Effects of Overweight and Obesity on Running Mechanics in Children

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ABSTRACT

BOWSER, B. J, and K. ROLES. Effects of Overweight and Obesity on Running Mechanics in Children. *Med. Sci. Sports Exerc.*, Vol. 53, No. 10, pp. 2101–2110, 2021. Although obesity has been linked to several differences in walking mechanics, few studies have examined movement mechanics of overweight and obese (OW/OB) children performing higher impact activities, such as running. **Purpose:** The purpose of this study is to determine differences in running mechanics between healthy weight (HW) children and children classified as OW/OB. **Methods:** Forty-two children (17 OW/OB, 25 HW) ran overground while kinematic and kinetic data were recorded using a motion capture system and force plate. Kinematic variables of interest included stance time, step length, and frontal and sagittal plane joint angles and excursions at the hip, knee, and ankle. Kinetic variables of interest included ground reaction forces and hip, knee, and ankle moments in the sagittal and frontal planes. **Results:** The OW/OB group spent more time in stance, took shorter steps, displayed less hip flexion during the first half of stance, had greater ankle inversion at foot strike, had greater knee abduction throughout stance, and had smaller knee flexion, knee adduction, and hip adduction excursions. In comparing unscaled ground reaction forces, the OW/OB group displayed greater peak vertical force, vertical impact peaks, and vertical loading rates. The OW/OB group also displayed greater unscaled plantar and dorsiflexion moments, knee flexion and extension moments, ankle inversion moments, and knee and hip abduction moments. **Conclusion:** These data suggest that increased body weight in children is associated with changes in running mechanics. Higher joint moments and ground reaction forces may indicate increased injury risk or the development of joint degeneration among overweight/obese children. **Key Words:** CHILDHOOD OBESITY, BIOMECHANICS, JOINT KINETICS, JOINT KINEMATICS

The prevalence of childhood obesity throughout the world has become a major health concern. The health risks associated with childhood obesity include cardiovascular disease, metabolic syndrome, depression, and social isolation (1). In addition to the negative physiological and psychological effects, excessive weight in children has been linked to movement disfunction, excessive joint loading, and the development of osteoarthritis and other joint pathologies (1–6).

Several differences in kinematics, ground reaction forces, and joint loading have been reported when comparing walking mechanics of healthy weight (HW) children to children classified as overweight and obese (OW/OB). Children classified as OW/OB display slower self-selected walking speeds, greater time spent in double support, shorter step lengths, and greater step width compared with HW children (7,8). These gait characteristics are typical of individuals trying to reduce energy expenditure or who have increased instability during walking. In the frontal plane, obese children display greater hip adduction moments and knee abduction angles and moments during the stance phase of walking (9–12). Repetitive stresses on the hip and knee joint due to greater joint excursions and moments in the frontal plane can result in increased joint loading to the lateral facet of the tibia and increased strain on the anterior cruciate ligament (ACL), patellofemoral pain, and ultimately disability (4,13,14). In the sagittal plane, obese children display decreased hip and knee joint flexion and increased extensor moments and greater leg stiffness during stance compared with HW children (8,9,13,15). The combination of decreased hip and knee flexion and increased leg stiffness has been associated with increased joint loading (6). The differences in walking mechanics between obese and nonobese children are cause for concern. Although mechanical loading is necessary for proper bone growth and muscle development in children, excessive loading may lead to joint injuries, joint degenerative diseases, and/or pain. Furthermore, the additional joint stress has been suggested to lead to musculoskeletal injury and malalignments in obese children, including slipped capital femoral epiphysis and tibia vara, respectively, (16–18).

Although obesity has been linked to several differences in joint kinematics and kinetics and increased vertical loading during walking, few studies have examined movement mechanics

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Submitted for publication November 2020.
Accepted for publication April 2021.

0195-9131/21/5310-2101/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0000000000002686

of OW/OB children performing higher impact activities, such as running. It is likely that many of the differences between OW/OB and HW children during walking will also exist for running, but with greater magnitude (17). In a sample of healthy adults, tibiofemoral contact forces were 2–3 times greater in running compared with walking (19). Similarly, youth (11–18 yr) classified as obese display greater nonnormalized frontal and sagittal plane knee moments during running when compared with HW youth (17). In addition, prepubescent children display significant increases in peak pressure and maximum force on the foot as they increase their gait speed from walking to running (7,20).

Running is one of the most popular and common forms of exercise recommended to reduce obesity and improve health. However, there are only a few known studies that have examined running mechanics in prepubescent children (3,7,20). These studies primarily focused on comparing plantar pressure differences between OW/OB and HW children. They reported that both OW/OB and HW children display significant increases in peak plantar pressure on the foot when going from walking to running (7,20). In addition, a positive relationship between peak plantar pressure and body mass index (BMI) was observed (3). When directly compared with HW children, OW/OB children on average displayed up to 25% greater peak vertical force (FZ_{max}) and 45% greater peak pressure on the foot during running (7). Rubinstein and colleagues (7) suggest that obesity-related changes to plantar loading could place OW/OB children at greater risk of overuse injuries. Increased plantar loading has been associated with flatter arches, increased foot pain, and increased risk of fractures to the foot (3,7,20,21). Increased foot pressure in children has also been associated with increased sedentary time and decreased moderate–vigorous physical activity (22). Although elevated plantar pressure observed in OW/OB children running suggests greater vertical loading compared with HW children, plantar pressure does not provide any information on lower extremity joint kinematics and kinetics. By examining both running kinematics and kinetics of OW/OB children, greater insight can be provided on the potential risks that running may have for these children. Therefore, a running analysis using motion capture and ground reaction forces is needed to capture more fully the differences in running mechanics between OW/OB and HW children.

