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The purpose of this study was to determine the effects of age, load amount and load symmetry on lower extremity kinematics during carrying tasks. Forty-two participants in four age groups (8–10 years, 12–14 years, 15–17 years and adults) carried loads of 0%, 10% and 20% body weight (BW) in large or small buckets unilaterally and bilaterally. Reflective markers were tracked to determine total joint range of motion and maximum joint angles during the stance phase of walking. Maximum hip extension, hip adduction and hip internal rotation angles were significantly greater for each of the child/adolescent age groups as compared with adults. In addition, maximum hip internal rotation angles significantly increased when carrying a 20% BW load. The observation that the 8–10-year-old age group carried the lightest absolute loads and still displayed the highest maximum hip internal rotation angles suggests a particular necessity in setting carrying guidelines for the youngest children.

Statement of Relevance: Bucket-carrying tasks were analysed as a function of age group, load amount and load symmetry. Hip joint rotations significantly increased when carrying 20% BW loads and in children as compared to adults, which suggests a particular necessity in setting carrying guidelines for the youngest age group (8–10 year olds).

Keywords: biomechanics; gait; load carriage; youth

1. Introduction

According to the United States Department of Agriculture (2004), children suffered 23,000 agricultural-related injuries in 2001. Studies involving children participating in agricultural work have often focused on fatal and/or traumatic injuries (Rivara 1985, Bancej and Arbuckle 2000, Reed and Claunch 2000, Gerberich *et al*. 2001). To avoid hazardous activities, children commonly perform animal care tasks that are deemed to be relatively safe, such as carrying feed and water, lifting bales and spreading bedding (Marlenga *et al*. 2001, Allread *et al*. 2004). However, these tasks may require children to carry loads asymmetrically that are proportionally large and/or heavy. Children do work with adult equipment or perform tasks designed for adults who are larger and stronger (Miller and Kaufman 1998, Allread and Waters 2007). Thus, children may suffer musculoskeletal disorders due to a lack of strength or because they are still developing the movement skills to perform these challenging tasks. One study found sprains/strains to be the most common type of farm injury and the upper limbs, lower limbs and back to be the most commonly affected sites (Pickett *et al*. 1995). Similarly, surveys of farm children have found that muscle strains of the legs, arms, shoulders and back are considered everyday occurrences (Bartels *et al*. 2000). A field study

confirmed that farm children perform lifting and carrying motions that are equivalent to those associated with high injury risk jobs in industry (Allread *et al*. 2004).

Farm children and adults have been studied to determine the effects of different bucket-carrying tasks on upper extremity and low back moments (Gillette *et al*. 2009). The 8–10-year-old age group displayed lower maximum normalised shoulder abduction and L5/S1 lateral bending moments than adults across carrying conditions. One explanation for these results is that the 8–10 year olds were able to compensate for smaller anthropometry by altering their carrying technique and upper body posture. What remains unknown is whether simultaneous adjustments in lower body kinematics are also required.

Prior studies suggest that whole body gait parameters do not necessarily change in adults when carrying a load. Unilateral load carrying at 15% body weight (BW) produced only minor changes in walking speed and stride frequency as compared to unloaded gait in adults (Crowe and Samson 1997). Similarly, walking speed and stride frequency were not significantly different for unilateral carrying (average 20% BW) and bilateral carrying (average 38% BW) as compared to unloaded gait in adults (Nottrodt and

Manley 1989). Previous studies were inconclusive as to whether or not whole body gait parameters change in children when loads are carried. For example, decreased stride length and increased stride frequency were observed for 11–13 year olds carrying one-strap backpacks at 17% BW (Pascoe *et al.* 1997). In addition, increased stance duration was reported for 10-year-old boys carrying dual-strap backpacks when walking on a treadmill at 20% BW loads (Hong and Brueggemann 2000). However, another study did not find significant differences in walking length and stride frequency for 9–10-year-old boys carrying dual-strap backpacks over ground at 20% BW (Hong and Cheung 2003). When focusing on individual joint kinematics, increased hip sagittal range of motion (RoM) and maximum hip adduction during stance were reported for adolescent girls carrying dual-strap backpacks at 15% BW (Chow *et al.* 2006). Thus, it appears likely that children do alter their joint coordination during carrying tasks, but few studies have examined lower extremity kinematics across a range of ages and different loading conditions.

