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Lower Extremity Joint Moments During Carrying Tasks in Children

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Farm youth often carry loads that are proportionally large and/or heavy, and field measurements have determined that these tasks are equivalent to industrial jobs with high injury risks. The purpose of this study was to determine the effects of age, load amount, and load symmetry on lower extremity joint moments during carrying tasks. Three age groups (8–10 years, 12–14 years, adults), three load amounts (0%, 10%, 20% BW), and three load symmetry levels (unilateral large bucket, unilateral small bucket, bilateral small buckets) were tested. Inverse dynamics was used to determine maximum ankle, knee, and hip joint moments. Ankle dorsiflexion, ankle inversion, ankle eversion, knee adduction, and hip extension moments were significantly higher in 8–10 and 12–14 year olds. Ankle plantar flexion, ankle inversion, knee extension, and hip extension moments were significantly increased at 10% and 20% BW loads. Knee and hip adduction moments were significantly increased at 10% and 20% BW loads when carrying a unilateral large bucket. Of particular concern are increased ankle inversion and eversion moments for children, along with increased knee and hip adduction moments for heavy, asymmetrical carrying tasks. Carrying loads bilaterally instead of unilaterally avoided increases in knee and hip adduction moments with increased load amount.

Keywords: biomechanics, ergonomics, gait, load carriage, posture, youth

Farm youth commonly perform animal care tasks that are deemed to be relatively safe such as lifting, carrying, and dumping feed and water (Allread et al., 2004). However, these tasks are often designed for adults, resulting in children carrying asymmetric loads that are proportionally large and/or heavy (Allread & Waters, 2007). Youth are also particularly susceptible to repetitive strain injuries as musculotendinous units increase in tension during periods of rapid growth (Kidd et al., 2000). Therefore, children may suffer musculoskeletal disorders due to strength deficits, anatomical factors, and/or lack of experience performing these challenging movements. Not surprisingly, sprains/strains of the legs, arms, shoulders, and back are identified as the most common types of farm injuries and are considered everyday occurrences by children (Bartels et al., 2000; Pickett et al., 1995). In addition, field measurements have determined that lifting and carrying tasks performed by farm children are equivalent to industrial manual material handling tasks that pose high injury risks (Allread et al., 2004). Excessive lower extremity loading may have a cumulative lifetime effect, as male farmers have odds ratios of 5.1 for total knee replacement and 3.6 for total hip replacement due to osteoarthritis (Franklin et al., 2010).

Differences in gait mechanics between children and adults would be expected to contribute to age-related differences in lower extremity kinetics during carrying tasks performed by farm youth. When comparing gait kinematics, interlimb coordination for 4 year olds was similar to adults, although movement variability was higher (Zijlstra et al., 1996). When examining gait kinetics, children 2–7 years of age were continuing to develop a more defined second peak in their vertical ground reaction forces (Sutherland, 1997). Children appeared to display adult-like patterns for joint moments by 4 years of age, but relied more on hip flexors/extensors and less on ankle plantarflexors than adults (Sutherland, 1997). Reduced ankle plantar flexion joint moments during walking have also been observed in children 7–8 years of age as compared with older children and adults (Ganley

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& Powers, 2005; Chester et al., 2006). Taken together, it appears that young children produce lower ankle plantar flexion moments during gait, while loading in the frontal plane has received less attention.

Changes in carrying requirements such as load amount and load symmetry would also be expected to contribute to task-related differences in lower extremity loading. Unilateral (Nottrodt & Manley, 1989) and bilateral load carrying (Crowe & Samson, 1997) did not affect walking speed or stride frequency in adults, while differences in gait parameters for children 9–13 years of age carrying loaded backpacks are inconsistent across studies (Pascoe et al., 1997; Hong & Brueggemann, 2000; Hong & Cheung, 2003). However, adults displayed increased vertical and anteroposterior ground reaction forces (Birrell et al., 2007) when carrying loaded backpacks. In addition, hip abduction, knee extension, and ankle plantar flexion moments increased for adolescent girls carrying loaded backpacks (Chow et al., 2006). Thus, load carriage appears to increase joint moments in multiple planes, while gait parameters may not be sensitive enough to detect these changes in lower extremity loading.

Bucket carrying differs from backpack carrying in that the primary load balance is in the frontal plane for buckets and in the sagittal plane for backpacks. Upper body kinetics and lower body kinematics have been found to change as a function of age, load amount, and load symmetry for bucket carrying tasks. Increasing the load amount from 10% to 20% body weight (BW) and carrying the load in a unilateral bucket instead of bilateral buckets increased shoulder flexion, shoulder abduction, and L5/S1 lateral bending moments (Gillette et al., 2009). For lower extremity kinematics, hip extension and adduction were greater for children from 8 to 17 years old as compared with adults during bucket carrying (Gillette et al., 2010). It is still unknown whether the changes in upper body kinetics and lower body kinematics as a function of carrying task are also present in lower body kinetics.

The North American Guidelines for Children's Agricultural Tasks suggest that children should limit work that involves lifting and moving objects greater than 15% BW (Lee & Marlenga, 1999). It is of concern that studies of children performing common farm tasks have reported that load amounts appear to often exceed these levels (Allread et al., 2004). One method for determining specific carrying task guidelines is to set limits below the level where biomechanical parameters are first seen to significantly change from unloaded values. Chow et al. (2006) supported a guideline of 10% BW for backpack carrying, since parameters increased from a plateau value at load amounts above this level. Moore et al. (2007) also suggested a guideline of 10% BW for backpack loads based on pain assessments, while noting potentially increased risks for younger students and females.