The purpose of this study is to determine differences in running mechanics between OW/OB and HW children. Based on the movement mechanics and plantar pressure data observed in obese children during walking and running, we hypothesize that OW/OB children will display higher vertical loading during running compared with HW children. Furthermore, we expect joint moments to be higher for the OW/OB children. Lastly, we expect decreased sagittal plane angles and excursions and increased frontal plane angles and excursion at the knee, and ankle joints in the OW/OB group during running. We expect no group differences in hip angles and excursions. Understanding the differences in running mechanics between OW/OB and HW children can help to identify potential risk factors associated with OW/OB children running. Furthermore, teachers, parents, and other clinicians will be better equipped in prescribing appropriate physical activities for OW/OB children that can safely meet the recommended physical activity guidelines for children.

METHODS

Participants. The Physical Activity Readiness Questionnaire, an injury history questionnaire, and informed assent and consent waivers as approved by the Institutional Human Subjects Review Board were completed by the participant and participant's guardian before participation. All participants had to be deemed healthy and free of injury during the previous 3 months to be eligible. An *a priori* power analysis using pilot data was used to determine the sample size needed to achieve statistical significance. Based on the power analysis, 42 participants were needed to adequately power this study (effect size = 0.80, $\alpha = 0.05$, $\beta = 0.20$). Forty-two children between 8 and 12 yr of age were recruited to participate in this study. Participants were recruited from the local community via word of mouth, flyers placed in public areas, and flyers e-mailed to various youth clubs and organizations. Upon completion of participation in the study, each child received a $40 Amazon gift card. Participants included 16 OW/OB participants (BMI ≥85th percentile) and 26 HW participants (BMI < 85th percentile). Participant demographics are displayed in Table 1.

Instrumentation. Twenty-seven reflective markers and two cluster markers were used to identify anatomical landmarks of the lower extremities using a modified Helen Hayes marker set. The inclusion of iliac crest and greater trochanter markers as well as thigh and shank clusters was used to limit skin movement artifact for the OW/OB children. Three-dimensional marker coordinates were collected using an eight-camera (Oqus-3) Qualisys motion capture system (Qualisys, Gothenburg, Sweden) at a sampling frequency of 200 Hz. Ground reaction forces (1000 Hz) were collected using an AMTI force platform (AMTI, Newton, MA) embedded in a 15-m runway.

Procedures. Participants underwent a single 2-h testing session at a university biomechanics laboratory. After assent and consent, the participant's name, date of birth, and sex were recorded. Height (m) and weight (lb) were measured using a stadiometer and an AMTI force plate (AMTI), respectively. Both height and weight were used in calculating BMI percentile via the CDCP's BMI percentile calculator, which uses height, weight, age, and gender in its calculations (23). All participants wore standardized footwear (Nike Pegasus) to control for the

TABLE 1. Participant demographics of the HW and OW groups.

Variables	HW	OW/OB	*P*
Sex	M = 12, F = 14	M = 8, F = 8	
Age (yr)	9.8 ± 1.3	10.2 ± 1.3	0.30
Height (m)	1.4 ± 0.1	1.5 ± 0.1	0.26
Mass (kg)	36.5 ± 7.2	52.7 ± 10.3	<0.01*
BMI percentile	52.7 ± 22.6	93.9 ± 4.7	<0.01*

*Significant difference between groups ($P < 0.05$).

effect of footwear on running mechanics. Participant's leg length was measured bilaterally from the anterior superior iliac spine to the medial malleolus. Retroreflective markers were placed on the anterior, posterior, and lateral portions of the shoe; lateral and medial malleolus; lateral and medial condyles of the knee; greater trochanter; anterior superior iliac spine; superior border of the iliac crest; and lumbosacral section of the spine. Clusters of four markers on rigid base plates were attached to the thigh and shank (Fig. 1). A 5-min warm-up that included light jogging and stretching was performed after the placement of reflective markers. A static calibration trial was then collected while the participant stood on a single force platform in the center of the capture volume. After static calibration, anatomical markers were removed from the participant, leaving only the tracking markers on the participant during the movement trials. Next, participants ran across a 15-m runway, embedded with a ground reaction force platform, at a given speed of 3.5 $\text{m}\cdot\text{s}^{-1}$ ± 5% (Fig. 1). Two to three practice trials were performed to help familiarize participants with the correct running speed, to help establish starting position, and to ensure participants contacted the forceplate with the correct foot. Participants then repeated the running trials 8–10 times. After each running trial, participants walked back to the starting position and were provided a minimum of 60–120 s of rest before starting their next trial. No participants reported being tired and did not appear winded for any of the trials. Trials were excluded and repeated if the participant (a) did not strike the force plate entirely with their dominant foot, (b) ran outside of the accepted speed range during the set speed trials, (c) adjusted their running mechanics based on force plate location, and/or (d) sped up or slowed down while crossing the forceplate. The first three to five trials that met each of the above criteria were used for analysis. Foot dominance was defined as the foot the participant would use to kick a ball. Running speed was monitored using a photocell timing system.

Data reduction. The CDCP's BMI percentile calculator was used to determine participant placement into the OW/OB or HW groups (23). Participants classified ≥85th percentile were placed into the OW/OB group, whereas participants ≥5th and <85th percentile were placed into the HW group. BMI percentile was used because of its wide acceptance among clinicians and researchers as a valid and reliable tool to screen children for overweight and obesity.

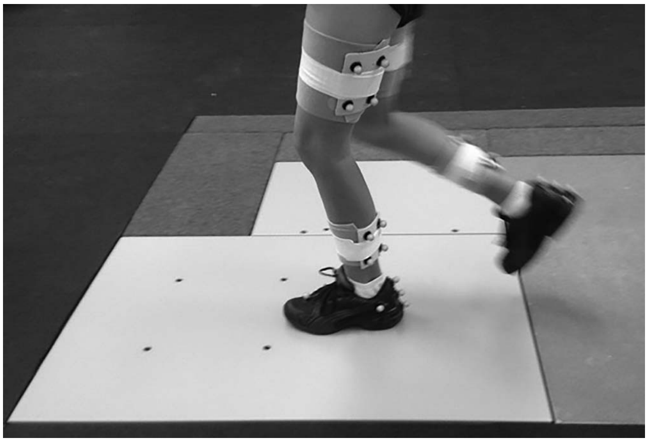

FIGURE 1—Participant with tracking markers completing a running trial.

