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Human locomotion: examining energy costs and human behavior associated with load-carrying

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Abstract

The energy expenditure during load-carrying depends on the mass of the load, the position of the load on the body, and if tools are used to help transfer the load. When the load being carried is a human child, strategies employed to cope with the increased energetic burden should include males carrying older and heavier children, arm use decreasing as children become older, and tool use increasing as children become older. To uncover whether people make energetically-mediated decisions to carry children, 236 adult males and 314 adult females were observed walking around parks in Seattle, WA, while carrying a child. Details recorded included position of the child, what tools were available to carry the child, the adult's relationship to the child, and the child's sex and age. Males, when carrying, carried male children significantly more often ($p < 0.001$). Dual tool use increased significantly between 7-12 months and 18-24 months ($p < 0.001$). This study indicated that people will tend to make more energetically efficient decisions in carrying, but might be willing to pay extra energy costs to increase bonding or physical contact with the child and for more comfortable carrying positions.

Human Locomotion: Examining Energy Costs and Human Behavior Associated with Load-Carrying

Introduction

Bipedalism is generally considered the hallmark of the human lineage, with an emergence of terrestrial bipedalism marked prior to 4 million years ago. With the onset of terrestrial bipedalism, a number of new load carrying opportunities emerged, because the arms and hands were free from locomotion and could be used for the transport of materials, food, and offspring (Wang and Crompton, 2004;Videan and McGrew, 2002). That being said, there are clearly different ways of carrying loads, and, even for quadrupeds carrying loads on the back, all load carrying comes at increased energetic costs. The following paper examines the energetics and patterns of commonly used load-carrying positions among humans, as an attempt to uncover whether people make energetically-mediated decisions to carry goods and children using the smallest amount of energy possible.

Carrying a load requires more energy expenditure than walking without the object (Fig 1). This additional energy cost depends a number of factors which include the mass of the object, the position in which it is carried, and if the object is carried in the arms or if tools are used to help. Carrying an object around the waist, at the center of mass, is the least costly way of carrying, but is not a feasible way of carrying most loads. When transporting loads, back-loading (Fig. 2, position C) is the most energetically costly carry position (Fig. 1) since back loading energy costs are directly proportional to the increase relative to the individual's body mass. In other words, carrying a load that is 20% of an individual's body mass leads to a 20% increase in energy expenditure (Quesada et al., 2000, Rork 1990, Huang and Kuo, 2014).

Another common method of transport in much of the world is head-loading (Fig. 2, position A). The energy cost for head loading is equivalent to back loading costs as it is proportional to the increase in body mass (Lloyd et al 2010). There are exceptions to this finding, as some studies indicate that African women can carry up to 20% of their body weight without an increase in energy expenditure (Maloiy, et al., 1986). Carrying loads on the front (Fig. 2 position B) or side (Fig. 2 position G) is less costly than head or back loading (Fig. 1). Carrying children in this way is generally done with a sling, which is more efficient than carrying in the arms (Wall-Scheffler et al., 2007). Carrying a single load in both arms is more costly than spreading the mass out into equal smaller weights carried in each hand (Watson et al., 2008).

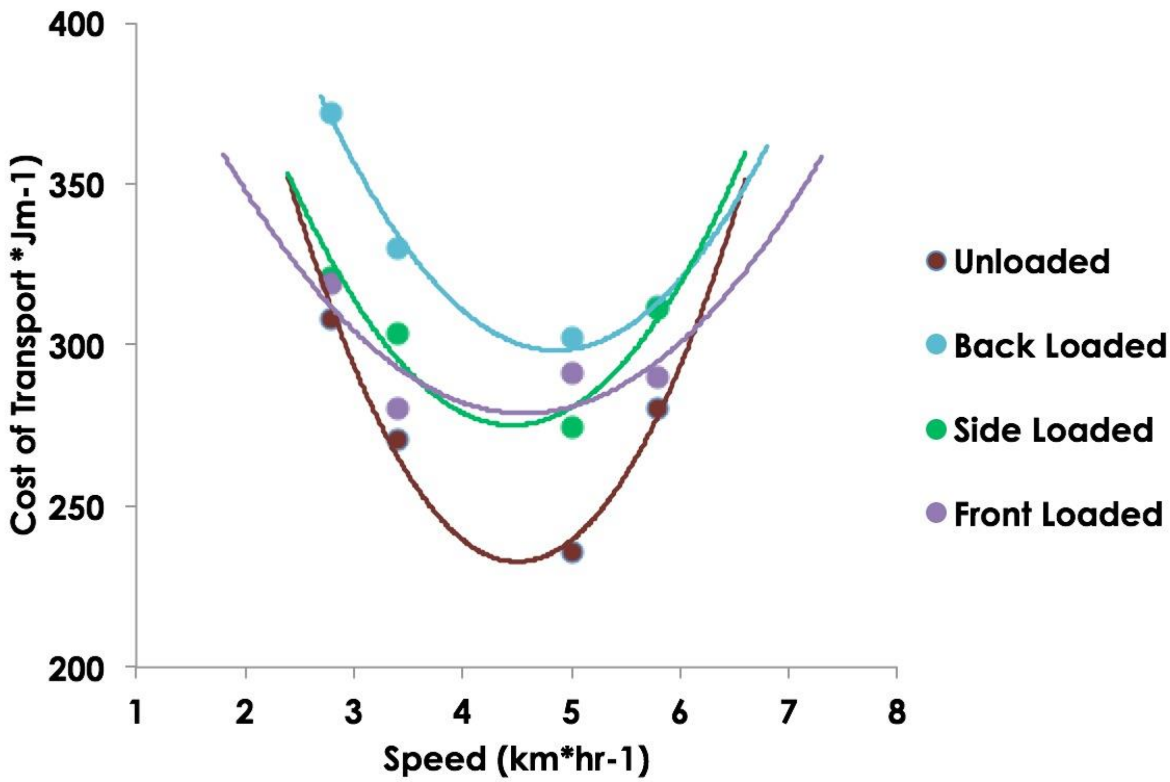
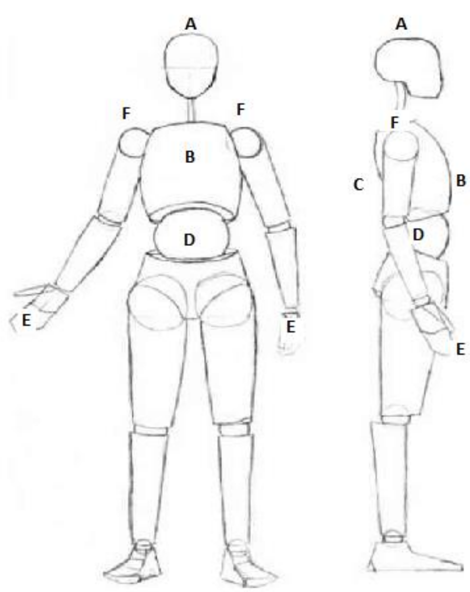