The purpose of this study was to examine the changes in lower extremity moments as a function of load amount, load symmetry, and age for bucket carrying tasks. Previous research indicated that upper body joint moments in the frontal plane were the most sensitive to changes in carrying tasks for children and adults (Gillette et al., 2009). If changes in upper body kinetics are reflected in lower body kinetics, then we would also expect to see differences in hip, knee, and ankle frontal plane joint moments. Since balancing frontal plane moments becomes more difficult with increased bucket loads, it was hypothesized that hip and knee abduction/adduction moments would be significantly greater when increasing the load amount from 0% to 20% BW. For children, the frontal plane challenges associated with bucket carrying are combined with potentially reduced ankle joint moment generating capacity to control joint movement control. Therefore, it was also hypothesized that 8–10 year old children would have significantly greater ankle inversion/eversion moments as compared with adults.

Methods

Thirty-six participants in three age groups (8–10 years old, 12–14 years old, and adults 23–26 years old) participated in this study. Participant characteristics for each of these age groups were as follows (gender distribution; average age, height, mass with standard deviations):

- 8–10 year olds: 6 males, 3 females; 8.8 ± 1.0 year, 1.37 ± 0.08 m, 34 ± 7 kg
- 12–14 year olds: 7 males, 6 females; 12.6 ± 1.0 year, 1.56 ± 0.07 m, 53 ± 13 kg
- Adults: 8 males, 6 females; 24.0 ± 1.7 years, 1.76 ± 0.09 m, 72 ± 14 kg

To achieve a 95% confidence interval, sample size calculations estimated that 26 total participants were required for hip and knee abduction moment comparisons (Hypothesis 1), and 9 participants were required in each age group for ankle inversion moment comparisons (Hypothesis 2). These individuals were a subset of a larger pool of 72 participants over a 3-year period that had their upper and/or lower body biomechanics analyzed during carrying tasks.

Each individual provided informed consent (or assent for minors) as approved by the Iowa State University Institutional Review Board before taking part in this 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 organizations, sponsored by the United States Department of Agriculture, where participants regularly perform farming tasks. Children begin activities in 4-H as early as 5 years of age and may progress in animal care responsibilities toward state competitions at 10 years of age. Exclusion criteria included any balance, neurological, or musculoskeletal injuries or disorders that would affect the ability to complete bucket-carrying tasks, which was determined through verbal interview with the participant (and parents of minors).

Two sizes of buckets were carried: large five-gallon (18.9 L, 36.8 cm high, 30 cm diameter) and small one-gallon (3.8 L, 19.5 cm high, 16.7 cm diameter). These buckets were filled using sealed bags of lead shot at three load amounts based on body weight: 0%, 10%, and 20% BW. The carrying tasks were designed to test three levels of load symmetry: unilateral large bucket, unilateral small bucket, and bilateral small buckets. 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 studied due to the difficulty observed in some 8 year old children completing this task during initial testing. Buckets were carried unilaterally with the self-selected dominant hand, and the load was evenly split between the buckets during the bilateral conditions (Figure 1). The dominant hand was determined by allowing the participant to choose which side they preferred to carry a single large bucket, and all participants chose the right hand. In total, three repetitions of the nine conditions (3 load amount × 3 load symmetry combinations) were completed. The order of the 27 trials was randomized to reduce potential effects of learning and fatigue.

Participants carried buckets 6 m while reflective markers placed on the right leg were tracked by an eight-camera optical system (Peak Motus, Centennial, CO). The children and adults were instructed to walk at a comfortable pace while looking straight ahead. Ground reaction forces were measured by a force platform (AMTI, Watertown, MA) at the halfway point of the walking path. A Helen Hayes lower body marker set was modified to avoid the arms and/or carried buckets from contacting markers of the thighs and calves. The marker set included the great toe, heel, lateral malleolus, medial malleolus, anterior/medial tibia surface at ankle/knee midpoint, lateral tibial condyle, medial tibial condyle, and anterior thigh at knee/hip midpoint (Figure 1). In addition, markers were placed on the right and left greater trochanters. A static standing trial was captured with the full marker set and then the medial malleolus and medial tibial condyle markers were removed to avoid contact while carrying buckets. During the dynamic experimental trials, the medial malleolus and medial tibial condyle marker positions were recreated using transformations derived from the static standing trials (Robertson et al., 2004). The video and force platform data were collected at 120 Hz, and noise was reduced with a fourth-order, low-pass Butterworth filter at a cutoff frequency of 6 Hz.

Using inverse dynamics, joint moments were calculated during the stance phase on the right side of the body (Robertson et al., 2004). Initiation of the stance phase was detected when the vertical ground reaction force exceeded 50 N, and termination was detected when the vertical ground reaction force fell below 50 N. The ankle joint center was defined as the midpoint of the lateral and medial malleoli and the knee joint center as the midpoint of the lateral and medial tibial condyle. The hip joint center was estimated as 25% of the distance from the right trochanter to the left trochanter. Lower extremity segment masses, center of mass positions, and moments of inertia were estimated according to de Leva's (1996) anthropometric equations for males and females. Ankle plantar flexion / dorsiflexion, ankle inversion/eversion, knee flexion/extension, knee abduction/adduction, hip flexion/extension, and hip abduction/adduction moments were calculated and transformed to the distal segment

Figure 1 — Representative eight-year-old child with reflective marker set. Left—unilateral large bucket carrying. Center—bilateral small bucket carrying. Right—segment and global coordinate systems.

coordinate system (Figure 1). Maximum joint moments were determined for each trial and normalized by the product of body mass and height (BM·ht). Maximum joint moments were chosen for analysis as an estimate of the instance where injury was most likely to occur and to allow extremes of opposing rotational directions to be considered (i.e., both maximum ankle inversion and eversion values). All calculations were performed in Matlab (Natick, MA).