Reflective markers were labeled then digitized using Qualisys Track Manager Software (Qualisys). The digitized markers were used to calculate joint motion using Visual 3-D (C-Motion, Inc., Germantown, MD). Functional hip joint centers were calculated using the method outlined by Hicks and Richards (24). Marker data were filtered with a recursive fourth-order Butterworth filter at 5 Hz (25). Kinematic variables of interest included sagittal and frontal plane joint angles and excursions of the hip, knee, and ankle joints. Excursions for early stance were calculated from foot strike (FS) to vertical impact peak (VIP) and FS to FZ_{max}. Total joint excursion was calculated as the difference between the maximum and the minimum joint angles during stance.

Ground reaction force data were filtered with a recursive fourth-order Butterworth filter with a cutoff frequency of 50 Hz. Kinetic variables of interest from the ground reaction force data during running included VIP, average vertical load rate, instantaneous vertical load rate, FZ_{max}, peak braking force, and peak propulsive force. Three-dimensional joint and segment angles were calculated with Visual 3-D software (C-Motion, Inc.) using an X, Y, Z Euler angle rotation sequence (26). Segment inertial properties were used to calculate internal joint moments (27,28). Customized software (LabVIEW 18.0; National Instruments, Austin, TX) was used to extract and calculate all the variables of interest from the Visual 3-D motion files.

Because OW/OB children have a more mass than HW children, it would be expected that OW/OB children would display significantly greater unscaled ground reaction forces and joint moments than HW children. However, as body mass increases, there is not a proportionate increase in bone density, joint surface area, and/or muscle mass to accommodate for the increased load (29). Greater unscaled force distributed over a similar, or slightly larger joint surface area, would likely result in greater overall stress at that joint. For this reason, both scaled and unscaled ground reaction force and joint moment variables are reported. For the scaled variables, ground reaction forces were scaled to body mass, and joint moments were scaled to body mass and height.

Statistical analysis. For all variables of interest, the average of three to five trials was used for statistical comparisons. Kinematic variables of interest included stance time, step length, and frontal and sagittal plane joint angles and excursions at the hip, knee, and ankle. Kinetic variables of interest included ground reaction forces and peak hip, knee, and ankle moments in the sagittal and frontal planes. A one-way ANOVA (group as factor) was used to compare group differences for all variables of interests using SPSS software (Version 25.0; IBM® SPSS® Statistics, Chicago, IL). Effect sizes were calculated using Cohen's d with 0.2, 0.5, and 0.8 considered small, medium, and large effects, respectively (30). Box plot analyses were used to

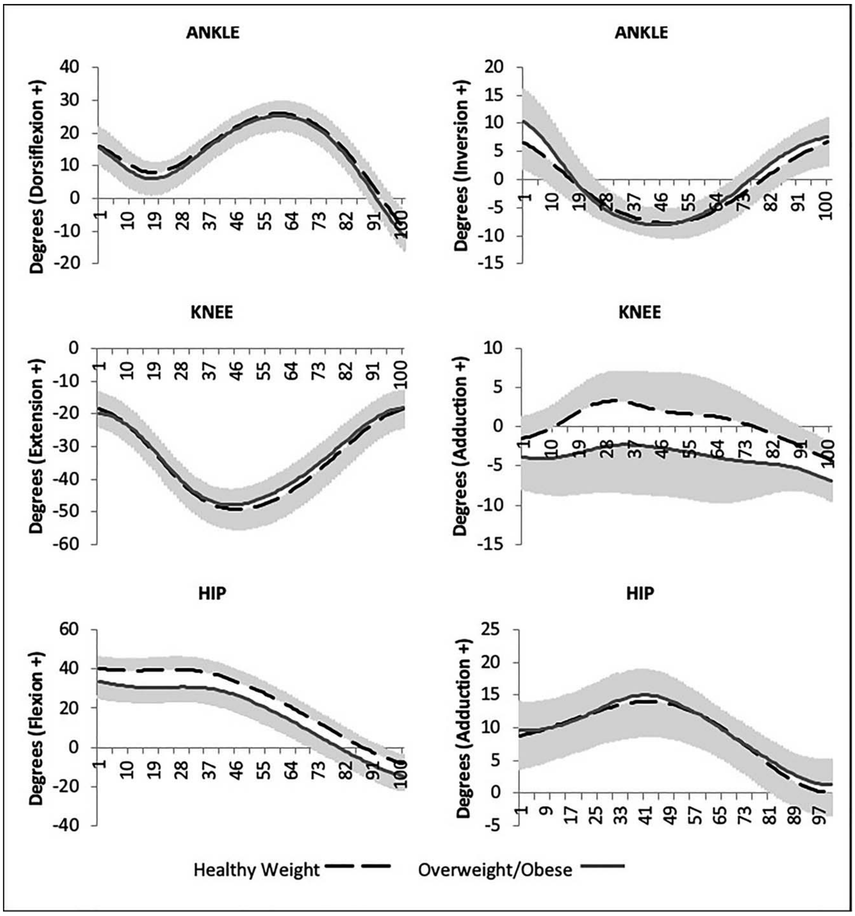

FIGURE 2—Joint angle curves of the ankle, knee, and hip in the sagittal and frontal planes during the stance phase of running.

identify and remove outliers. The level of significance was set at $P < 0.05$. Data are presented as mean and SD.

RESULTS

Spatial–temporal variables. All participants ran between the given speeds of 3.3 and 3.68 m·s^{-1} (3.5% ± 5%) (OW/OB = 3.47 ± 0.04 m·s^{-1}, HW = 3.49 ± 0.04 m·s^{-1}, $P = 0.23$). However, the time spent in stance was 24% longer for the OW/OB group compared with the HW group (OW/OB = 0.37 ± 0.13 s, HW = 0.29 ± 0.10 s, $P = 0.06$). In addition, the OW/OB group displayed significantly shorter step lengths during running than the HW control group (OW/OB = 0.73% ± 0.07% body height, HW = 0.79% ± 0.07% body height, $P = 0.009$). Both differences were associated with a moderate effect ($d = 0.73$ and 0.72, respectively).