Figure 1: Comparison of energy expenditure while walking either unloaded or loaded with a weight in various positions (Unpublished data, Wall-Scheffler).

When the mass carried is a human child, strategies for carrying become especially important as children become larger and more of an energetic burden, because human children cannot contribute to their own transportation in the same way that other mammals can (Rheingold and Keene, 1965). The carrying strategies employed for children differ from carrying strategies for inanimate objects, particularly for men (Rheingold and Keene, 1965). Since men and women are of different sizes (in any given human population), and the cost of carrying seems to depend upon the percentage of body mass of a given load, it is reasonable that men and women might choose different strategies of carrying. Even within the energy rich environment of American culture, given the evolutionary history of unstable and unpredictable resources, we predict that adults will still tend to make energetically favorable choices in carrying children, which include men carrying heavier children, and as a child's age and mass increases, tools should be used more for transportation. Additionally, due to the unpredictable nature of resource acquisition, humans may be particularly good at stylizing for variable environments (Potts, 1998) and minimizing energy expenditure (Selinger et al. 2015).

One means of minimizing energy expenditure might be by pushing a stroller instead of carrying an infant. Though limited data have been collected on the energy cost of pushing a carriage, it is assumed to be less costly than carrying the child on the body. An additional means of minimizing energy expenditure would be using multiple tools for carrying. With multiple tools, adults should increase their options for transporting children by being able to switch between postures that might cause fatigue if used for too long. By using more tools, or using tools that minimize the cost of moving with children, people might both reduce costs and increase the amount of time they can travel with a burden.

However, factors beyond energy cost could influence the carry style used. One factor is the size of the child, as it will dictate the types of carriers the child will fit into, what will be most comfortable for the child, and how long a position can be used before the adult fatigues. Comfort level of the adult can be another factor influencing carry position used. Different tools or carrying positions will place strain on different areas of the body, which could potentially affect an adult's decision to use a one carrying strategy over another. Further, available tools can differ based on location. These factors may outweigh the choice for energetic savings, causing adults to transport children in less efficient ways.



Carry position (from least to most costly)	Effect on energy cost
F-shoulders	Less costly than front loading
B-front loading	Less costly than head or back loading
A-head carry	Increase proportionally to mass increase
C- back loading	Increase proportionally to mass increase
E- arms	Cost increase is greater than proportional to mass increase
D- around center of mass	Most efficient, also most impractical

Figure 2: human analog showing the potential options for carrying that come with bipedalism. Objects can be loaded on the head (position A), front-loaded (position B), back-loaded (position C), around the center of mass (position D), in the arms or hands (position E), on the shoulders (position F), or on the side (position G). Table summarizes the carry positions in order of least to most costly and indicates what is known on the specific energy costs.

Materials/Methods

This study was approved by Seattle Pacific University's IRB. All people who were approached were given a flyer containing information about the study and contact information regarding their rights as potential participants in a research study.

236 adult males and 314 adult females were observed walking around parks in Seattle, WA, during summertime while carrying a child. When an observer noticed a dyad, an adult carrying a child, with or without a baby carriage, the observer would note how the adult was transporting the child, what tools were available to carry the child, and other objects carried by the adult. The observer then approached dyad to explain the study to the adult and ask if the adult could answer a few questions. People generally responded favorably and answered questions relating to the adult's relationship to the child, the adult's handedness, and the child's sex, age. By the end of the study the observer would also ask about parity.