Trials with discontinuities due to marker obscuring were eliminated from the analysis. Overall, 882 out of 972 possible trials were analyzed (91%), for an average of 2.7 trials per condition for each subject. Maximum joint moments were calculated for qualified trials and averaged per condition for each participant. Multivariate ANOVA was used to test for main effects of age group, load amount, load symmetry, and their interactions (SPSS, Chicago, IL). The significance level was set to $p < .05$ with a Bonferroni correction of 12 (number of dependent variables). Eleven of the 12 maximum joint moment variables were not normally distributed about their mean values as indicated by the Shapiro–Wilk tests of normality ($p < .05$). Therefore, when significant main effects were found, Mann–Whitney U nonparametric comparisons were made at a significance level of $p < .05$. Adults, 12–14 year olds, and 8–10 year olds were compared with one another to test the effects of age group on maximum joint moments. The 0% BW trials were compared with the 10% and 20% BW trials to test the effects of load amount. Unilateral small bucket trials were compared with unilateral large bucket (bucket size effect) and bilateral small bucket trials (bilateral vs. unilateral effect) to test the effects of load symmetry.

Results

Maximum joint moments were significantly dependent upon age group ($p < .01$), load amount ($p < .01$), load symmetry ($p < .01$), and the interaction between load amount and load symmetry ($p < .01$). Peak values for ankle dorsiflexion, knee extension, knee adduction, hip adduction, and hip extension moments tended to occur during the initial stance phase; ankle inversion and knee flexion moments during midstance; and ankle plantar flexion and hip flexion moments during terminal stance. Other moments regularly displayed multiple peaks, such as ankle eversion, knee abduction, and hip abduction moments during initial and terminal stance.

There were significant differences in sagittal plane joint moments as a function of age group (Figure 2). Maximum ankle dorsiflexion ($p < .001$) and hip extension ($p < .001$) moments were significantly greater for 8–10 and 12–14 year olds as compared with adults. Ankle dorsiflexion ($p < .001$) moments were also significantly greater for 8–10 year olds as compared with 12–14 year olds. In contrast, knee extension ($p < .001$) and hip flexion ($p < .001$) moments were significantly lower for 8–10 and 12–14 year olds as compared with adults.

There were significant differences in frontal plane joint moments as a function of age group (Figure 3). Maximum ankle inversion ($p < .001$), ankle eversion ($p < .001$), and knee adduction ($p < .003$) moments were significantly greater for 8–10 and 12–14 year olds as compared with adults. Hip adduction ($p < .001$) moments were also significantly greater for 8–10 year olds as compared with adults. In addition, ankle inversion ($p < .003$), ankle eversion ($p < .006$), and hip adduction ($p < .001$) moments were significantly higher for 8–10

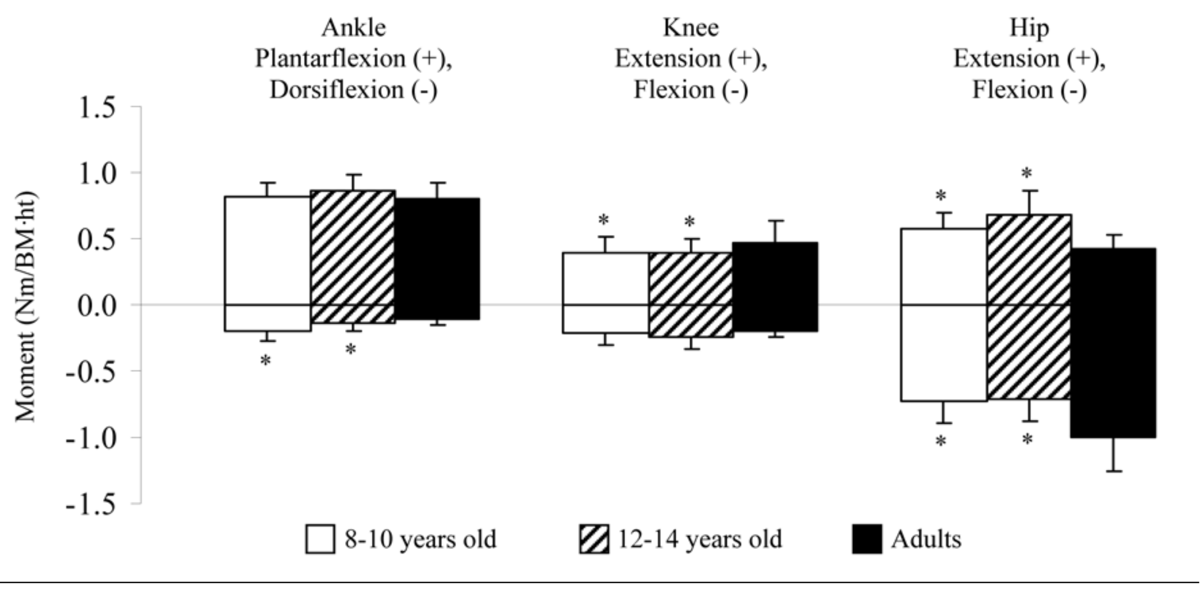

Figure 2 — Sagittal plane moments as a function of age group. Maximum joint moments are reported as averages across conditions with standard deviations. Labels above the graphs indicate the positive and negative moment directions. Significant differences in maximum joint moments for the 8–10 and 12–14 year old age groups as compared with the adult age group are denoted by an asterisk ($p < .05$).

year olds as compared with 12–14 year olds. In contrast, knee abduction moments ($p < .001$) were significantly lower for 8–10 and 12–14 years olds as compared with adults. Hip abduction ($p < .001$) moments were also significantly lower for 8–10 year olds as compared with adults. In addition, hip abduction ($p < .001$) moments were significantly lower for 8–10 year olds as compared with 12–14 year olds.