One potentially confounding variable in the assessment of load-carrying tasks is physical maturation. When adjustments were made for body size, changes in stride frequency as a function of walking velocity during unloaded gait were found to be similar when comparing children 4–10 years old with adults (Zijlstra *et al.* 1996). Similarly, a review of youth gait concluded that adult-like walking velocity and stride frequency are achieved by 4 years of age when adjusting for leg length (Sutherland 1997). This review also reported differences in joint coordination, in that younger children use hip flexors/extensors more and ankle plantar flexors less than adults to achieve similar whole body gait parameters. Another study found that 7-year-old children have similar hip and knee joint angle patterns to adults during gait, but reported reduced ankle control (Ganley and Powers 2005). Taken together, these studies indicate that while children's normalised whole body gait parameters may be similar to adults, children may rely more on control of hip rotations to achieve these patterns. There also appears to be a relative lack of joint kinematic data comparing children and adults in the frontal and transverse planes during carrying tasks. Compared to unloaded gait, the additional strength and balance challenges of bilateral and unilateral load carrying may magnify kinematic differences between children and adults.

Changes in lower extremity kinematics from unloaded gait to carrying tasks indicate that adjustments were necessary to complete the movement. Adjustments that bring joint rotations near the limits of their ranges of motion are of particular concern in regard to soft tissue strains and injury. Ultimately,

changes in lower extremity kinematics may be a factor to consider when developing load-carrying guidelines for children. For load amount, studies discussed above suggested that loads carried should not exceed 10–15% BW in children (Hong and Brueggemann 2000, Hong and Cheung 2003). Similarly, the North American Guidelines for Children's Agricultural Tasks recommend limiting children's work that involves lifting and moving objects greater than 15% BW (Lee and Marlenga 1999). However, field data suggest that these standards are exceeded for children during common farm tasks (Allread *et al.* 2004). For load asymmetry, unilateral carrying may increase frontal plane motion. In addition, unilateral carrying of a proportionally large bucket positions the load further from the body and may further increase frontal plane motion. These factors are in need of more investigation for children participating in agricultural work.

The purpose of this study was to determine the effects of age, load amount and load symmetry on lower extremity kinematics during carrying tasks in adults and in children at different ages. Consistent with increased use of hip flexors/extensors in young children (Sutherland 1997) and increased hip sagittal plane RoM during dual-strap backpack carrying (Chow *et al.* 2006), the first set of hypotheses was that 8–10 year olds would display increased hip sagittal plane RoM and greater maximum hip flexion angles during bucket carrying as compared to adults. Consistent with potentially reduced ankle control in children (Ganley and Powers 2005) and frontal plane loading asymmetry during bucket carrying, the second set of hypotheses was that 8–10 year olds would display increased ankle frontal plane RoM and maximum ankle eversion angles during bucket carrying as compared to adults. Carrying greater load amounts unilaterally in larger buckets was expected to be the most challenging tasks for all participants in this study, particularly for the youngest age group.

2. Methods

2.1. Subjects

In total, 42 participants in four age groups (8–10 years, 12–14 years, 15–17 years and adults between 21 and 26 years) volunteered for this study. These individuals were a subset of a larger pool of 72 participants over a 3-year period who had their upper and/or lower body biomechanics analysed during carrying tasks. Each individual provided informed consent as approved by the Office of Research Assurances prior to taking part in the study. Parental informed consent was also obtained for the minors participating in the data collection. Children were recruited through the county extension offices and the local 4-H chapters, which are

youth organisations sponsored by the United States Department of Agriculture, where participants regularly perform farming tasks. Gender distributions, average age, average height and average mass for each age group are presented in Table 1.

2.2. *Experimental protocol*

Two sizes of buckets were carried: large 5-gallon (18.9 litre volume, 36.8 cm high, 30 cm diameter); small 1-gallon (3.8 litre volume, 19.5 cm high, 16.7 cm diameter). The buckets were filled using sealed bags of lead shot amounting to three levels of load based on BW, 0%, 10% and 20% BW, in addition to the weight of the bucket. Unilateral carrying tasks were performed with both large and small buckets, while bilateral carrying tasks were only performed with small buckets. Bilateral carrying with large buckets was not performed due to the difficulty observed in some 8-year-old children completing this task during initial testing and due to potential fatigue considerations limiting the number of conditions. In Figure 1, a representative 8–10-year-old child and an adult are

shown carrying a large bucket unilaterally and a pair of small buckets bilaterally as an example of the experimental protocol. Nine conditions were analysed: unilateral large 0% BW; unilateral large 10% BW; unilateral large 20% BW; unilateral small 0% BW; unilateral small 10% BW; unilateral small 20% BW; bilateral small 0% BW; bilateral small 10% BW; bilateral small 20% BW buckets. Buckets were carried unilaterally with the self-selected dominant hand and the load was evenly split between the buckets during the bilateral conditions. Three repetitions of the nine conditions were completed and the order of the trials was balanced to reduce potential effects of learning and fatigue.