Data were analyzed within SPSS by use of one-way ANOVA for single vs. dual tool use and t-tests for sex differences and age category vs. number of tools used. All carriers were analyzed together for overall trends and sex differences, and then carriers were split into single tool use and dual tool use, and were analyzed for tool use trends. A carrier was considered to be using a single tool if the child was observed to be carried in one position, and the individual did not have a second tool on them. A carrier was considered to be using dual tools if the child was observed to be carried in more than one position. Dual tool use was also assumed if the adult had more than one tool (i.e. both a carriage and a sling, or if child was carried in the arms but the carrier also had a carriage or a sling).

Results

Overall Patterns

We noticed differences in the carrying patterns of men and women. Overall, more women were observed carrying children than men (314 women vs. 236 men). We observed a significant ($p < 0.001$) difference in the sex of the child carried by men versus women. If a male adult was carrying, he was carrying a male child 71% of the time. If a female adult was carrying, she was carrying a female child 61% of the time (Fig 3). Males were also more likely to carry the older, heavier babies while females were more likely to carry younger babies. More babies (0-6 months) were observed to be carried than other ages.

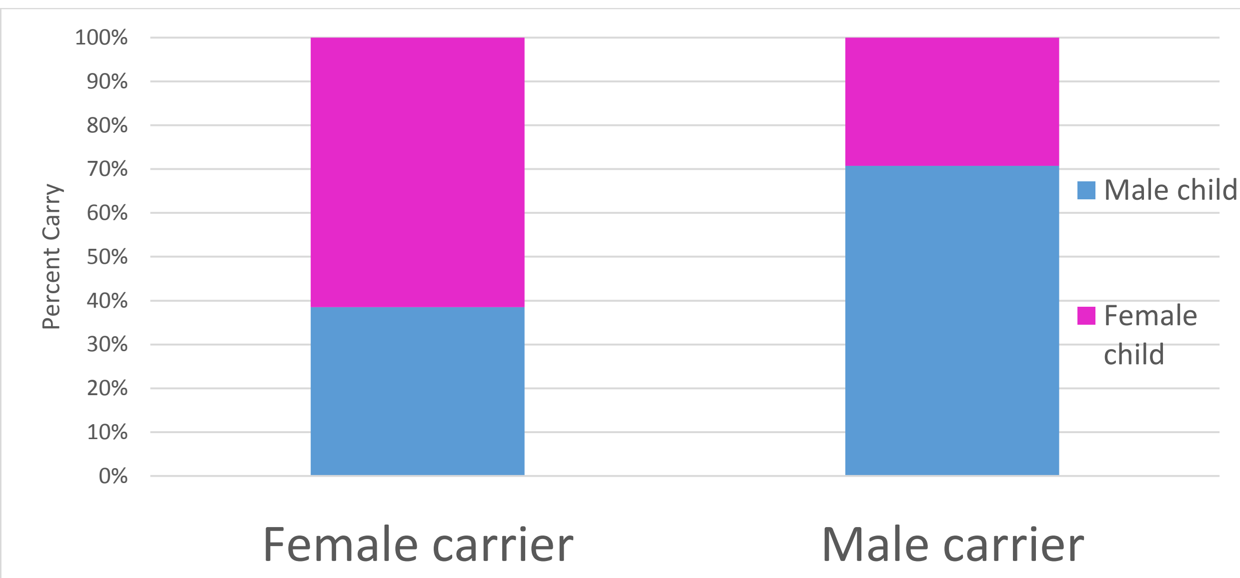


Figure 3: When carrying, percentage of time each sex of child was carried by male (n=236) and female (n=314) carriers. Difference between sexes carried is significant ($p < 0.001$).

Overall, the use of carriage stayed constant across age categories (Fig 4), indicating that if an individual was going to use a carriage, they would use it to carry the child no matter the child's age. However, when carriage use was broken into either single tool use or use with another carrying tool, different patterns emerged.