There were significant differences in sagittal plane joint moments as a function of load amount (Figure 4). Maximum ankle plantar flexion ($p < .001$), knee extension ($p < .003$), and hip extension ($p < .05$) moments were significantly greater for the 10% BW and the 20% BW loads as compared with the 0% BW load. In addition, ankle dorsiflexion ($p < .001$) moments were significantly greater for the 20% BW load as compared with the 0% BW load. There were significant differences in ankle frontal plane joint moments as a function of load amount (Figure 5). Maximum ankle inversion ($p < .007$) moments were significantly greater for the 10% BW and the 20% BW loads as compared with the 0% BW load.

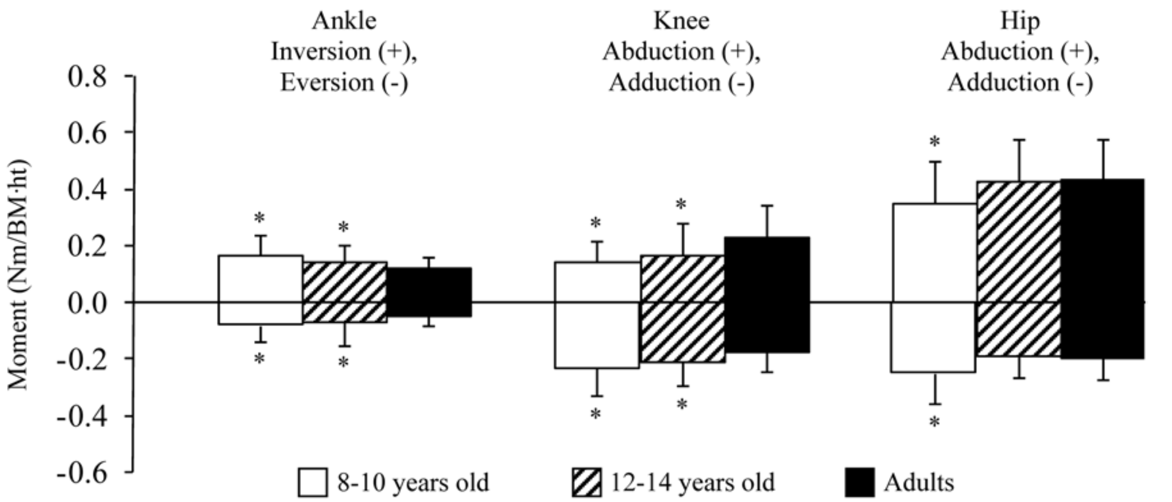

Figure 3 — Frontal plane moments as a function of age group. Maximum joint moments are reported as averages across conditions with standard deviations. Labels above the graphs indicate the positive and negative moment directions. Significant differences in maximum joint moments for the 8–10 and 12–14 year old age groups as compared with the adult age group are denoted by an asterisk ($p < .05$).

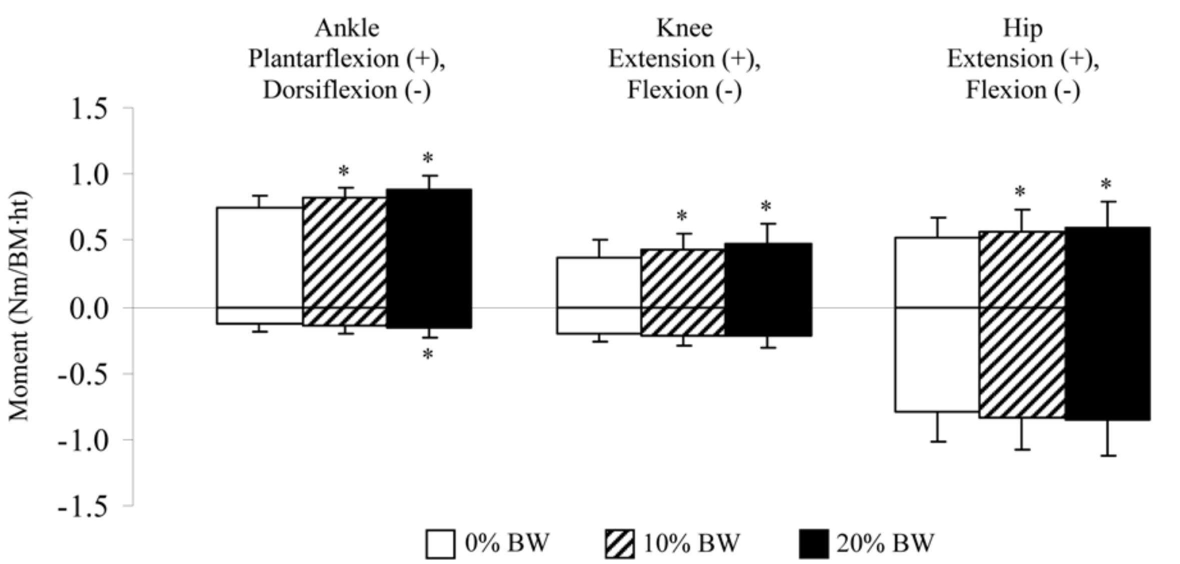

Figure 4 — Sagittal plane moments as a function of load amount. Maximum joint moments are reported as averages across age groups with standard deviations. Labels above the graphs indicate the positive and negative moment directions. Significant differences in maximum joint moments for the 10% BW and 20% BW load as compared with the 0% BW load are denoted by an asterisk ($p < .05$).

