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Differences in Running Mechanics and Tibial Plateau Dimensions between Overweight/Obese and Healthy Weight Children

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DIFFERENCES IN RUNNING MECHANICS AND TIBIAL PLATEAU DIMENSIONS BETWEEN OVERWEIGHT/OBESE AND HEALTHY WEIGHT CHILDREN

BY

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This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science in Nutrition and Exercise Science degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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ABBREVIATIONS

ACL	Anterior Cruciate Ligament
ASIS	Anterior Superior Iliac Spines
AVLR	Average Vertical Load Rate
BMI	Body Mass Index
BF	Body Fat
CDCP	Center for Disease Control and Prevention
DENS	Density
DXA	Dual-Energy X-Ray Absorptiometry
GRF	Ground Reaction Forces
HW	Healthy Weight
IC	Iliac Crest
IVLR	Instantaneous Vertical Load Rate
MaxFz	Peak Vertical Ground Reaction Force
OW/OB	Overweight/Obese
pQCT	Peripheral Quantitative Computed Tomography
VIP	Vertical Impact Peak

ABSTRACT

DIFFERENCES IN RUNNING MECHANICS AND TIBIAL PLATEAU DIMENSIONS BETWEEN OVERWEIGHT/OBESE AND HEALTHY WEIGHT CHILDREN

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INTRODUCTION: Overweight and obese (OW/OB) children display increased knee joint loading during running, which may lead to excessive frontal plane motion and moments at the knee joints. The relationship between tibial plateau dimensions and knee vertical loading may explain the loading related injuries OW/OB children experience. PURPOSE: Compare knee mechanics during running and tibial plateau dimensions between healthy weight (HW) and OW/OB children. METHODS: Ten HW children and ten OW/OB children aged 9-12 participated in the study. Kinematic and kinetic data were captured as participants ran across a force platform at 3.5m/s. Tibial plateau area and density were collected by peripheral quantitative computed tomography. Frontal and sagittal plane knee angles and moments, vertical ground reaction forces (GRF) and temporal data were calculated. Mass, vertical GRF and joint moments were scaled by tibial plateau dimensions. A series of one-way ANOVAs were performed to compare group differences. RESULTS: OW/OB children displayed greater knee abduction during the stance phase of running. Mass, vertical GRF and knee joint moments scaled by tibial plateau dimensions were greater in the OW/OB group. DISCUSSION/CONCLUSION: OW/OB children display different running mechanics and loading patterns compared to HW children. The variables scaled by tibial plateau dimensions indicate that OW/OB

children experience excessive loading at the knee during the stance phase of running. The excessive loading may lead to injuries such at ACL tears or osteoarthritis.

INTRODUCTION

One in three children in the United States are classified as overweight or obese (OW/OB) (1). Childhood obesity has been associated with increased risk for cardiovascular disease, greater prevalence of metabolic syndrome, type 2 diabetes, increased depression, and social isolation (2). In addition to the well documented, negative physiological and psychological effects, there are several biomechanical differences that have been suggested to place OW/OB children at increased risk for orthopedic injuries and joint pathologies (2).

Several differences in walking mechanics have been observed between OW/OB and HW children. During the stance phase of walking, OW/OB children display greater hip adduction angles and moments, and greater knee abduction angles and moments (3-7). Additionally, OW/OB children exhibit greater knee valgus alignment (8). In the sagittal plane, OW/OB children display decreased flexion and increased extensor moments at the hip and knee joints during walking (3, 4, 9). Decreased flexion and increased extensor moments at the hip and knee have been associated with increased leg stiffness and increased joint loading (10). Schultz and colleagues report that during walking OW/OB children displayed two times greater joint loading than HW children (3). Increased leg stiffness has also been shown to create higher plantar loading in OW/OB children during walking and running compared to HW children (11). Increased plantar loading has been associated with flatter arches that can lead to foot and ankle pain and fractures (11-14).

Increased body weight combined with increased hip adduction angles and moments can create excessive shear stress at the femoral epiphysis (15). Subsequently, the excessive shear stress can lead to fractures in the growth plate causing the epiphysis to slip out of place (15). Knee valgus alignment has been associated with excessive hip adduction and knee abduction moments during the stance phase of walking (8). The increased moments associated with knee valgus alignment create greater loading on the lateral facet of the tibia and increased strain of the anterior cruciate ligament (ACL) (16, 17). The increased loading and strain at the knee increase the risk of ACL tears and the development of osteoarthritis later in life (16).

One facet that has been overlooked regarding joint loading is tibial plateau dimensions. It has been shown that OW/OB adults have increased tibial plateau surface area, but tibial plateau area has not been shown to increase proportionally to increases in weight and vertical loading. A study by Ding et al. determined the OW/OB mass scaled to tibial plateau area ratio was 0.3 while the HW ratio was 0.2 (18). In OW/OB children, researchers have determined tibial plateau surface area is greater than HW children but have yet to determine the proportionality of the tibial plateaus to mass and vertical loading (19). With the increased loading and relatively smaller tibial plateau area, it is likely that OW/OB children will have increased loading at their joints. Currently there is no data regarding ground reaction forces during running and their relationship between OW/OB children's tibial plateau dimensions. This information could lead to greater clarity on the impact of ground reaction forces on joint loading. Additionally, the research comparing running mechanics between obese and non-obese children has been limited to examining plantar pressure. Plantar pressure can provide meaningful data on loads placed on the foot but does not provide information on lower extremity joint kinematics and kinetics. A running analysis using motion capture and ground reaction forces is needed to determine differences in joint mechanics between OW/OB and HW children.