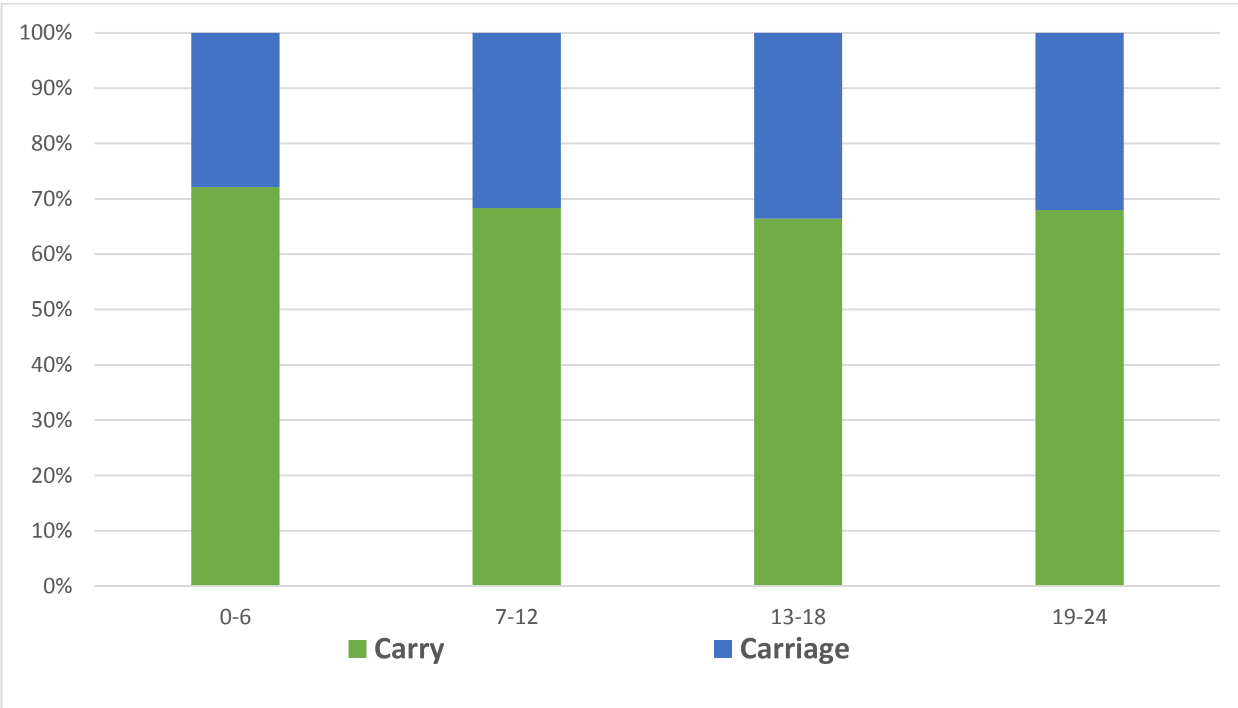


Figure 4: Breakdown of the percentage of children carried by adult (n=371) versus being pushed in a carriage (n=165) for each age category.

Tool Flexibility Results

When tool use was examined, 33% of individuals carrying infants 0-6 months old used dual tools in transporting the child. One third of carriers with infants 0-6 months employed dual tools, as most people with newborns used both a carriage and a sling. Following this, dual tools decreased to 21% at 7-12 months, but then increased significantly as the child's age increased ($p < 0.001$) (Fig 5).

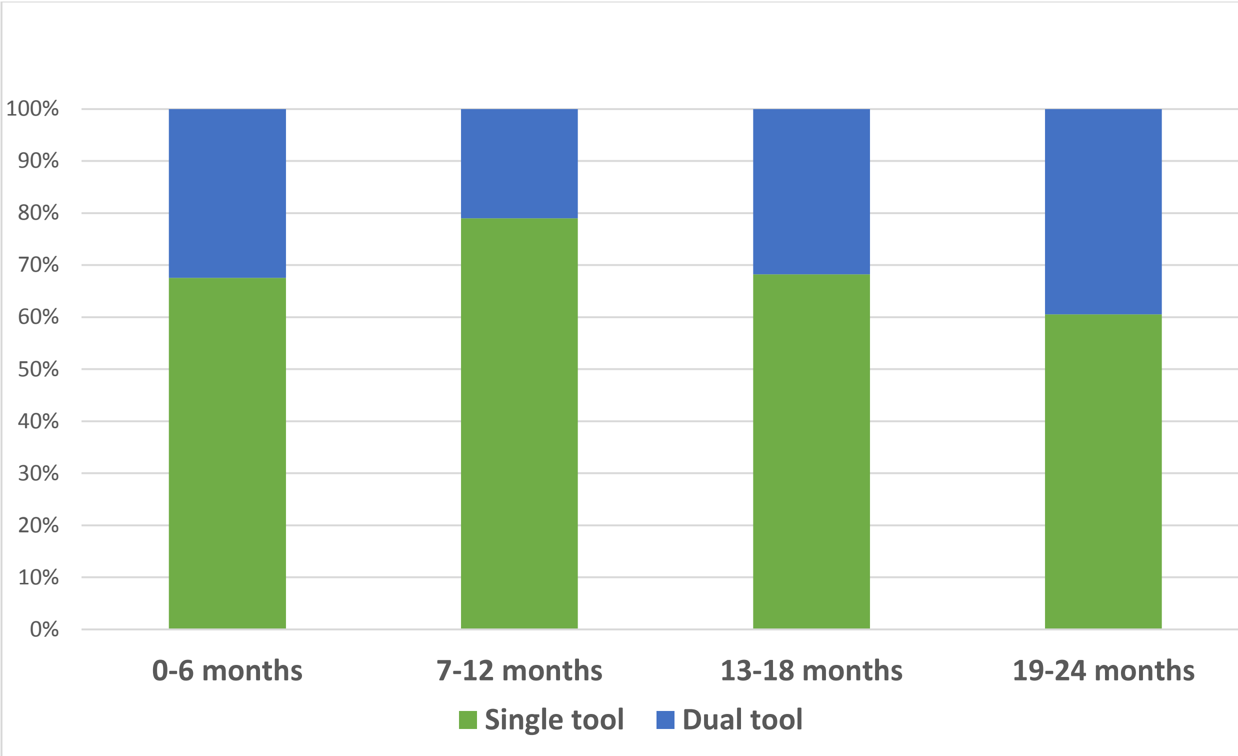


Figure 5: comparison of single vs dual tool use in participants observed. There was a significant ($p < 0.001$) increase in dual tool use between 7-12 months and 19-24 months. There was also significant increases between 7-12 and 13-18 months ($p < 0.001$) and between 13-18 months and 19-24 months ($p < 0.05$)

Single Tool Behavior

When individuals were observed using only one tool, use of a front sling decreased as the child's age increased. Use of arms increased as age increased. Shoulder and back sling stayed constant. Carriage use stayed constant after 7 months (Fig 6).