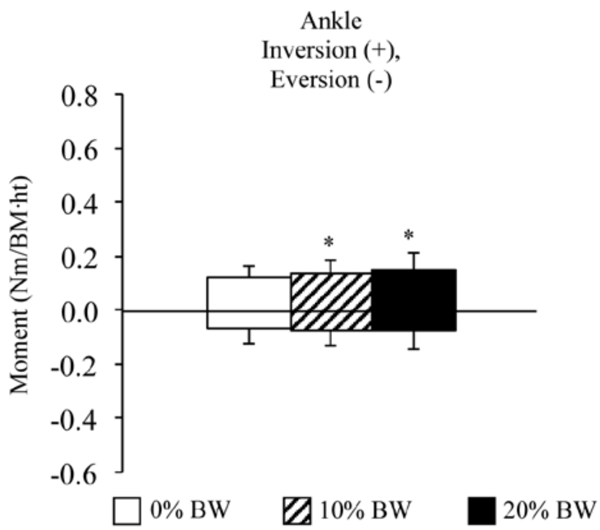

Figure 5 — Ankle frontal plane moments as a function of load amount. Maximum joint moments are reported as averages across age groups with standard deviations. Labels above the graphs indicate the positive and negative moment directions. Significant differences in maximum joint moments for the 10% BW and 20% BW load as compared with the 0% BW load are denoted by an asterisk ($p < .05$).

There were significant differences in maximum knee abduction and adduction moments as a function of the interaction between load amount and load symmetry (Figure 6). Knee adduction moments were significantly greater for 10% ($p < .02$) and 20% ($p < .001$) as compared with 0% BW load when carrying a unilateral large bucket or a unilateral small bucket. In contrast, knee abduction moments were significantly lower for 20% ($p < .001$) BW loads with a unilateral large bucket or a unilateral small bucket. Maximum knee abduction moments were significantly greater when carrying bilateral small buckets as compared with carrying a unilateral small bucket at 10% ($p < .002$) and 20% ($p < .001$) BW loads (bilateral vs. unilateral effect). In contrast, knee adduction moments were significantly lower when carrying bilateral small buckets as compared with carrying a unilateral small bucket at a 20% ($p < .02$) BW load (bilateral vs. unilateral effect).

There were significant differences in maximum hip abduction/adduction moments as an interaction between load amount and load symmetry (Figure 7). Hip adduction moments were greater for 10% ($p < .009$) and 20% ($p < .001$) as compared with 0% BW when carrying a unilateral large bucket. Hip adduction moments were also greater for 20% BW ($p < .002$) with a unilateral small bucket. In contrast, hip abduction moments were greater for 20% BW ($p < .003$) with bilateral small buckets. Hip abduction moments were lower for 10% ($p < .006$) and 20% ($p < .001$) BW with a unilateral large bucket and for 20% BW ($p < .001$) with a unilateral small bucket. Hip abduction moments were greater with bilateral small buckets as compared with a unilateral small bucket at 10% ($p < .002$) and 20% BW ($p < .001$, bilateral vs. unilateral effect). In contrast, hip adduction moments were lower with bilateral small buckets as compared with a unilateral small bucket at a 20% BW ($p < .002$, bilateral vs. unilateral effect). Hip abduction moments were lower when carrying a unilateral large bucket as compared with