Joint kinematics. Sagittal and frontal plane curves for the hip knee and ankle joint angles can be found in Figure 2. In the sagittal plane, the HW group displayed greater hip flexion angles at FS, VIP, and FZ_{max} when compared with the OW/OB group ($P \leq 0.01$, $d \geq 0.90$) (Table 2). During early stance, hip extension excursion was significantly greater in the OW/OB group ($P < 0.01$, $d = 1.36$), whereas knee flexion excursion was significantly greater in the HW group ($P \leq 0.03$, $d \geq 0.74$) (Table 3). In the frontal plane, the OW/OB group displayed greater ankle eversion at FS and knee abduction at FS, VIP, and FZ_{max} compared with the HW group ($P \leq 0.05$, $d \geq 0.61$) (Table 2). Compared with HW children, the OW/OB group displayed greater ankle eversion excursion and less knee and hip adduction excursions during the first part of the stance phase ($P \leq 0.04$, $d \geq 0.69$) (Table 3). Total ankle excursion in the frontal

TABLE 2. Mean ± SD, *P* values, and effect sizes (Cohen's *d*) of joint angles (degrees) at FS, VIP, and FZ_{max} for the HW and OW/OB groups.

Variables		HW	OW/OB	*P*	*d*
Dorsiflexion	FS	16.0 ± 6.1	15.7 ± 5.4	0.89	
	VIP	8.23 ± 3.6	7.00 ± 4.5	0.33	
	FZ_{max}	21.6 ± 4.3	19.7 ± 6.7	0.26	
Knee flexion	FS	−18.4 ± 6.0	−20.1 ± 6.2	0.39	
	VIP	−31.2 ± 5.5	−29.7 ± 4.3	0.38	
	FZ_{max}	−49.3 ± 6.6	−46.7 ± 5.9	0.20	
Hip flexion	FS	40.6 ± 6.3	34.5 ± 7.3	0.01*	0.90
	VIP	39.8 ± 6.6	31.1 ± 6.4	<0.01*	1.32
	FZ_{max}	34.2 ± 6.9	27.4 ± 7.8	<0.01*	0.92
Ankle inversion (+)/ Eversion (−)	FS	6.56 ± 4.9	10.1 ± 5.2	0.03*	0.71
	VIP	−0.93 ± 3.7	−0.46 ± 3.3	0.69	
	FZ_{max}	−7.72 ± 2.9	−7.81 ± 2.9	0.92	
Knee adduction (+)/ Abduction (−)	FS	−1.61 ± 2.9	−3.91 ± 4.5	0.05*	0.61
	VIP	1.33 ± 3.6	−3.41 ± 5.1	<0.01*	1.07
	FZ_{max}	1.90 ± 5.3	−2.91 ± 6.4	0.01*	0.82
Hip adduction	FS	8.97 ± 5.3	9.69 ± 4.5	0.67	
	VIP	11.7 ± 5.5	11.1 ± 4.3	0.71	
	FZ_{max}	14.3 ± 5.3	14.8 ± 3.5	0.78	

*Significant difference between groups ($P < 0.05$)

TABLE 3. Mean ± SD, *P* values, and effect sizes (Cohen's *d*) of total joint excursion (max–min), joint excursions from FS to VIP, and joint excursions from FS–FZ_{max} for the HW and OW/OB groups.

Variables		HW	OW/OB	P	d
Sagittal plane					
Dorsiflexion (+)/	Max–min	19.0 ± 3.3	19.3 ± 2.5	0.75	
Plantarflexion (–)	FS–VIP	–8.26 ± 3.6	–8.75 ± 3.1	0.66	
	FS–FZ_{max}	5.63 ± 5.6	3.93 ± 6.9	0.39	
Knee flexion	Max–min	31.2 ± 5.6	28.0 ± 4.9	0.07	
	FS–VIP	–12.7 ± 3.7	–9.60 ± 4.6	0.02*	0.76
	FS–FZ_{max}	–30.9 ± 5.7	–26.6 ± 6.0	0.03*	0.74
Hip flexion (+)/	Max–min	29.4 ± 3.5	29.2 ± 3.0	0.87	
Extension (–)	FS–VIP	–0.86 ± 2.0	–3.37 ± 1.7	<0.01*	1.36
	FS–FZ_{max}	–6.46 ± 4.0	–7.07 ± 3.5	0.64	
Frontal plane					
Ankle inversion (+)/	Max–min	14.8 ± 4.0	18.6 ± 4.6	<0.01*	0.89
Eversion (–)	FS–VIP	–7.49 ± 3.8	–9.62 ± 3.3	0.07	
	FS–FZ_{max}	–14.3 ± 4.2	–18.0 ± 4.7	0.01*	0.83
Knee adduction (+)/	Max–min	6.67 ± 2.7	6.55 ± 3.1	0.89	
Abduction (–)	FS–VIP	2.94 ± 2.1	0.50 ± 3.2	<0.01*	0.92
	FS–FZ_{max}	3.51 ± 4.4	1.00 ± 5.5	0.12	
Hip adduction	Max–min	8.62 ± 1.7	8.98 ± 2.5	0.60	
	FS–VIP	2.76 ± 1.7	1.39 ± 2.2	0.04*	0.69
	FS–FZ_{max}	5.33 ± 2.6	5.06 ± 3.3	0.79	

*Significant difference between groups ($P < 0.05$).

plane throughout stance was also significantly greater in the OW/OB group compared with the HW group ($P = 0.007$, $d = 0.89$) (Table 3). No other significant group differences were detected for the remaining joint kinematic variables of interest ($P > 0.05$).