Trends of personal preferences of carrying tool were found to be different depending on the child's age category. When an individual used only a single tool to carry the child, infants (0-6 months) were more likely to be carried on the front in either the arms or a sling. The use of a either a front or back sling decreased as the child's age increased. Infants 0-6 months were less likely to be transported in a carriage. After the 0-6 month stage, the child was mostly carried in the arms or pushed in a carriage. The use of arms and carriage increased as the child's age increased. The use of shoulders stayed constant across all age categories (Fig 6).

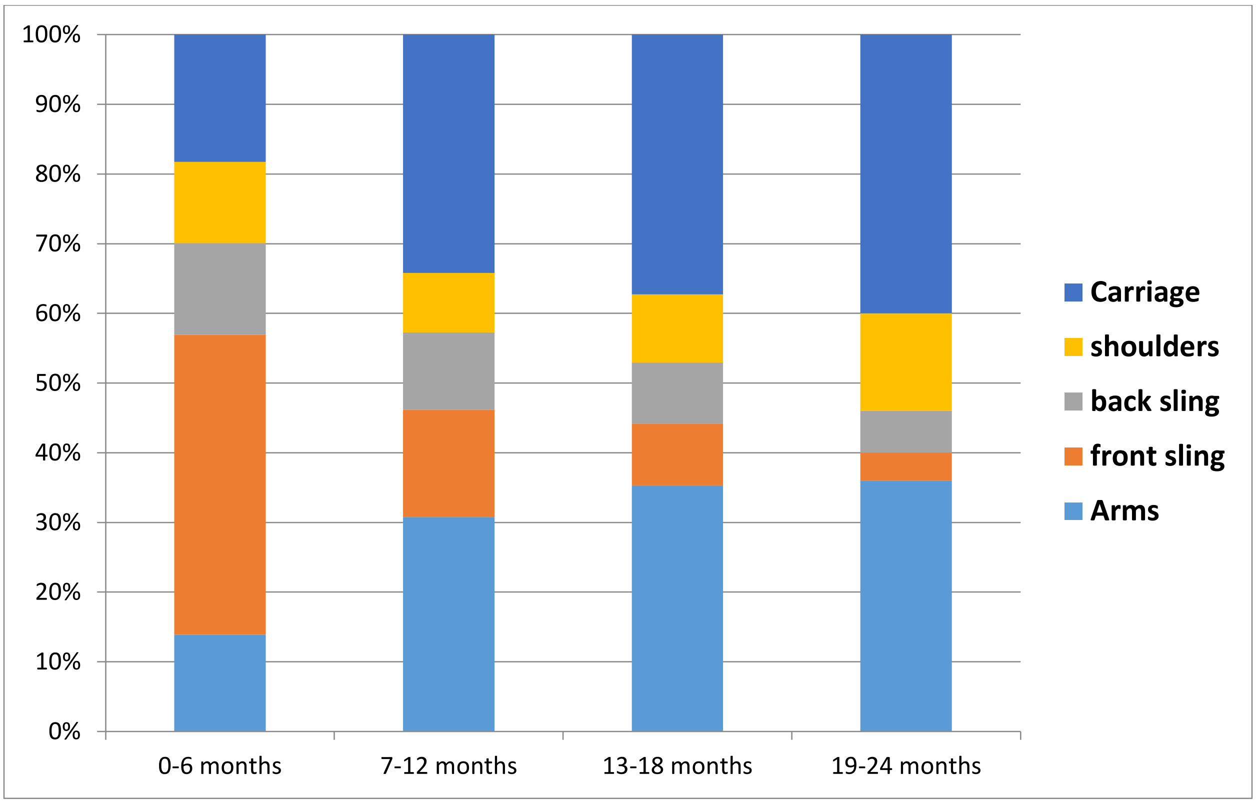


Figure 6: Position of carry for each age group when only one tool was being used. Shoulder and back sling use stayed constant. Front sling use decreased with increasing child age. Arm and carriage use increased as child age increased.

<u>Dual Tool Behavior</u>

When an individual used dual tools for carrying, carrying trends were different than the trends for single tool use. Carriage use as a resource was much more common with children 0-6 months than carriage use as a single tool for that age range. From 7-12 months carriage use decreased, then it increased with age. Carriage use as a second tool also increased with the child's age. Front sling use increased with the child's age. Carrying in the arms was most common at 7-12 months, and then decreased as the child's age increased. Back sling and shoulder use remained constant across the age groups (Fig 7).