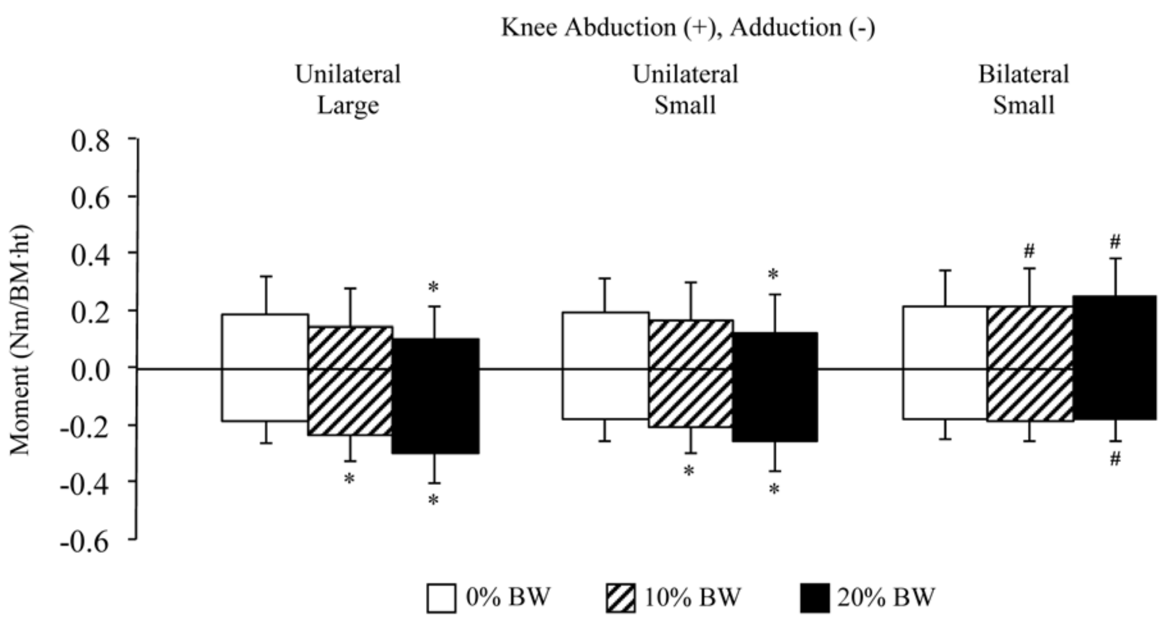

Figure 6 — Knee abduction/adduction moments as a function of the interaction between load amount and load symmetry. Significant differences in maximum joint moments for the 10% BW and 20% BW load as compared with the 0% BW load are denoted by an asterisk ($p < .05$). Significant differences for the unilateral large (large vs. small bucket) and the bilateral small (bilateral vs. unilateral) conditions as compared with the unilateral small condition are denoted by a # symbol ($p < .05$).

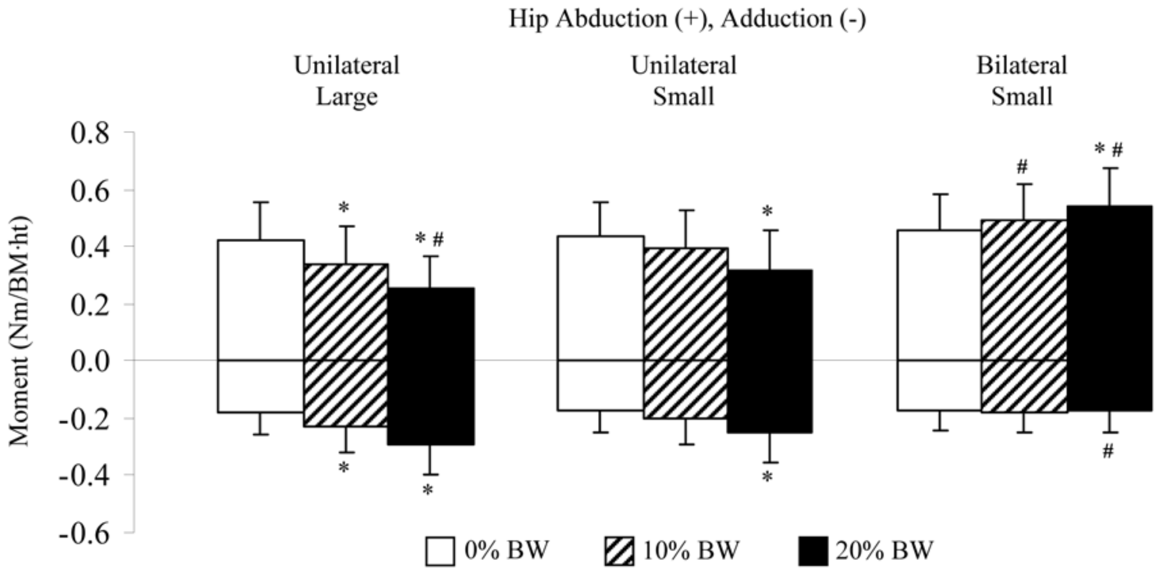

Figure 7 — Hip abduction/adduction moments as a function of the interaction between load amount and load symmetry. Significant differences in maximum joint moments for the 10% BW and 20% BW load as compared with the 0% BW load are denoted by an asterisk ($p < .05$). Significant differences for the unilateral large (large vs. small bucket) and the bilateral small (bilateral vs. unilateral) conditions as compared with the unilateral small condition are denoted by a # symbol ($p < .05$).

carrying a unilateral small bucket at a 20% BW ($p < .05$, bucket size effect).

It is of interest to test if there are any significant differences as a function of gender. When pooling all age groups (children plus adults), males had significantly higher maximum ankle dorsiflexion ($p < .005$) moments, while females had significantly higher ankle eversion ($p < .001$), knee flexion ($p < .006$), knee abduction ($p < .004$), and hip abduction ($p < .001$) moments. When pooling the combined 8–10 and 12–14 year olds (children only), males had significantly higher ankle dorsiflexion ($p < .001$) and ankle inversion ($p < .007$) moments, while females had significantly higher ankle plantar flexion ($p < .02$), ankle eversion ($p < .005$), knee flexion ($p < .006$), knee abduction ($p < .02$), hip extension ($p < .004$), and hip abduction ($p < .02$) moments.

Discussion

The first hypothesis was that knee and hip abduction/adduction moments would increase when the load was increased from 0% to 20% BW. This hypothesis was not supported because while knee and hip adduction moments increased with load amount when carrying a bucket unilaterally, hip abduction moments actually decreased (Figures 6–7). In contrast, Chow et al. (2006) reported increased hip abduction moments with increased backpack loads. However, backpack carrying involves more symmetrical loading than the bucket carrying in our experimental protocol. In our study, knee and hip abduction moments were reduced with more asymmetrical unilateral bucket carrying, while hip abduction moments increased at 20% BW when carrying buckets bilaterally (Figure 7). Hip abduction moments further decreased when carrying a large unilateral bucket, which was the most asymmetrical carrying task. Reduced knee and hip abduction moments were likely a result of step width manipulation in response to increased frontal plane balance challenges, which is consistent with previous observations of decreased hip adduction angles with increased load (Gillette et al., 2009).

