly negatively correlated ($P = 0.027$, Pearson Correlation = −0.864) with the normalized caloric usage while carrying the IM in the arms (BNAS). This implies that as pelvic width increases, the relative increase in caloric drain caused by carrying an infant in one's arms decreases (see Fig. 3). It seems feasible that taking shorter, more rapid strides may itself be quite costly, and the wider pelvis is offsetting this by allowing longer strides and a more increased contact time (though again this is a trend only at BNAS). This three-way relationship between bi-trochanteric width, stride length, and cost is illustrated in Figure 4.

To better assess the cost of carrying a baby in an annual perspective, published data on the Hadza were used to determine how the 16% increase in cost between carrying a baby in the arms and carrying a baby in a sling would affect the daily cost of travel of a commonly

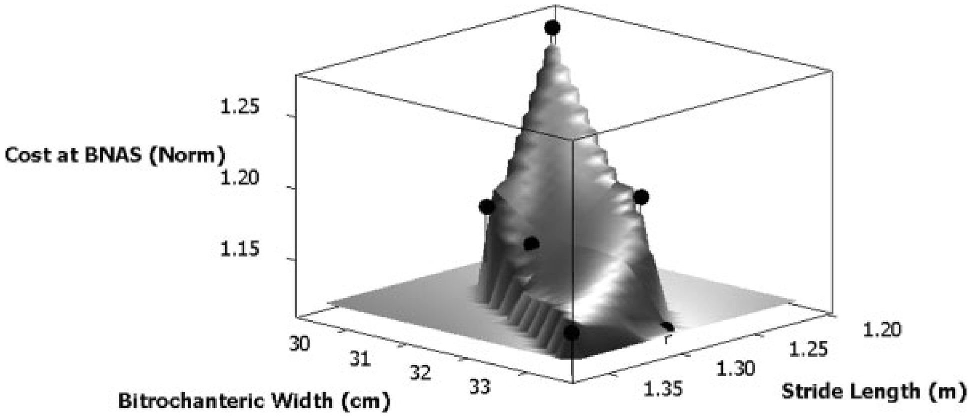


Fig. 4. A three-dimensional expression of the relationship between bi-trochanteric width and stride length and their combined effect on cost. It is quite obvious that the lower bi-trochanteric width corresponds with much reduced stride length and increased cost.

cited hunter-gatherer population. Using the values for Hadza female mass and stature (Hiernaux and Hartono, 1980), and regression equations for unloaded females developed from the data presented in Steudel-Numbers and Tilkens (2004) for four different speeds (1.16, 1.25, 1.34, and 1.43 m s^{-1}), we determined the cost of travel of Hadza females for the wet and dry seasons based on the time-spent-travelling data from Hawkes et al. (1989). The higher speeds shown are considered relevant because it is exactly at higher speeds that females are observed, as well as predicted, to carry older offspring as opposed to the juveniles walking under their own power (Altmann and Samuels, 1992; Kramer, 1998). Figure 5 shows these results in terms of the calories necessary to travel during each of the two seasons—wet and dry. The cost values are the result of multiplying the Cal/min outcomes from the regression equations by the average number of minutes Hawkes et al. (1989) observe women travelling during the two seasons. The time spent travelling given by Hawkes et al. (1989) is time spent travelling away from the central site in one direction. It is reasonable then that for 1 day these values could be doubled—walking to the foraging ground and then walking back again.

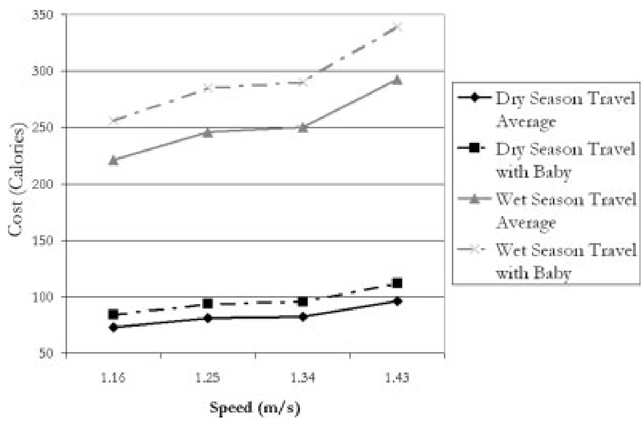


Fig. 5. This graph illustrates the increase in cost of carrying an infant in the arms above the unloaded costs of walking at different speeds. The cost (Calories) is calculated by multiplying average time (minutes) spent walking to a gathering site by the estimate of Cal/min from regression equations. The amount of minutes spent walking is based on data from the Hadza (Hawkes et al., 1989). The regression equations are based on data from Steudel-Numbers and Tilkens (2004). The solid lines represent the average cost (Calories) of walking at the given speeds. The dotted lines represent the increased cost (Calories) of walking while carrying a baby without a sling. The black lines are data from the dry season; the grey lines are data from the wet season.