2.3. *Lower extremity kinematics*

Participants carried the buckets 6 m at a self-selected walking speed while reflective markers were tracked by an eight-camera Peak Motus motion analysis system (Vicon, Centennial, CO, USA). The marker set included bilateral toes, heels, lateral malleoli, medial malleoli, distal calves, lateral knee joint lines, medial

Table 1. Subject characteristics.

| Age group | Gender | | Age (years) | Height (m) | Mass (kg) |
	Male	Female			
8–10 years	6	1	9.0 ± 1.0	1.37 ± 0.09	31.2 ± 6.4
12–14 years	6	4	12.4 ± 0.8	1.55 ± 0.07	47.1 ± 7.9
15–17 years	5	4	16.0 ± 0.9	1.67 ± 0.10	61.1 ± 9.7
Adult	9	7	23.2 ± 1.6	1.76 ± 0.09	72.4 ± 12.9

Note: Mean values are reported for each age group with standard deviations.
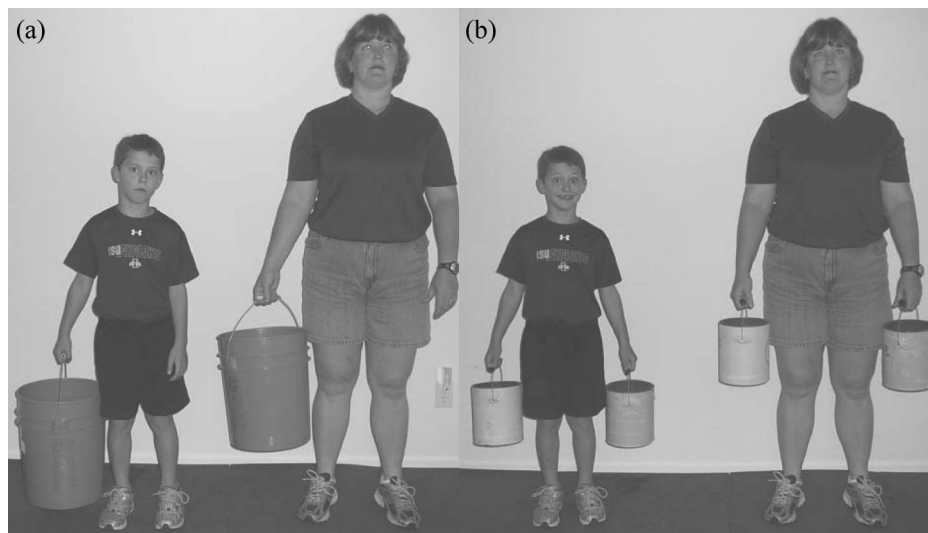

Figure 1. A representative 8–10-year-old child and an adult are shown in (a) the unilateral large bucket-carrying condition and in (b) the bilateral small bucket-carrying condition.

knee joint lines, distal thighs, greater trochanters and acromion processes. In addition, a single marker was placed at the L5/S1 interspace and at the supersternale. A static standing trial was captured with the full marker set and then the medial malleoli and medial knee joint line markers were removed to avoid contact while carrying buckets. The relative marker positions for the medial malleoli and medial knee joint lines were determined in reference to the lateral malleoli, distal calves and lateral knee joint lines. During the dynamic experimental trials, the medial malleoli and medial knee joint line marker positions were recreated using these static standing trial transformations. The video data were collected at 120 Hz and noise was reduced with a fourth-order, low-pass Butterworth filter at a cut-off frequency of 6 Hz.

Lower extremity kinematics were analysed during the stance phase of the dominant foot (side of unilaterally carried loads) near the halfway point of the 6-m walking path. Initiation of the stance phase was detected when either the dominant toe or heel marker lowered from the swing phase to a point within 1 cm of the vertical static trial positions of these markers. Similarly, termination of the stance phase was detected with both the dominant toe and heel marker lifted to a point 1 cm above the static trial vertical marker positions. The ankle joint centres were estimated as the midpoint of the lateral and medial malleoli and the knee joint centres as the midpoint of the lateral and medial knee joint lines. Right and left trochanter markers were used to find the midpoint of the hip joints (mid-hip) and the hip joint centres were located at the midpoint between the trochanters and the mid-hip. Joint angles were defined as three successive rotations: flexion/extension; abduction/adduction; internal/external rotation. The static standing trial was used to define the anatomical neutral position, which was used to adjust the joint angle values calculated for the experimental carrying trials. Maximum joint angles for ankle plantar flexion/dorsiflexion, ankle inversion/eversion, knee flexion/extension, hip flexion/extension, hip adduction/abduction and hip internal/external rotation during the stance phase were determined. Ankle sagittal RoM, ankle frontal RoM, knee sagittal RoM, hip sagittal RoM, hip frontal RoM and hip transverse RoM were each determined as the difference between the maximum joint angles in opposing directions. All calculations were performed in MatLab (Natick, MA, USA).