Ground reaction forces. Results of the ground reaction force variables can be found in Table 4. FZ_{max} was the only ground reaction force variable scaled to body weight that exhibited a significant group difference. Children classified as HW displayed significantly greater FZ_{max} when compared with children classified as OW/OB ($P = 0.004$, $d = 1.01$). When the unscaled ground reaction force variables were compared across the two groups, the OW/OB group displayed significantly greater vertical and horizontal loading in all variables of interest ($P \leq 0.03$, $d \geq 0.79$).

Joint kinetics. Results of the peak joint moments can be found in Table 5. Curves for the unscaled sagittal and frontal plane moments at the ankle, knee, and hip can be found in Figure 3. When moments are scaled to body mass and height, the results indicate that children who are classified as OW/OB display significantly greater peak knee adduction and hip abduction moments than HW children ($P \leq 0.05$, $d > 0.71$). Peak hip extension moments scaled to body mass and height were significantly higher in the HW children ($P = 0.03$, $d = 0.78$). No other differences in peak moments scaled to body mass and height were detected.

TABLE 4. Mean ± SD, *P* values, and effect sizes (Cohen's *d*) for GRF variables scaled to BW and unscaled GRF (N) for the HW and OW/OB groups.

Variables	HW	OW/OB	P	d
GRF scaled to BW				
FZ_{max} (BW)	2.58 ± 0.22	2.38 ± 0.17	<0.01*	1.01
VIP(BW)	1.76 ± 0.41	1.87 ± 0.41	0.48	
VILR ($BW \cdot s^{-1}$)	74.4 ± 33.3	75.7 ± 33.2	0.90	
VALR ($BW \cdot s^{-1}$)	62.8 ± 27.7	61.4 ± 29.8	0.88	
Peak braking force (BW)	–0.35 ± 0.07	–0.34 ± 0.05	0.60	
Peak propulsive force (BW)	0.32 ± 0.03	0.31 ± 0.03	0.22	
Unscaled GRF				
FZ_{max} (N)	911.3 ± 231	1221.3 ± 201	<0.01*	1.43
VIP (N)	604.3 ± 157	958.6 ± 291	<0.01*	1.51
VILR ($kN \cdot s^{-1}$)	24.68 ± 10.5	39.09 ± 19.8	0.01*	0.91
VALR ($kN \cdot s^{-1}$)	20.87 ± 8.60	31.87 ± 17.7	0.03*	0.79
Peak braking force (N)	–123.9 ± 30.1	–173.4 ± 41.3	<0.01*	1.37
Peak propulsive force (N)	113.3 ± 27.9	158.6 ± 28.9	<0.01*	1.59

*Significant difference between groups ($P < 0.05$).

GRF, ground reaction force; BW, body weight; N, newtons; OW/OB, overweight/obese; VALR, average vertical loading rate; VILR, instantaneous vertical loading rate.

TABLE 5. Mean ± SD, *P* values, and effect sizes (Cohen's *d*) for peak joint moments scaled to body mass and height (N·kg) and unscaled to body mass and height (N·m) for the HW and OW/OB groups.

Variables	HW	OW/OB	P	d
Moments scaled to mass (N·kg)				
Sagittal plane				
Dorsiflexion	0.23 ± 0.08	0.21 ± 0.06	0.47	
Plantarflexion	–1.56 ± 0.22	–1.55 ± 0.15	0.88	
Knee extension	1.34 ± 0.27	1.30 ± 0.17	0.58	
Knee flexion	–0.30 ± 0.09	–0.32 ± 0.06	0.47	
Hip Extension	–1.88 ± 0.40	–1.59 ± 0.35	0.03*	0.78
Hip flexion	0.03 ± 0.08	0.05 ± 0.20	0.64	
Frontal plane				
Ankle inversion	0.24 ± 0.07	0.24 ± 0.07	0.98	
Ankle eversion	–0.01 ± 0.02	–0.02 ± 0.02	0.32*	
Knee adduction	0.12 ± 0.09	0.21 ± 0.15	0.02*	2.79
Knee abduction	–0.38 ± 0.14	–0.39 ± 0.22	0.90	
Hip adduction	0.18 ± 0.11	0.18 ± 0.18	0.92	
Hip abduction	–0.92 ± 0.27	–1.09 ± 0.21	0.05*	0.71
Unscaled moments (N·m)				
Sagittal plane				
Dorsiflexion	12.0 ± 4.8	16.9 ± 7.3	0.01*	0.79
Plantarflexion	–84.6 ± 29	–120 ± 23	<0.01*	1.34
Knee extension	73.0 ± 28	102 ± 27	<0.01*	1.04
Knee flexion	–15.6 ± 5.0	–24.8 ± 8.1	<0.01*	1.37
Hip extension	–100 ± 35	–117 ± 30	0.15*	
Hip flexion	0.86 ± 4.4	0.77 ± 9.5	0.97	
Frontal plane				
Inversion	12.9 ± 5.1	18.8 ± 6.7	<0.01*	0.99
Eversion	–0.59 ± 0.9	–1.11 ± 1.1	0.12*	
Knee adduction	8.21 ± 9.8	14.5 ± 10	0.06	
Knee abduction	–20.9 ± 10	–30.8 ± 21	0.05*	0.60
Hip adduction	9.22 ± 6.4	14.2 ± 12	0.12	
Hip abduction	–54.2 ± 33	–80.1 ± 22	0.01*	0.94

*Significant difference between groups ($P < 0.05$).

Several differences were detected when the absolute values of the peak moments were compared across the HW and OW/OB groups of children. In the sagittal plane, children classified as OW/OB displayed significantly greater unscaled plantarflexion and dorsiflexion moments compared with HW children ($P \leq 0.01$, $d \geq 0.79$). Unscaled peak knee flexion and extension moments were also significantly greater in the OW/OB group ($P \leq 0.001$, $d \geq 1.04$). In the frontal plane, the OW/OB group displayed greater unscaled peak ankle inversion, knee abduction, and hip abduction moments compared with the HW group of children ($P \leq 0.05$, $d \geq 0.60$).