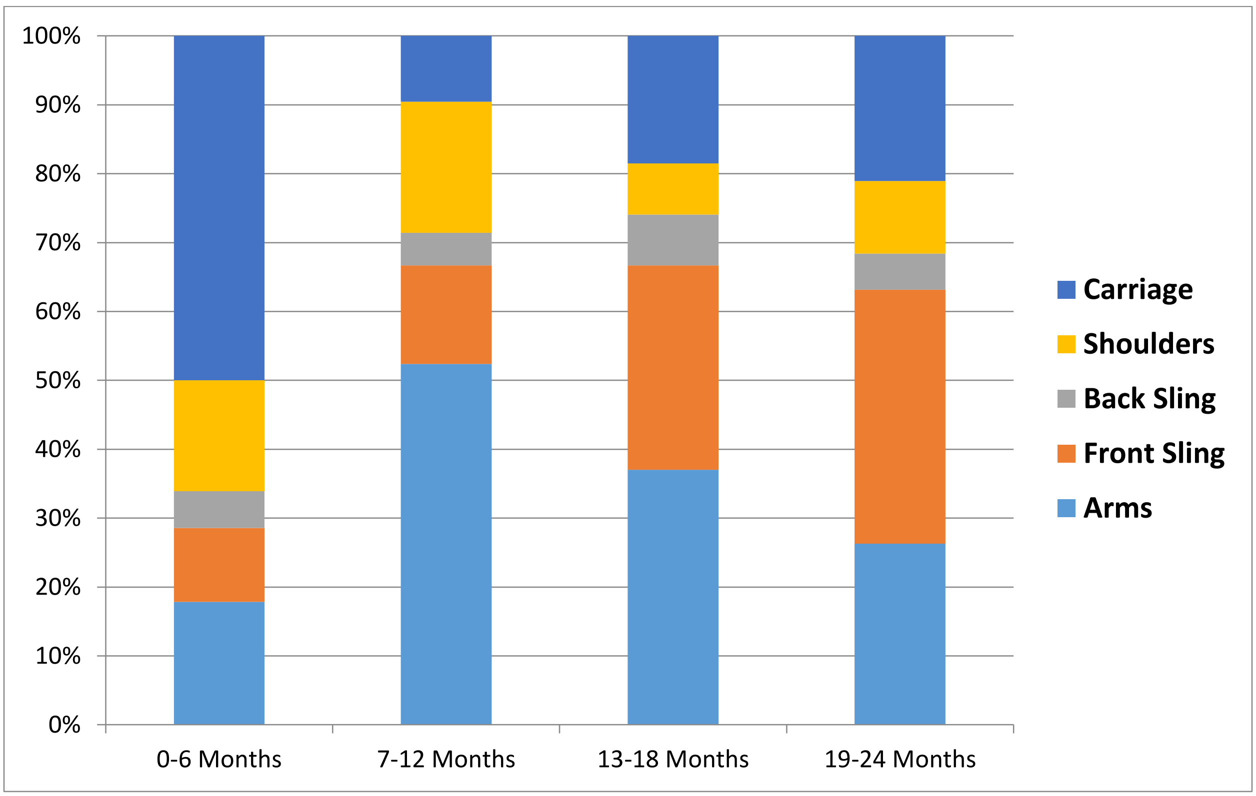


Figure 7: Position of carry for each age group when dual tools were used to carry child. Shoulder and back sling use stayed constant. Front sling use increased. Carriage use decreased for 7-12 months then increased with age. Arm use decreased as child's age increased.

Discussion

Males and females showed different carrying strategies for managing the energetic load of children. Females, especially mothers, potentially carry children more often than males for social and cultural reasons. Men naturally carrying male children more often than female children could be influenced by father-son bonding, as 92% of observed males were fathers. However, it is also energetically favorable to allow the men to carry the older and heavier children, as this reduces the energetic burden of the lactating mother.

All carriers also showed some similar general trends when examined as using either single or dual tools. Front slings were favored over back slings for both categories. A back sling is more energetically costly than a front sling (Fig. 2), and as such, front slings are a more energetically efficient choice. Carrying on the front of the body also allows for bonding with the child. Skin-to-skin contact, especially for the first months of life, have been shown to improve mother-child interactions and newborn health (Moore et al., 2009). Carrying a child in a front sling or in the arms rather than on the back would be favorable both energetically and socially, so it is reasonable that front-loading happened more often than back-loading.

Shoulder carry was the least popular way of carrying (Fig. 6 and Fig. 7), most likely because of the increased fatigue caused by holding the arms above the head for long periods of time. As loading on the shoulders requires the infant to have considerable head control, which comes for most children around 6-9 months (Important Milestones: Your Baby at 9 Months, Centers for Disease Control and Prevention), it would not be the most useful strategy for carrying children. Further, placing a baby on the back does not allow for contact with the child, and the child does not have visibility of where he or she is going. Carrying on the shoulders or in a back sling is less optimal for both energy expenditure and social bonding.

For both single and dual tool use, the 0-6 month carrying patterns varied widely from the trends starting at 7 months and continuing as the child's age increased. Since more than one-third of all child deaths before the age of five happen within the first month of life (Child Mortality, World Health Organization), the focus of a having child in the 0-6 month age category will simply be to keep the child alive and to build a routine with a new infant. The carrying patterns of this age group have the potential to be wildly different from the carrying trends of the other age groups. After a child reaches the 7-12 month category, carrying patterns reset and a general trend is seen in carrying patterns as the child's age increases.