2.4. Data analysis

Trials with discontinuities due to marker obscurement were eliminated from the analysis, with total joint RoM and maximum joint angles averaged across remaining trials for each participant. Multivariate ANOVA (SPSS Inc., Chicago, IL, USA) was used to test for main effects of age group, load amount, load symmetry and their interactions. The significance level was set to $p < 0.05$ with a Bonferroni correction of six (number of dependent variables) for the total joint RoM analysis and 12 for the maximum joint angle analysis. The majority of the variables were not normally distributed about the mean values as indicated by Shapiro–Wilk tests of normality ($p > 0.05$). Therefore, when significant main effects were found, Mann–Whitney U non-parametric comparisons were made at a significance level of $p < 0.05$. Adults were compared to the 8–10, 12–14 and 15–17 year olds to test the effects of age group on total joint RoM and maximum joint angles. The 0% BW trials were compared to the 10% BW and 20% BW trials to test the effects of load amount. Finally, the unilateral small bucket trials were compared to the unilateral large bucket trials and the bilateral small bucket trials to test the effects of load symmetry.

3. Results

Total joint RoM were significantly dependent upon age group ($p < 0.01$) and load amount ($p < 0.01$), but were not dependent upon load symmetry ($p = 0.17$) or any interactions between comparisons ($p = 0.28$ and higher). Similarly, maximum joint angles were significantly dependent upon age group ($p < 0.01$) and carrying condition ($p < 0.01$), but were not dependent upon load symmetry ($p = 0.16$) or any interactions between comparisons ($p = 0.99$).

3.1. Effects of age group on total joint range of motion

There were significant differences in ankle, knee and hip sagittal plane RoM between the child/adolescent age groups and the adults (Figure 2). Ankle sagittal plane RoM was significantly lower for 8–10 year olds ($p = 0.013$) and significantly greater for 15–17 year olds ($p = 0.011$) as compared to adults. Knee sagittal plane RoM was significantly lower for 12–14 ($p = 0.042$) and 15–17 ($p = 0.028$) year olds as compared to adults. Hip sagittal plane RoM was significantly greater for 8–10 year olds ($p < 0.001$) as compared to adults. In addition, there were significant differences in ankle frontal and hip transverse plane RoM between children/adolescents and adults (Figure 3). Ankle frontal plane RoM was significantly greater for 8–10 ($p = 0.025$) and 15–17 ($p = 0.009$) year olds as compared to adults. Hip transverse plane RoM was significantly greater for 8–10 ($p < 0.001$), 12–14 ($p = 0.047$) and 15–17 ($p < 0.001$) year olds as
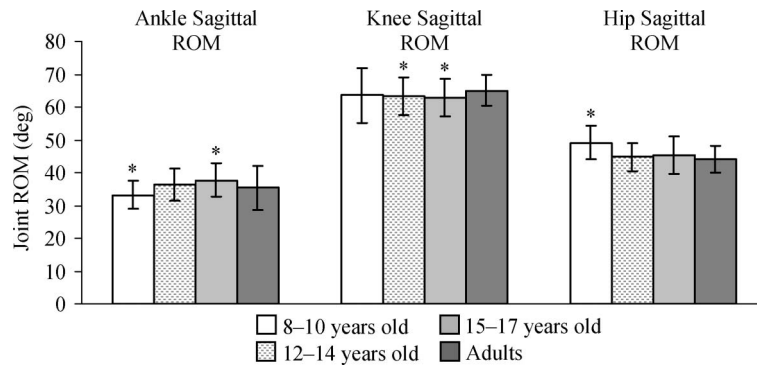
Figure 2.   Ankle, knee and hip sagittal range of motion (RoM) as a function of age group. Total joint RoM are reported as averages across carrying conditions with standard deviations. *Indicates statistical differences in total joint RoM for the child/adolescent age groups as compared to the adult age group ($p < 0.05$).
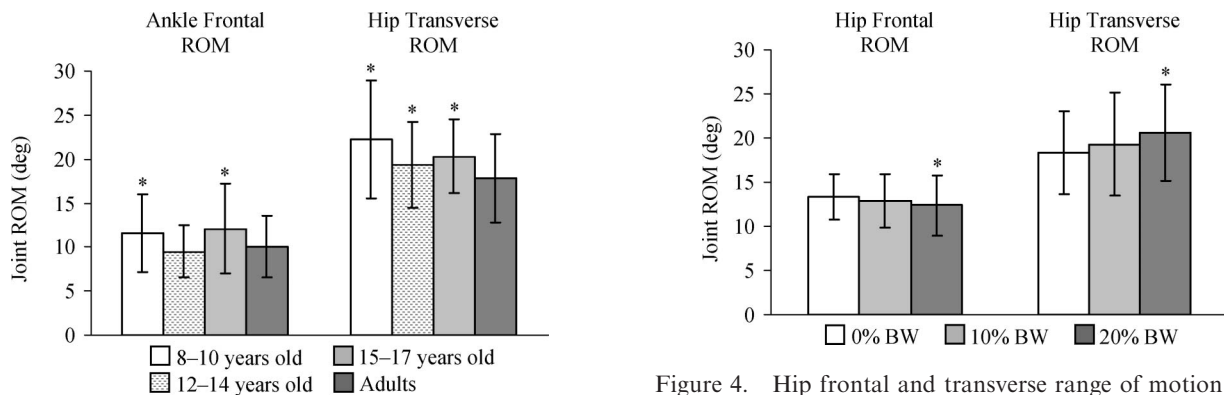