DISCUSSION

The purpose of this study was to compare running mechanics between children classified as overweight or obese (OW/OB) and children classified as having HW. We hypothesized that the OW/OB group would display increased vertical loading, joint moments, and frontal plane joint angles and excursions and decreased sagittal plane joint angles and excursions compared

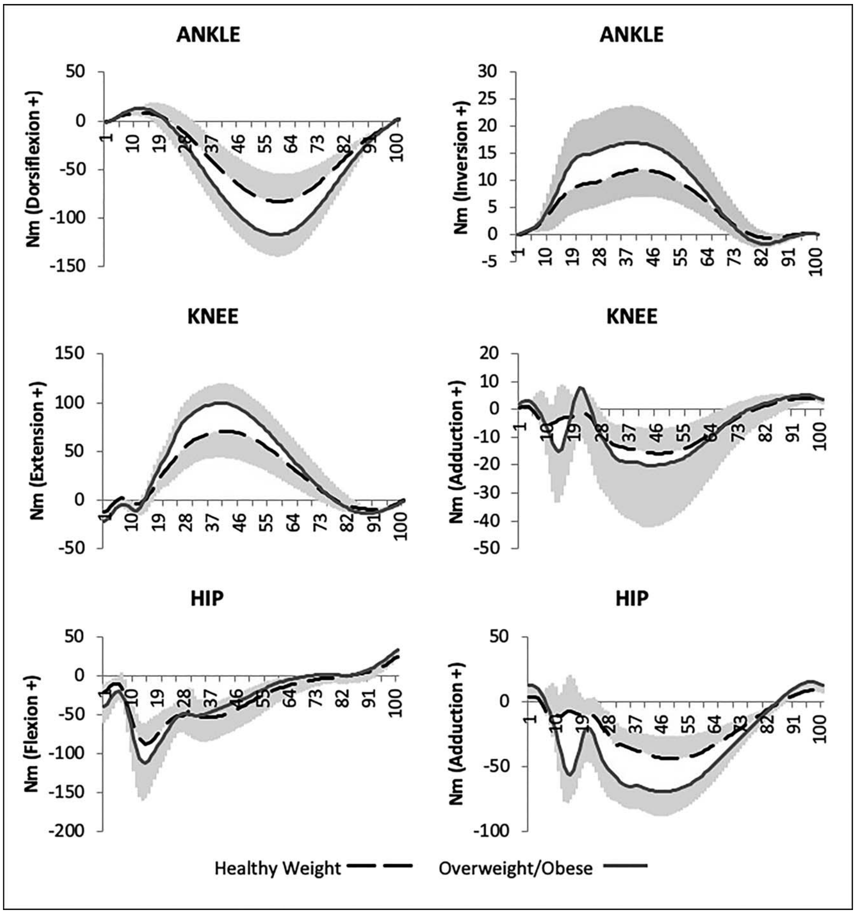

FIGURE 3—Unscaled joint moments of the ankle, knee, and hip in the sagittal and frontal planes during the stance phase of running.

with the HW group. Based on our results, there appear to be several kinematic and kinetic differences in running mechanics between these two groups of children, confirming many of our predictions.

Spatiotemporal Differences

Even with both groups running the trials at the same speed, the OW/OB children displayed shorter step lengths and spent more time in the stance phase compared with the HW group of children. These findings are consistent with previous research studies reporting that obese children display shorter step lengths during walking and running and spend more time in the stance phase during running compared with HW children (7,31). Huang and colleagues (31) suggest that obese children use a shorter step length during walking to avoid the higher metabolic cost needed to transport excess body mass. However, the obese children in their study also displayed significantly slower walking velocities compared with the HW children, which likely explains their shorter step lengths. With no group differences in running speeds for our study, it is unknown if shorter steps would result in decreased or increased energy expenditure.

Another possible explanation for the group differences in step length and stance time may be the decreased range of motion and poor balance observed in obese children. Compared with HW children, obese children demonstrate significantly lower joint ranges of motion with the largest differences in the lower extremity joints (32). The OW/OB group in our study did display significantly lower hip flexion angles during the first part of stance as well as smaller knee flexion excursions compared with the HW group. Although we did not directly measure joint range of motion in our study, it is possible that OW/OB children ran with shorter steps due to a limited range of motion at the knee and hip joints. Regarding balance, previous studies have demonstrated that children have greater postural instability compared with their HW counterparts (33). Colné and colleagues (33) explain that overweight children experience greater difficulty in controlling the fall of their center of gravity during gait. Colné et al. go on to explain that using shorter step lengths and spending more time in stance may help overweight children better control the fall of the center of gravity during each step helping them to maintain equilibrium during gait. Our findings indicate that the OW/OB children in this study ran with shorter steps and spent more time in the stance phase. If these changes are due to limited range of motion and/or impaired balance, clinicians may need to incorporate flexibility and balance training into the daily activities of OW/OB children. More research is needed to definitively determine whether these differences were due to limited range of motion and/or postural instability of the OW/OB group.

Differences in Joint Kinematics

Differences in the sagittal plane joint angles and excursions occurred exclusively at the hip and knee joints. As predicted, the OW/OB group of children displayed greater knee and hip flexion excursions compared with the HW group of children. These differences occurred primarily in the early portion of the stance phase (Tables 2–3). Although this is the first study to examine differences in joint angles and excursions of OW/OB children during running, our results are consistent with previous studies reporting that obese children display decreased hip and knee angles and excursions during the stance phase of walking (8,13). The decreased knee and hip flexion during early stance is suggested to be indicative of a more rigid gait pattern that could potentially result in greater vertical loading on the body (8). Qualitatively, approximately half of the children classified as HW (n = 12) displayed hip flexion during early stance with the other half displaying hip extension. In comparison, only one child classified as OW/OB displayed hip flexion during early stance. The lack of flexion during early stance may be due to a decreased range of motion at the lower extremity joints, which may be related to the increased amount of adiposity. If the OW/OB children are unable to reach a higher degree of flexion during high-impact activities, such as running, their body may not absorb as much shock as the body of someone who goes into greater flexion.