Relationships between knee and hip adduction/abduction moments and carrying condition require further examination due to the interaction between load amount and load symmetry (Figures 6–7). In general, knee and hip adduction moments increased and abduction moments decreased during carrying tasks involving higher load amounts and increased load asymmetry. Carrying a unilateral large bucket with a 20% BW load was considered the most challenging combination of load amount and asymmetry. In contrast, 0% BW loads were expected to result in similar joint moments regardless of unilateral versus bilateral carrying or bucket size. Load amount effects were most pronounced with a unilateral large bucket, with increases in hip adduction and decreases in abduction moments occurring at both 10% and 20% BW. Load symmetry effects were most pronounced with a 20% BW load, where unilateral carrying resulted in increased knee and hip adduction and decreased abduction moments as compared with bilateral carrying. The only effect of bucket size was reduced hip abduction moments when carrying a large as compared with a small bucket with a 20% BW load. As expected, there were no differences in knee and hip adduction/abduction moments between carrying tasks at 0% BW loads.

The second hypothesis was supported in that 8–10 year olds displayed significantly higher ankle inversion and eversion moments than adults (Figure 3). Across joints, children relied more on ankle dorsiflexion and hip extension moments, while adults relied more on knee extension and hip flexion moments (Figure 2). Ganley and Powers (2005) and Chester et al. (2006) found reduced ankle plantar flexion moments in 7–8 year olds, while we observed no significant differences between 8–10 year olds and adults. These studies examined unloaded walking, while we found increased ankle plantar flexion moments when carrying 10% and 20% BW loads (Figure 4). Ankle inversion moments also increased when carrying 10% and 20% BW loads (Figure 5). Increased ankle inversion and eversion moments for 8–10 and 12–14 years olds, along with increased ankle inversion moments at 10% and 20% BW loads are of practical concern for ankle sprains, especially in rough and/or muddy terrain beyond idealized laboratory conditions. It is estimated that 85% of ankle sprains result from excessive supination (Whiting & Zernicke, 2008), which involve a combination of ankle plantar flexion and inversion.

There are study limitations that affect interpretation of the results. First, joint moments were used as an injury risk indicator, and it is difficult to determine a threshold at which damage occurs. Further epidemiologic data, EMG measurements, and tissue loading models would provide additional evidence of injury risk. Second, anthropometric scaling differences in children may introduce errors in joint moment calculations. However, models using participant segments lengths and circumferences (Hanavan, 1964) produced negligible differences when compared with joint moments calculated using de Leva's (1996) anthropometric equations. This was probably due to dominating effects of ground reaction forces during slow carrying movements. Therefore, to simplify the data analyses, it was decided to use de Leva's (1996) equations. Third, the children were divided into mixed gender age groups of 8–10 and 12–14 years of age. Differing maturation rates for boys and girls complicates efforts to establish an age cutoff where a load amount presents an unacceptably high injury risk. Preliminary testing of gender effects resulted in ankle inversion, ankle plantar flexion, and hip extension moment differences for children that were not apparent in adults. These joint moment differences merit further study with expanded gender comparison groups.

In terms of developing carrying guidelines, joint moments are of particular interest when they significantly increase with load amount and are greater than what occurs in everyday activities. As a comparison, previous studies have determined joint moments for walking (Kerrigan et al., 1998; Nordin & Frankel, 2001) and running (Edwards et al., 2008; Hamill & Knutzen, 2009). Increases in ankle joint, knee extension, and hip extension moments with increased load amounts remained within one standard deviation of values reported for walking and running. In contrast, maximum knee and hip adduction moments fell outside of commonly reported values when carrying unilateral 20% BW loads (Figures 6–7). Internal knee adduction moments are consistent with lateral compression of the knee joint, whereas medial joint compression is associated with progression of knee osteoarthritis (Butler et al., 2009). However, any substantial deviation from normal joint loading may be cause for concern, which is further magnified by the observation that 8–10 year olds had higher knee and hip adduction moments than adults (Figure 3). In response, a simple intervention to lower knee and hip adduction moments was to carry a load bilaterally instead of unilaterally (Figures 6–7). Even at 20% BW loads, knee and hip adduction moments did not significantly increase as compared with 0% BW loads when carrying bilateral small buckets.

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References

Allread, W.G., & Waters, T.R. (2007). Interventions to reduce low-back injury risk among youth who perform feed handling and scooping tasks on farms. *Journal of Agricultural Safety and Health, 13,* 375–393. PubMed

Allread, W.G., Wilkins, J.R., III, Waters, T.R., & Marras, W.S. (2004). Physical demands and low-back injury risk among children and adolescents working on farms. *Journal of Agricultural Safety and Health, 10,* 257–273. PubMed

Bartels, S., Niederman, B., & Waters, T.R. (2000). Job hazards for musculoskeletal disorders for youth working on farms. *Journal of Agricultural Safety and Health, 6,* 191–201. PubMed

Birrell, S.A., Hooper, R.H., & Haslam, R.A. (2007). The effect of military load carriage on ground reaction forces. *Gait & Posture, 26,* 611–614. PubMed doi:10.1016/j.gaitpost.2006.12.008

Butler, R.J., Minick, K.I., Ferber, R., & Underwood, F. (2009). Gait mechanics after ACL reconstruction: implications for the early onset of knee osteoarthritis. *British Journal of Sports Medicine, 43,* 366–370. PubMed doi:10.1136/bjsm.2008.052522

Chester, V.L., Tingley, M., & Biden, E.N. (2006). A comparison of kinetic gait parameters for 3-13 year olds. *Clinical Biomechanics (Bristol, Avon), 21,* 726–732. PubMed doi:10.1016/j.clinbiomech.2006.02.007