Figure 3.   Ankle frontal and hip transverse range of motion (RoM) as a function of age group. Total joint RoM are reported as averages across carrying conditions with standard deviations. *Indicates statistical differences in total joint RoM for the child/adolescent age groups as compared to the adult age group ($p < 0.05$).

Figure 4.   Hip frontal and transverse range of motion (RoM) as a function of load amount. Total joint RoM are reported as averages across age groups with standard deviations. *Indicates statistical differences in total joint RoM for the 10% and 20% body weight (BW) loads as compared to the 0% BW loads ($p < 0.05$).

compared to adults. No significant differences between children/adolescents and adults were found for hip frontal plane RoM.

3.2.   Effects of load amount on total joint range of motion

There were significant differences in hip frontal and transverse plane RoM as a function of load amount (Figure 4). Hip frontal plane RoM was significantly lower when carrying a 20% BW load ($p = 0.003$) than when carrying a 0% BW load. In contrast, hip transverse plane RoM was significantly greater when carrying a 20% BW load ($p = 0.004$) than when carrying a 0% BW load. No significant differences in RoM were found at any joint when comparing a 10% BW load to a 0% BW load. In addition, no significant differences were found for ankle RoM, knee RoM or hip sagittal plane RoM as a function of load amount.

3.3.   Effects of age group on maximum joint angles

There were significant differences in maximum ankle plantar flexion/dorsiflexion, knee flexion/extension and hip flexion/extension between the child/adolescent age groups and the adults (Figure 5). Maximum ankle plantar flexion was significantly lower for 8–10 year olds ($p < 0.001$) and was significantly greater for 15–17 year olds ($p = 0.010$) as compared to adults. Maximum ankle dorsiflexion was significantly greater for 8–10 year olds ($p < 0.001$) as compared to adults. Maximum knee flexion was significantly lower for 8–10 ($p = 0.008$), 12–14 ($p < 0.001$) and 15–17 ($p < 0.001$) year olds as compared to adults. Maximum knee extension was significantly greater for 12–14 year olds ($p < 0.001$) as compared to adults. Maximum hip flexion was significantly greater for 8–10 year olds ($p = 0.007$) and significantly lower for 12–14 ($p < 0.001$) and 15–17 ($p = 0.005$) year olds as compared to adults. Maximum hip extension was

significantly greater for 8–10 ($p < 0.001$), 12–14 ($p < 0.001$) and 15–17 ($p < 0.001$) year olds as compared to adults.

There were also significant differences in maximum ankle inversion/eversion, hip adduction/abduction and hip internal/external rotation between the child/adolescent age groups and the adults (Figure 6). Maximum ankle inversion was significantly lower for 12–14 year olds ($p = 0.004$) as compared to adults. Maximum ankle eversion was significantly greater for 8–10 ($p < 0.001$) and 12–14 ($p = 0.038$) year olds as compared to adults. Maximum hip adduction was significantly greater for 8–10 ($p < 0.001$), 12–14 ($p < 0.001$) and 15–17 ($p < 0.001$) year olds as compared to adults. In contrast, maximum hip abduction was significantly lower for 8–10 ($p < 0.001$), 12–14 ($p < 0.001$) and 15–17 ($p = 0.008$) year olds as compared to adults.

Maximum hip internal rotation was significantly greater for 8–10 ($p < 0.001$), 12–14 ($p < 0.001$) and 15–17 ($p < 0.001$) year olds as compared to adults. In contrast, maximum hip external rotation was significantly lower for 8–10 ($p < 0.001$), 12–14 ($p < 0.001$) and 15–17 ($p = 0.001$) year olds than for adults.