Several group differences were also detected in the frontal plane. The OW/OB group displayed significantly greater inversion at FS. However, no group differences in the ankle eversion angle were detected at FZ_{max}, which occurs close to midstance. Subsequently, the OW/OB children displayed significantly greater eversion excursions at the ankle during the first part of stance (P = 0.01). Furthermore, an examination of the steeper slope for ankle inversion/eversion in Figure 2 suggests that the OW/OB may have also had greater eversion velocity. Excessive heel eversion excursions and eversion velocity has previously been linked to various running-related injuries, including tibial stress fractures, patellofemoral pain syndrome, and Achilles tendonopathy (34–36).

As predicted, the OW/OB group displayed greater knee abduction than the HW group of children. Consistent with previous findings, the OW/OB spent the entirety of stance in an abducted knee position (13). In comparison, the HW group began in a slightly abducted knee position, quickly transitioned to a knee adducted position before returning to a knee abducted position for the last 25% of the stance phase (Fig. 2). Increased knee abduction angles during dynamic movements have been identified as a mechanism for noncontact ACL injuries and have been associated with increased strain on the ACL (37,38). In addition, increased knee abduction angles during running have been reported to increase contact forces on the lateral patellofemoral joint (39). The increased knee abduction angles exhibited by the OW/OB during running may potentially increase their risk of developing patellofemoral pain syndrome and ACL injuries. In comparing the frontal plane knee excursions, the HW group displayed greater knee adduction excursions during the first part of stance compared with the OW/OB groups. However, the total knee excursions were similar across groups. These findings can partially be explained by comparing the knee abduction/adduction curve in Figure 2. During the first 5%–10% of stance, the OW/OB group displays a small knee abduction excursion before starting to abduct, whereas the HW group starts adducting at the knee at FS. As predicted, no group differences were detected for frontal plane hip angles and hip joint excursion throughout stance. Our findings are consistent with other studies who also did not find differences in frontal plane hip angles and excursions between obese and HW children during walking (9,12,40).

Differences in Ground Reaction Forces and Joint Moments

As expected, several of the ground reaction force and joint moment variables of interest were significantly greater in the OW/OB compared with HW group. Unscaled ground reaction forces and joint moments accounted for most of these group differences. With few exceptions, ground reaction forces and joint moments scaled to body mass were not significantly different across groups. However, it is important to note that scaling ground reaction forces and joint moments to body mass does not consider that increases in plantar and joint surface areas are not proportionate to increases in body mass (29). It has been reported that a 49% increase in body mass in children is associated with a 20% increase in their foot contact area during running (7). Ding and colleagues (29) reported that a 48% increase in body mass was associated with only an 8% increase in tibial plateau surface area. Furthermore, it has also been reported that overweight children have reduced bone mineral density and reduced bone strength compared with HW children (41). Findings from these studies suggest that even if ground reaction forces and joint moments scaled to body mass are similar across groups, because of greater mass, OW/OB children may experience greater loading on less dense bones and across relatively smaller surface areas. Although plantar and joint surface areas and bone density were not evaluated in this study, examining the unscaled ground reaction forces and joint moments can provide greater insight into the loads experienced by children during running.

Ground reaction forces. All unscaled GRF variables of interest were significantly greater in the OW/OB children. These results confirm our hypothesis that OW/OB children would display greater vertical loading during running compared with HW children. Of major concern is our finding that VIP, average vertical loading rate, and instantaneous vertical loading rate were over 40% higher in the OW/OB children compared with the HW children. These findings are consistent with Rubinstein et al. (7) who reported the greatest difference in FZ_{max} between overweight and HW children is in the heel region of the foot during early stance. Both retrospective and prospective studies have linked increased vertical loading during early stance to several overuse running injuries, including tibial stress fractures, patellofemoral pain syndrome, iliotibial band syndrome, plantar fasciitis, and other soft tissue injuries (42–44). A prospective study of 242 runners reported that those with high loading rates were at a three times greater risk of developing a running-related injury compared with those with low loading rates (42). Of further concern is that even with significantly greater surface area of the foot in contact with the ground, OW/OB children display significantly greater peak pressures on the plantar surface of their feet during running (3,7,20). Increased vertical loading and foot pressure for obese children has been linked to increased foot discomfort, pain, and injury. In addition, higher plantar pressure of overweight children is inversely associated with physical activity levels (45). These findings are problematic considering running is a component in many of the moderate- to vigorous-intensity activities recommended for children by the World Health Organization and the U.S. Department of Health and Human Services.

FZ_{max} was the only GRF scaled to body mass that displayed a significant group difference. Compared with the OW/OB children, the HW children demonstrated significantly greater FZ_{max} scaled to body weight. Anecdotally, we observed that many of the HW children appeared to run with a more bounding/up and down motion compared with the OW/OB children. Considering that FZ_{max} represents the push off in the vertical direction, a greater FZ_{max} would likely result in greater vertical displacement of the body's center of mass. However, follow-up analysis revealed no group differences for vertical center of mass displacement scaled to height (HW = 5.4% ± 1.0% body height, OW/OB = 5.3% ± 1.3% body height, $P = 0.77$). At this time, it is unclear why the FZ_{max} scaled to body mass is greater in the HW group. However, unlike the other ground reaction force variables that occur during the loading phase of stance, FZ_{max} occurs during the push-off phase of stance and has not been found to be a significant predictor of injury (42). The lower rate of loading that commonly precedes FZ_{max} likely explains why it has not previously been linked to injury (42).

Joint moments. As predicted, several significant group differences were detected with the OW/OB children displaying greater peak joint moments compared with the HW children. Our results are consistent with Briggs et al. (17), who reported unscaled peak knee moments in the frontal and sagittal planes are significantly greater in obese adolescents (age 12–18 yr) during both walking and jogging. Similarly, Shultz and colleagues (9) reported overweight children display higher unscaled hip, knee, and ankle joint moments in the frontal and sagittal planes during walking. In a study by Gushue et al. (12), unscaled ankle plantarflexion and knee abduction moments during walking were also significantly greater in overweight children.