Most individuals utilized only a single tool (Fig. 8). When the single tool used was a carriage, or a sling, the carrier was making an energetically efficient choice compared to carrying in the arms. Both a carriage and a sling can also become dual tools when the carrier also uses their arms or allows older children to walk on their own. At least half the individuals using a single tool used either a carriage or sling across all age categories, indicating that people are taking energetically efficient steps.

A front sling was the most popular single tool choice for infants, but decreased as the child became older (Fig. 6), possibly for comfort as older children are less still and more awkward to carry in a sling. Once a child moved into the 7-12 month category, a carriage or arms was used most often to transport the child. Both carriage and arm use increased as the child's age increased.

Arm use matched carriage use as the most used tool at 13-18 months and 19-24 months (Fig. 6). This is the age at which children are able to walk on their own (Important Milestones: Your Child at Eighteen Months, Centers for Disease Control and Prevention). Consequently, arm use for carrying older children can be seen as an energetically favorable choice if the child is also allowed to walk on his or her own. Energy is a limited resource, even in nutrient-rich environments, (Smith, 1983), and until a child is completely weaned, the mother provides all of the child's nutrition and therefore indirectly provides the child's energy. After the child is weaned, the mother is still in charge of providing the child's energy indirectly (Kramer, 1998). Since the mother is the source of the child's nutrition (and therefore energy), it is energetically favorable to allow the child to walk separately unless the child and mother together expend more energy than the mother would carrying the child (Kramer, 1998). However, when children are learning to walk, they fatigue quicker than adults and will need to be transported some of the time. The use of arms for transportation would allow for the child to walk on their own, but for the adult to carry the child when the child became tired. Allowing the child to walk would decrease the energetic burden on the carrier (Kramer, 1998) and make the carrying older walking children in the arms part-time more energetically favorable than for carrying younger children only in the arms. This system will provide flexibility for the carrier as well as allow the child to use some of the energy stores that otherwise would go unused. Transporting older children in the arms can be more energetically efficient than transporting an inanimate object in the same position.

Flexibility for the carrier in terms of multiple options for carry is important for reducing metabolic costs. In a laboratory setting, constraints in gait and speed, such as walking on a treadmill, has been shown to increase metabolic costs required for transport (Myers et al., 2016). When a load is added flexibility becomes more important for reducing energy expenditure. When the carrier gets tired of transporting the child in one position, they can switch the child to a new position. This increase in flexibility is especially important as the child's age and subsequent energetic burden increases.

Dual tools changed the way the oldest children were carried, and these changes reflected added flexibility to move the child to a different position when an individual gets tired. When dual tools were employed, a carriage along with another tool was the most common for 0-6 month category. The use of a carriage as a second object can allow the carriage to function as a “shopping cart” in which to carry diapers, snacks, toys, and other necessary supplies. A front sling can also be used in that way, and was used more often as a dual tool than as a single tool. When using dual tools an individual can use the arms less frequently, which allows for a decrease in energy expenditure when carrying a child. As the child’s age increased, the use of arms decreased and the use of slings increased, which is an energetically favorable trade (Wall-Scheffler et al., 2007). The use of a carriage or sling as a second tool could also be utilized to carry a second child, however not enough data were collected on parity to conclude dual tool use for carrying another child.

As the age of the child being carried increased, there was a significant increase in the amount of tools being used. If only one tool was used, there was a natural increase in arms, and therefore in allowing children of walking age to walk by themselves. This study indicate that humans have a natural inclination to adapt to more energetically favorable carrying styles as the energetic burden of a child’s weight increases. This result is consistent with Selinger et al. (2015) who showed that people, when given the option, people will tend to make more energetically efficient movements. However, we observed that some people are willing to pay extra energy costs, possibly to increase social bonding and physical contact by keeping the child in the arms or a sling as the child becomes older, or possibly because a more costly form of transport was more comfortable. Further research should be done on the social and cultural factors involved in child carrying in public to define the factors other than energy cost that contribute to load carrying decisions.