3.4. Effects of load amount on maximum joint angles

There were significant differences in maximum knee extension and hip flexion/extension as a function of load amount (Figure 7). Maximum knee extension ($p = 0.021$) was significantly greater when carrying a 20% BW load. Maximum hip flexion ($p < 0.001$) was significantly greater and extension ($p < 0.001$) was significantly lower when carrying a 20% BW load. In
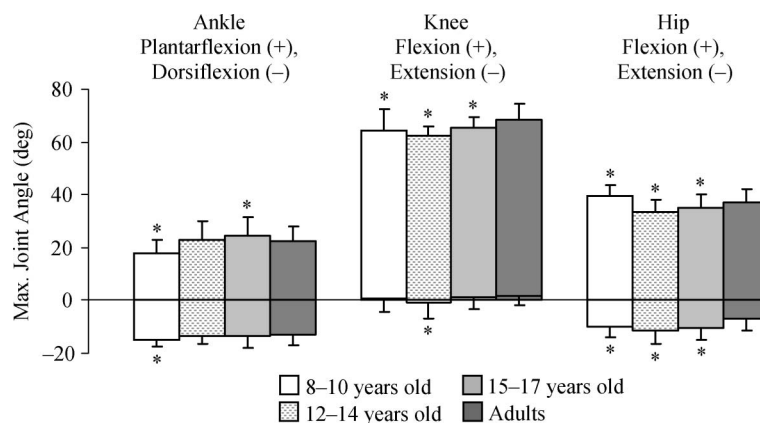

Figure 5. Maximum ankle, knee and hip flexion/extension angles as a function of age group. Maximum joint angles are reported as averages across carrying conditions with standard deviations. Labels above the graphs indicate the positive and negative angle designations. *Indicates statistical differences in maximum joint angles for the child/adolescent age groups as compared to the adult age group ($p < 0.05$).
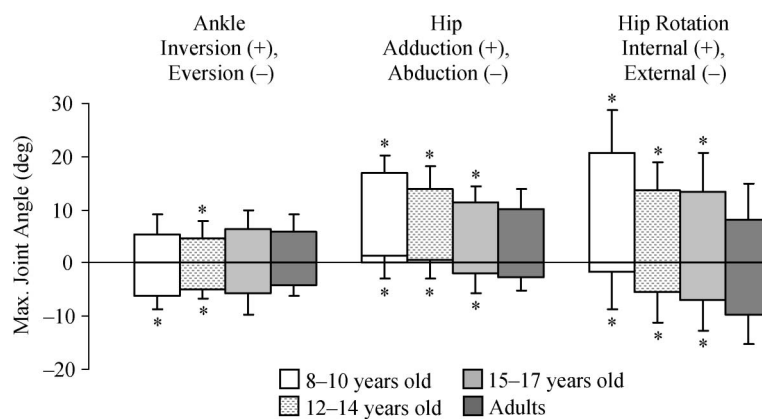

Figure 6. Maximum ankle inversion/eversion, hip adduction/abduction and hip internal/external rotation angles as a function of age group. Maximum joint angles are reported as averages across carrying conditions with standard deviations. Labels above the graphs indicate the positive and negative joint angle designations. *Indicates statistical differences in maximum joint angles for the child/adolescent age groups as compared to the adult age group ($p < 0.05$).

addition, there were significant differences in maximum hip adduction and internal/external rotation as a function of load amount (Figure 8). Maximum hip adduction ($p = 0.003$) was significantly lower when carrying a 20% BW load. Maximum hip internal rotation ($p < 0.001$) was significantly greater and external rotation ($p = 0.031$) was significantly lower when carrying a 20% BW load. No significant differences in maximum joint angles were found when comparing a 10% to a 0% BW load. In addition, no significant differences were found for maximum ankle plantar flexion/dorsiflexion, knee flexion, ankle inversion/eversion and hip abduction as a function of load amount.
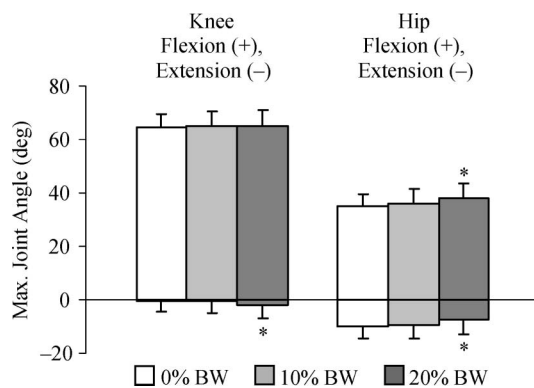