The increased joint moments exhibited by the OW/OB children in our study may partially be explained by their more rigid running pattern. As mentioned previously, only one of the children classified as OW/OB displayed hip flexion during early stance. In addition, knee flexion excursions were also significantly lower for the OW/OB children. The more rigid gait pattern accompanied by greater unscaled ground reaction forces likely contributed to the greater unscaled joint moments observed in the OW/OB children.

Greater joint moments at the hip, knee, and ankle during walking and running suggest greater joint loading, increased risk of malalignments, and increased risk of joint injury and/or joint damage for children classified as OW/OB (9). A common joint injury observed in obese children is slipped capital femoral epiphysis. Researchers suggest that increased hip extensor moments and hip abduction angles will, respectively, increase the compressive and shear forces on the capital femoral growth plate potentially, resulting in femoral neck fractures or slipped capital femoral epiphysis (18,46). Unscaled hip abduction was significantly greater in the OW/OB group of our study potentially increasing their risk for developing these hip injuries. Higher than normal frontal plane joint moments at the hip and knee have also been linked to the development of genu valgum and tibia vara, malalignments often observed in obese individuals (16). Although knee alignment was not directly evaluated in this study, children classified as OW/OB displayed an abducted knee position throughout the stance phase (Fig. 2). This finding would be consistent with someone who displays genu valgum. Subsequently, the abducted knee position and greater knee abductor moments displayed by the OW/OB group in our study may indicate increased lateral compartment loading of the tibial femoral joint. For OW/OB children who may be predisposed to varus alignment, increased knee adductor moments may also be problematic. Increased knee adductor moments have been linked to increased compressive loads on the medial compartment of the tibial femoral joint and may result in tibia vara (4). Although tibia vara is not as common as genu valgum among obese children, both malalignments have been linked to uneven loading at the tibiofemoral joint. In addition, higher than normal frontal plane joint moments at the hip and knee during running have also been linked to increased joint loading at the patellofemoral joint and the development of both patellofemoral pain syndrome and knee osteoarthritis (47).

Consistent with previous literature, we also observed significantly higher unscaled ankle plantarflexion and inversion moments in children classified as OW/OB (9,12). Ankle inverter moments are necessary to help slow down and control ankle eversion during early stance of running. Subsequently, the OW/OB children in our study may have increased inversion moments to help control their increased ankle eversion displacement during early stance. Increased plantarflexion moments observed in the OW/OB children in this study are likely explained by the need to propel a greater body mass forward (46). Unfortunately, increased plantarflexion moments during running have been linked to increased loads on the Achilles tendon resulting in the increased risk of developing Achilles tendinopathy (48). Shultz and colleagues (9) suggest that increased plantarflexion moments during gait may also increase peak pressure under the forefoot and metatarsal heads, leading to increased risk of metatarsal stress fractures and general foot pain. As such, increased plantarflexion and inversion moments during running may place increased loads on the structures of the foot and ankle that place OW/OB children at an increased risk for developing these injuries.

Although several group differences were detected for the unscaled joint moments in our study, there were only a few group differences detected for the joint moments scaled to body weight. Interestingly, all but one significant group difference for joint moments scaled to body weight indicated greater joint moments in children classified as OW/OB. These findings further emphasize the impact that excessive weight has on increased joint moments and loading during running.

Limitations

One limitation of this study was the lack of physical activity and sedentary time data from participants. Because a child's daily activity, or lack thereof, can greatly influence how their body adapts to daily loading, knowing the child's activity level could give further insight into how running, regardless of weight, may impact the lower extremity joints. Another potential limitation to this study is using a standard running speed across all participants. While using a given running speed can minimize the impact of different running speeds on differences in running mechanics, a given running speed may not represent the typical running mechanics of children who may prefer a slower or faster running speed. It is possible that OW/OB children may choose running speeds that result in running mechanics that are more similar to the HW children. Future studies that include self-selected running speeds of OW/OB and HW children may provide additional information on potential differences between these two groups. Another potential limitation is skin movement artifact caused by excess adipose tissue. To minimize the impact of movement artifact and to improve accuracy of our kinematic data, we used the recommended methods of previous researchers who evaluated 3D kinematics in obese children (9,12,13,17) by having the same researcher place markers on all participants, using rigid marker clusters and using the spherical fit model to calculate functional hip joint centers. Lastly, because of the cross-sectional design of this study, a direct causal relationship between excess body mass and running mechanics cannot be determined. Longitudinal studies that examine the impact of body mass on running mechanics throughout adolescence and into adulthood are needed to provide additional insight.

CONCLUSIONS

This is the first known study where a running gait analysis, that includes both kinematic and kinetic data, has been conducted comparing children classified as OW/OB and HW. Several differences in running mechanics are present between OW/OB and HW children. Among the most notable are the higher ground reaction forces and unscaled joint moments, which may result in greater joint loading, malalignments, and potential joint pathologies. Encouraging participation in physical activity is crucial in reducing childhood obesity rates. Equally as important is prescribing appropriate exercise that do not place a child at an increased risk for developing other types of injuries or pathologies associated with excessive loading or malalignments. Progression from low- to high-impact activities may give the bone and muscle time to adjust to the increasing loads, potentially reducing and ideally eliminating the OW/OB children's increased risk of pain and injury. Creating a positive association with physical activity is important at a young age. By reducing a child's risk of pain and/or injury during physical activity, we may be able to increase the likelihood that they will enjoy and be willing to engage in physical activity throughout their life.

This project was supported by the Agriculture and Food Research Initiative (AFRI) grant no. 2011-67002-30202 from the USDA National Institute of Food and Agriculture. Childhood Obesity Prevention: Transdisciplinary Graduate Education and Training in Nutrition and Family Sciences or Child Development or Related Fields to Prevent Childhood Obesity–A2121.

The authors do not have any conflicts of interest related to this study. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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