DISCUSSION

The major results of this study are twofold. Firstly, we have shown that carrying an infant in a sling is more economical than carrying an infant in one's arms. We might further suggest that an increase in cost of on average 16% would incur a biologically significant energetic expenditure on an individual and be detrimental to her fitness. Secondly, it seems possible that a relatively wider pelvis, a characteristic of *Australopithecus afarensis*, may in fact offset some of the increased caloric cost of carrying an infant. By the time of *Homo erectus*, however, when both a relatively more narrow pelvis and even longer daily movement distances are assumed (Antón, 2003), tools must have been utilized to carry infants or other resources.

Among modern populations, those groups able to sustain themselves in relatively small ranges, and thus having smaller daily travel costs, are those situated in highly productive areas—generally tropical and subtropical (Binford, 2001). Data on the Hadza for example suggest that females forage for about 4 h a day (Hawkes et al., 1989; Marlowe, 2003) and during the wet season this can become 6 or 8 h (Hawkes et al., 1989). These foraging trips include travel times of a few minutes up to 2 h each way depending on the season (Hawkes et al., 1989). As suggested by Figure 5, only shorter travel times at slower speeds appear energetically reasonable while carrying an infant without a sling. Even 2 h of carrying an infant in the arms increases the cost between 50 and 75 Cal depending on the speed at which the mother is travelling. In addition, the obvious increase in cost with speed suggests that trying to carry an older (heavier) juvenile at higher speeds when the juvenile cannot keep up with the adults (Altmann and Samuels, 1992; Kramer, 1998) would be enormously costly for the mother—far exceeding the likely costs of simply the added mass of the child and approaching the cost of lactation itself (hypothesized to be around 500 Cal/day, but likely much lower than this (Dufour and Sauther, 2002 and references therin)). In fact, while most authors suggest that carrying an infant is merely the second most costly activity of reproduction (Nicolson, 1987; Altmann and Samuels, 1992)—below lactation—these data suggest that without a carrying device, the cost of carrying an infant far outweighs the cost of lactation.

Data on the environment at the origins of bipedality do, however, suggest a forested, woodland environment (Lee-Thorp et al., 2003; Senut, 2006) which may provide surroundings that allowed smaller daily movement distances (Binford, 2001); nonetheless, for bipedality to have been more advantageous than quadrupedalism, the majority of daily activities would likely have taken place on the ground in a bipedal posture (Foley and Elton, 1998) and stress because of baby carrying would have given a selective advantage to those that manufactured some carrying device or whose morphology minimized the cost differential.

To offset the cost of carrying without a sling, these data further suggest that a wider pelvis may have a number of effects on reducing the cost (of up to 12%) of carrying the infant in one's arms. A wider pelvis may provide more area to balance an infant, and thus the infant carrier may have to use less upper body strength to support the baby's mass. A wider pelvis might also be more stable, so that having a load on the side will not have a great impact on locomotion because excursion might be reduced. Wider bi-trochanteric width is also associated with longer strides and a longer contact time and this may act to offset any increase in cost caused by the shortening of the stride while carrying the infant (Fig. 4; see also Rak, 1991 for a discussion on the importance of a wide pelvis for lengthening the stride). An increased stride length may further allow individuals carrying an infant to maintain higher speeds, but this obviously needs much further testing.

Would any biped be able to travel far enough and fast enough to gather resources, escape from predators, and keep up with her group while incurring an average of a 16% increase in cost above the cost of the baby's mass alone? Would such a cost be too big to allow successful reproduction? At the very least, such a cost does suggest much greater inter-birth intervals than those of modern hunter gatherers. This research has suggested that the cost of carrying an infant in one's arms would have been meaningful enough to reward the development of carrying tools rapidly following the advent of bipedalism. The relationships between cost and speed, mass, and body proportions and the way in which early biped morphology might have accommodated a lack of efficient tool use are obvious areas in which further research can only work to illuminate.

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