Figure 7. Maximum knee and hip flexion/extension angles as a function of load amount. Maximum joint angles are reported as averages across age groups with standard deviations. *Indicates statistical differences in maximum joint angles for the 10% and 20% body weight (BW) loads as compared to the 0% BW loads ($p < 0.05$).
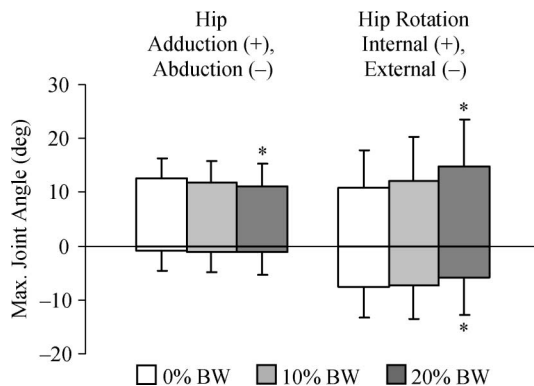

Figure 8. Maximum hip adduction/abduction and internal/external rotation angles as a function of load amount. Maximum joint angles are reported as averages across age groups with standard deviations. *Indicates statistical differences in maximum joint angles for the 10% and 20% body weight (BW) loads as compared to the 0% BW loads ($p < 0.05$).

4. Discussion

The purpose of this study was to test the effects of age, load amount and load symmetry on lower extremity kinematics. The first hypothesis was supported in that the 8–10-year-old age group had significantly greater hip sagittal plane RoM and maximum hip flexion angles when compared to adults (Figures 2, 5). One explanation for this difference as a function of age may be greater use of hip flexors and extensors by children during gait (Sutherland 1997). It was also found that the 8–10-year-old age group had significantly greater hip extension angles as compared to adults, which further supports the greater use of hip flexors/extensors (Figure 5). In a study of unloaded gait, Ganley and Powers (2005) did not find significant differences in maximum hip flexion or hip extension when comparing 7-year-old children to adults. This discrepancy in results may be due to the fact that the weight of the empty bucket itself was carried even in the 0% BW condition in the present study and that an impeded arm swing may have had more of an effect on the 8–10-year-old group than on adults.

The second hypothesis was also supported since there were significant increases in ankle frontal plane RoM and maximum ankle eversion angles comparing 8–10 year olds to adults (Figures 3, 6). In addition, the 8–10-year-old age group displayed increased maximum ankle dorsiflexion and decreased ankle plantar flexion as compared to adults (Figure 5). Reduced ankle plantar flexor moment generation and reduced ankle power absorption/generation as observed during gait in 7-year-old children seems like a plausible explanation (Ganley and Powers 2005), but it would require further kinetic analyses to confirm this. Maximum ankle eversion angles were significantly greater for both the 8–10- and 12–14-year-old age groups as compared to adults (Figure 6). Increases in maximum joint angles are of particular concern when they approach the limits of joint motion. As a point of comparison, the increases in maximum hip flexion, hip extension and ankle dorsiflexion angles mentioned thus far all remain within values commonly observed during the stance phase of running (Hamill and Knutzen 2009). While ankle pronation was not measured directly, ankle eversion can be viewed as a partial surrogate measure of pronation. Ankle pronation and internal rotation of the knee/tibia are mechanically linked due to the orientation of the subtalar joint (Inman 1976). Knee and tibial internal rotations have frequently been implicated in tissue strain and pain at the knee (James *et al.* 1978, Bellchamber and van den Bogert 2000) and have discriminated between healthy knees and anterior cruciate ligament (ACL)-deficient or reconstructed knees during walking (Ristanis *et al.* 2003, Andriacchi and Dyrby 2005), between subjects

with and without patellofemoral pain (Salsich and Perman 2007) and (in a prospective study) between healthy runners and those who developed iliotibial band syndrome (Noehren *et al.* 2007). In the context of the present study population, greater ankle eversion may be a precursor to knee pain from repetitive load-carrying tasks.

Perhaps the most interesting differences in movements as a function of age group occurred at the hip joint in the frontal and transverse planes of motion (Figures 3, 6). The 8–10-, 12–14- and 15–17-year-old age groups all displayed greater maximum hip adduction angles than adults (Figure 6). These adjustments may be used to reduce stride width in response to the frontal plane balance challenges associated with the carrying tasks. In addition, the 8–10-, 12–14- and 15–17-year-old age groups all displayed greater maximum hip internal rotation angles than adults (Figure 6). Hip transverse plane RoM and maximum hip internal rotation angles also increased across age groups when carrying a 20% BW load as compared to a 0% BW load (Figures 4, 8). In contrast, a study of adolescent girls carrying dual-strap backpacks did not find significant increases in hip transverse plane RoM with increased carried load (Chow *et al.* 2006). This apparent discrepancy may be attributed to asymmetrical loading for the majority of carrying conditions in the present study, where frontal and transverse plane adjustments are likely to have been more critical. The maximum hip internal rotation angles for the 8–10-year-old age group across carrying tasks (Figure 6) and for the 20% BW loads across age groups (Figure 8) appear to fall outside commonly observed values for walking and running (Hamill and Knutzen 2009). These increases in maximum hip internal rotation angles are of concern and further kinetic analysis is suggested to test if these movement changes are associated with increased torsional loading at the hip joint.