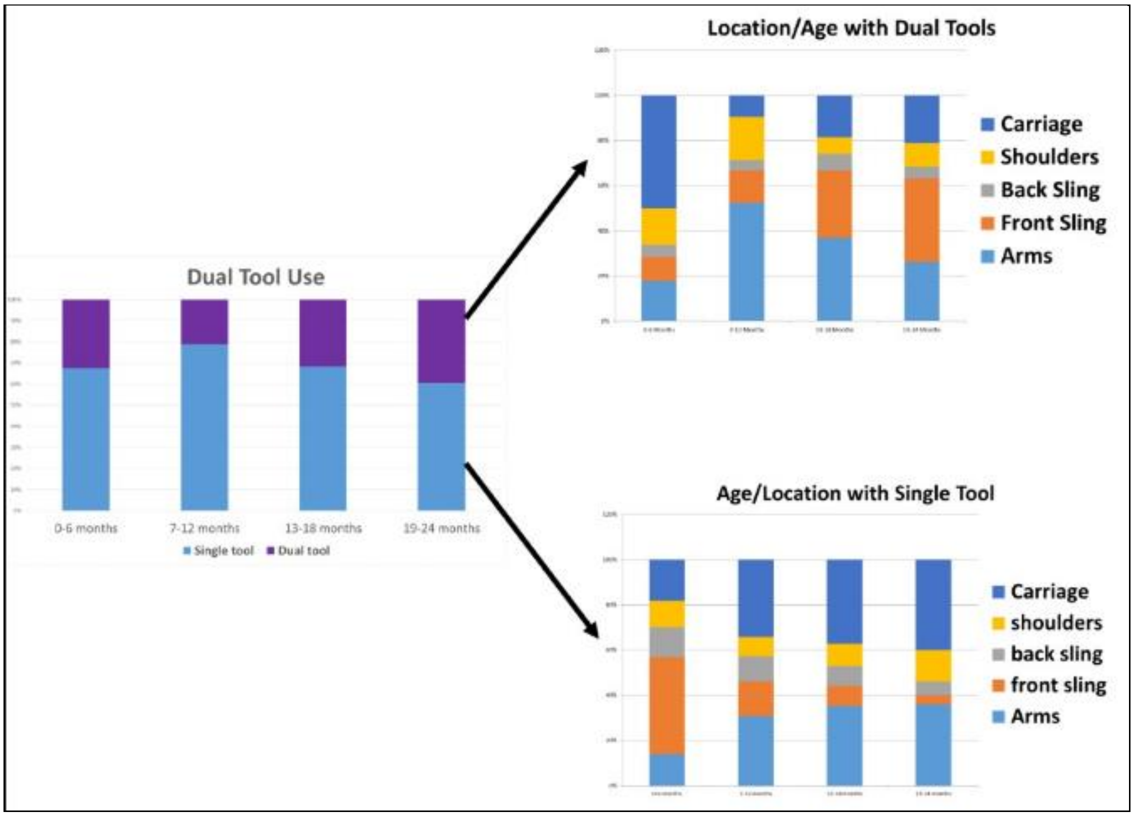


Figure 8: Visual breakdown of the single and dual tool use categories by tool used.

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Appendix on Faith and Learning

In 21st century America, the standard source for all knowledge is science. To convince an audience that something works, it must be corroborated by research findings. The discipline of science, as employed by the scientific method, is characterized by a systematic way of collecting data, analyzing it, and turning that data into facts. With an intense focus on provable natural phenomena, it is easy to believe the notion that there is no longer a place for faith in an academic and scientific society. Yet science and faith are not mutually exclusive. Both disciplines are examining the world, but approach with different methods and sometimes even different questions. Both are different ways of getting at Truth, and both have a place in intellectual society.

The way that faith plays into my personal practice of the scientific discipline is by giving me passion. My faith has given me a passion to learn more about God, and more about the world God created. As Dostoevsky states in *The Brothers Karamazov,* "if you love each thing, you will perceive the mystery of God in things" (Dostoevsky 319). This passion drives me to learn all I can about the natural world, as I am able to approach and better understand the universe, which in turn allows me to better understand the mysteries of God. Allowing faith to inform science, to me, means being curious about the natural world is being curious about God, and learning more about the natural world can lead to learning more about God.

From my faith-based perspective, being engaged in scientific scholarship is necessary. God gave humanity intellect, and as such it should be used to worship God by exploring the world God created. Part of being a Christian is pursuing scholarship, and part of engaging scholarship is a natural outcome of using God-given intellect. Faith may not drive the methods of the scientific method, but it can heavily drive the questions, and it can drive the interpretation and ethics followed during the pursuit of knowledge. I view the sciences as a way of understanding more of God's world. It goes far beyond knowing and giving the right answer. It becomes understanding how and why things work, not just that they work.

Yet there is still controversy being a Christian when scientific discoveries seem to contradict the bible. The questions asked and the approach taken by each discipline are different. C.S. Lewis explained the difference while speaking about the role of science:

> Why anything comes to be there at all, and whether there is anything behind the things science observes—something of a different kind—this is not a scientific question. If there is "Something Behind," then either it will have to remain altogether unknown to men or else make itself known in some different way. The statement that there is any such thing, and the statement that there is no such thing, are neither of them statements that science can make. And real scientists do not usually make them (Lewis, 1952).

Science is not sufficient to understand the spiritual nuances of the world we live in. It was not designed to answer those questions, as it assumes natural causes to every event. In the same vein, the bible never claimed to be a scientific document, and the bible is heavily steeped in context. As Michael Polanyi argues in his book Personal Knowledge; towards a Post-Critical Philosophy, "Christian faith does not express the assertion of observable facts and consequently you cannot prove or disprove Christianity by experiments or factual records" (1958). As the aims of the biblical text are not to be a scientific document, it should not be treated as such. The bible can inform on aspects of God not discovered through the examination of the physical world and has its place in the understanding of the Creator, but it cannot replace the scientific approach to learning. Yet, even though these two disciplines are different, they are not mutually exclusive. They can inform on each other, and must be in dialogue as neither can take the place of the other.

This dialogue between faith and science is still going on in my life. As a Christian and an aspiring scientist, I am learning to allow science to shape how I view the world, and in way allow it to shape my faith and how I interact with God. I am also learning how my faith can shape and inform on the way I ask questions and approach science. That doesn't mean that I explain everything that I see in the world by a supernatural cause. There are some ways that faith does not need to be brought into the scientific interpretation. Science is trying to answer questions about the natural world through natural phenomena. Faith-informed pursuit of science does not push God out of the picture of science, but rather it uses science to understand more about God by examining the universe God established.

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