Chow, D.H.K., Kwok, M.L.Y., Au-Yang, A.C.K., Holmes, A.D., Cheng, J.C.Y., Yao, F.Y.D., et al. (2006). The effect of load carriage on the gait of girls with adolescent idiopathic scoliosis and normal controls. *Medical Engineering & Physics, 28,* 430–437. PubMed doi:10.1016/j.medengphy.2005.07.013

Crowe, A., & Samson, M.M. (1997). 3-D analysis of gait: The effects upon symmetry of carrying a load in one hand. *Human Movement Science, 16,* 357–365. doi:10.1016/S0167-9457(96)00061-9

de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics, 29,* 1223–1230. PubMed doi:10.1016/0021-9290(95)00178-6

Edwards, W.B., Gillette, J.C., Thomas, J.M., & Derrick, T.R. (2008). Internal femoral forces and moments during running: Implications for stress fracture development. *Clinical Biomechanics (Bristol, Avon), 23,* 1269–1278. PubMed doi:10.1016/j.clinbiomech.2008.06.011

Franklin, J., Ingvarsson, T., Englund, M., & Lohmander, S. (2010). Association between occupation and knee and hip replacement due to osteoarthritis: a case-control study. *Arthritis Research & Therapy, 12,* R102. PubMed doi:10.1186/ar3033

Ganley, K.J., & Powers, C.M. (2005). Gait kinematics and kinetics of 7-year old children: a comparison to adults using age-specific anthropometric data. *Gait & Posture, 21,* 141–145. PubMed doi:10.1016/j.gaitpost.2004.01.007

Gillette, J.C., Stevermer, C.A., Meardon, S.A., Derrick, T.R., & Schwab, C.V. (2009). Upper extremity and lower back moments during carrying tasks in farm children. *Journal of Applied Biomechanics, 25,* 149–155. PubMed

Gillette, J.C., Stevermer, C.A., Miller, R.H., Meardon, S.A., & Schwab, C.V. (2010). The effects of age and type of carrying task on lower extremity kinematics. *Ergonomics, 53,* 355–364. PubMed doi:10.1080/00140130903402234

Hamill, J., & Knutzen, K.M. (2009). *Biomechanical basis of human movement* (3rd ed., pp. 449–450). Philadelphia, PA: Lippincott, Williams, & Wilkins.

Hanavan, E.P. (1964). A mathematical model of the human body. *AMRL-TR (6570th Aerospace Medical Research Laboratory),* 64–102). Wright-Patterson Air Force Base, OH.

Hong, Y., & Brueggemann, G. (2000). Changes in gait patterns in 10-year-old boys with increasing loads when walking on a treadmill. *Gait & Posture, 11,* 254–259. PubMed doi:10.1016/S0966-6362(00)00055-2

Hong, Y., & Cheung, C. (2003). Gait and posture responses to backpack load during level walking in children. *Gait & Posture, 17,* 28–33. PubMed doi:10.1016/S0966-6362(02)00050-4

Kerrigan, D.C., Todd, M.K., & Croce, U.D. (1998). Gender differences in joint biomechanics during walking. *American Journal of Physical Medicine & Rehabilitation, 77,* 2–7. PubMed doi:10.1097/00002060-199801000-00002

Kidd, P.S., McCoy, C., & Steenbergen, L. (2000). Repetitive strain injuries in youth. *Journal of the American Academy of Nurse Practitioners, 12,* 413–426. PubMed doi:10.1111/j.1745-7599.2000.tb00147.x

Lee, B., & Marlenga, B. (1999). *Professional Resource Manual: North American Guidelines for Children's Agricultural Tasks*. Marshfield, WI: Marshfield Clinic.

Moore, M.J., White, G.L., & Moore, D.L. (2007). Association of relative backpack weight with reported pain, pain sites, medical utilization, and lost school time in children and adolescents. *The Journal of School Health, 77,* 232–239. PubMed doi:10.1111/j.1746-1561.2007.00198.x

Nordin, M., & Frankel, V.H. (2001). *Basic Biomechanics of the Musculoskeletal System* (3rd ed., pp. 442–448). Philadelphia, PA: Lippincott, Williams, & Wilkins.

Nottrodt, J.W., & Manley, P. (1989). Acceptable loads and locomotor patterns selected in different carriage methods. *Ergonomics, 32,* 945–957. PubMed doi:10.1080/00140138908966856

Pascoe, D.D., Pascoe, D.E., Wang, T.W., Shim, D., & Chang, C.K. (1997). Influence of carrying book bags on gait cycle and posture of youths. *Ergonomics, 40,* 631–641. PubMed doi:10.1080/001401397187928

Pickett, W., Brison, R.J., Niezgoda, H., & Chipman, M.L. (1995). Nonfatal farm injuries in Ontario: A population-based survey. *Accident; Analysis and Prevention, 27,* 425–433. PubMed doi:10.1016/0001-4575(94)00080-6

Robertson, D.G.E., Caldwell, G.E., Hamill, J., Kamen, G., & Whittlesey, S.N. (2004). *Research Methods in Biomechanics* (pp. 151–156). Champaign, IL: Human Kinetics.

Sutherland, D. (1997). The development of mature gait. *Gait & Posture, 6,* 163–170. doi:10.1016/S0966-6362(97)00029-5

Whiting, W.C., & Zernicke, R.F. (2008). *Biomechanics of Musculoskeletal Injury* (2nd ed., pp. 120). Champaign, IL: Human Kinetics.

Zijlstra, W., Prokop, T., & Berger, W. (1996). Adaptability of leg movements during normal treadmill walking and split-belt walking in children. *Gait & Posture, 4,* 212–221. doi:10.1016/0966-6362(95)01065-3