There were several limitations to this study. One limitation was potential kinematic differences between males and females, which might be further complicated by differing rates of maturation. Significant differences between males and females for hip flexion and knee extension angles during walking have been reported (Oberg and Karsznia 1994, Kerrigan *et al.* 1998). Thus, different carrying guidelines might be appropriate for males and females, although a larger research participant pool would be needed to separate out movement changes as a function of age, maturation and gender. A second limitation was the use of total joint RoM and maximum joint angles as movement parameters since changes between age groups and carrying conditions tended to be subtle. While a kinematic-based analysis offers flexibility for potential data collection by video

cameras or observation in the field, changes in joint angles need to be distinct enough to be detectable outside laboratory conditions. A third limitation also relates to the use of kinematic parameters to predict injury risk, since increases in RoM may not result in clinically relevant increases in bone and soft tissue loading. In this study, lower extremity kinematics were analysed during the stance phase of walking, which does ensure that the increases in RoM are occurring during a time period in which the joints are simultaneously exposed to loading associated with supporting BW plus the carried load. However, further kinetic analyses of lower extremity joint moments, estimations of joint contact forces and electromyography would provide measures that are more likely to be directly related to injury risk. A fourth limitation was the idealised experimental conditions, such as the smooth/dry floor and stability of the load being carried. Carrying water over rough/muddy ground would be a greater neuromuscular challenge and could cause greater kinematic differences between age groups and load amounts while probably representing more realistic task conditions.

There are several points of interest that can be taken from this study. Maximum hip internal rotation angles were greater for each of the child/adolescent age groups as compared to adults. In addition, maximum hip internal rotation angles significantly increased when carrying a 20% BW load. Previous studies have suggested load-carrying guidelines at the point where significant changes occur in kinematic measures. Hong and Brueggemann (2000) suggested that backpack loads should not exceed 10% BW, based on the observation that trunk forward lean was similar to unloaded gait at 10% BW, but significantly increased at 15% BW. Similarly, Hong and Cheung (2003) suggested that backpack loads should not exceed 15% BW since significant increases in trunk inclination as compared to unloaded gait occurred at 20% BW loads. Applying this line of thought to the present study, suggested guidelines for unilaterally carried loads would be set at a level below 20% BW, where significant increases in maximum hip internal rotation were found to occur. As a measure of sensitivity, the entire 95% CI for changes in maximum hip internal rotation was positive at 20% BW, with increases ranging from 0.8–12.4°. This observation was also consistent across participants in this study, with 100% of 8–10 year olds, 100% of 12–14 of year olds, 89% of 15–17 year olds and 86% of adults displaying increases in maximum hip internal rotation at 20% BW. By setting carried load amounts as a percentage of BW, the experimental protocol in this study implemented carrying guidelines. Average loads for carrying feed and water measured in the field have been reported to

be 83 N (Allread *et al.* 2004). In comparison, the 8–10-year-old group carried less than this amount, on average at 20% BW, while the other age groups carried greater than this amount. The observation that the 8–10-year-old age group was tested at loads less than those measured in the field and still displayed the highest maximum hip internal rotation angles suggests a particular necessity in setting carrying guidelines for the youngest children. However, epidemiological data combined with further field observations and kinetic measurements would be required before a causal link could be directly established between changes in lower extremity kinematics and increased risk of injury.

5. Conclusions

In this study, lower extremity kinematics were analysed during bucket-carrying tasks to determine the effects of age, load amount and load symmetry. The child/adolescent age groups displayed significantly greater maximum hip extension, hip adduction and hip internal rotation angles as compared to adults. In addition, 20% BW load amounts resulted in significantly greater maximum hip internal rotation angles as compared to 0% BW load amounts. These increases in maximum hip internal rotation angles are of concern since they fell outside ranges commonly seen in gait studies and may indicate increased torsional loading at the hip joint. In addition, setting carrying guidelines for the 8–10-year-old group appeared to be particularly critical since this age group was tested at lower loads than commonly observed in the field, but still displayed the greatest maximum hip internal rotation angles.

Acknowledgements

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