The primary purpose of this study is to compare running mechanics between OW/OB and HW children. The secondary purpose is to compare tibial plateau dimensions between OW/OB and HW children and determine the relationship between tibial plateau dimensions and running kinetics. We hypothesize that there will be decreased knee flexion and increased knee abduction during the stance phase of running in OW/OB children compared to HW children. We also hypothesize that knee extension, and knee abduction joint moments during the stance phase of running will be greater in OW/OB children compared to HW children. We hypothesize that OW/OB children will have a larger tibial plateau surface area and density than their HW counterparts. Lastly, we hypothesize that OW/OB tibial plateau size will not be proportionate to their body mass, vertical ground reaction forces or joint moments during running.

The information from this study will be beneficial in identifying the risk factors running has for injury in OW/OB children. It can aid professionals and parents with creating programs that allow OW/OB children to exercise without the risk of injury. The findings of the study could lead to the creation of exercise programs tailored specifically to OW/OB children. These programs could lead to more children exercising and can aid in reducing the prevalence of childhood obesity and injuries associated with obesity.

METHODS

Participants

An a priori power analysis (alpha = 0.05. beta = 0.20) using an effect size of 1.20 (pilot data) determined that 20 participants were necessary to identify significant differences with large effects between OW/OB and HW children for each of the variables of interest. Therefore, twenty children between the ages of 8-12 years were recruited from the local community to participate in this study. Participants were included if they had been deemed healthy and free of injury. The children were classified into two groups (OW/OB and HW) based on their Body Mass Index (BMI) percentile. Informed assent and consent forms, as approved by the Institutional Human Subjects Review Board, were completed by the participant and their guardian prior to participation.

Instrumentation

Height and weight were measured using a stadiometer and AMTI force plate (AMTI, Newton, MA) respectively. BMI percentile was calculated using height, weight, age and gender via the Center for Disease Control and Prevention (CDCP) BMI percentile calculator (20). Because height, weight, and relative body fatness change during development, a child's BMI must be interpreted in relation to other children of the same sex and age. BMI percentiles express a child's BMI in relation to national survey data taken in the U.S. (21). Thirty-one retro-reflective markers, and 5 marker clusters, were placed on the participant's torso and legs to identify anatomical landmarks using an obesity specific marker set (22). A spring loading digitizing pointer was used to digitally create virtual markers for the anterior superior iliac spines (ASIS) and iliac crests (IC).

Digitally creating markers using a spring-loaded pointer has been shown to increase the reliability and validity of bony landmarks of the pelvis for obese individuals (22). Eight high speed cameras (Oqus-3, Qualisys, Gothenburg, Sweden) were used to collect (200Hz) movement data during the trials. Ground reaction forces were recorded (2000 Hz) using a force plate (AMTI, Newton, MA) embedded in a 15m runway. Photocells were used to determine running velocity and ensure participants ran at the correct speed for each of their running trials. Body composition (total body fat and bone mineral density) was collected using dual-energy X-ray absorptiometry (DXA) (Hologic Inc., Marlborough, MA). DXA scans have been shown to be a reliable and valid measure of body composition (23). Tibial plateau surface area, density and circumference were determined using peripheral quantitative computed tomography (pQCT) (Pforzheim, Germany). PQCT has been determined to be a valid and reliable measure of bone surface area, circumference and density (24).

Experimental Procedures

Following the completion of parental assent and participant consent, participant's name, date of birth and sex were recorded during their first visit. Participants completed two testing sessions, a running analysis and body composition testing. The two sessions were within one week of each other.

Running Analysis Visit

After providing a description to the participant of what would be completed during this visit, participants were provided running shorts and standardized footwear (Nike Pegasus). Leg length and waist circumference were then measured. Prior to placement of the retro-reflective markers, a 5-10 minute warm up consisting of light jogging and jumping jacks were completed. Using an obesity specific marker set, markers were placed on anatomical landmarks (22). The obesity specific marker set has previously been shown to be more reliable on participants with excess adipose tissue, specifically located in the region of the pelvis (22). Following marker placement, a static calibration trial was recorded with the participant standing on a force plate holding a spring-loaded digitizing pointer. Without moving the participant's feet, a pointer trial was then completed with the participant standing in the same position on the force plate. For this trial, a spring-loaded digitizing pointer was placed and depressed at the anterior superior iliac spine and iliac crest locations following the method outlined in Lerner et al. (22). Following the calibration and pointer trials, anatomical markers were removed, and participants completed five trials running at 3.5m/s ± 5%. Trials consisted of participants running across the force plate embedded in a 15m runway. Participants were given three to five practice trials before each set of trials and one to two minutes rest between each trial. 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 in the middle portion of a trial.

Body Composition Visit

After providing a description to the participant of what would be completed during this visit, body composition and bone mineral density testing was completed. For the DXA scan, the participant was asked to lay in a supine position with hands pronated and resting on the bed. The scanning arm passes over the right, middle and left sides of the body. The DXA scan was used to accurately determine participants' body fat percentage to ensure that BMI classifications are an accurate measure of obesity (23). For the subchondral volumetric bone mineral density scans, a scout scan of the tibiofemoral joint was performed first, after which a reference line was placed on the scout image at half the depth of the region of highest radio opacity near the surface of the tibia midway between the medial border of the medial compartment. An image was then obtained at 2% the depth proximal to the reference line. The scans were taken bilaterally. The pQCT scans were used to give an accurate measure of the surface area, density and circumference of the tibial plateau (24).

Data Reduction and Analysis

Raw data was processed using Visual3D software (C-Motion, Inc, Germantown, MD) and a customized LabView (National Instruments, Austin, TX) program. Force and marker data were filtered using a 4^{th} order low-pass filter at 50 and 6 Hz respectively. Using a 20 N threshold, foot strike and toe-off were identified from vertical ground reaction forces. A subject-specific model was created using the digitally created hip markers in Visual3D. This model was then applied to each of the running trials. Using Visual 3D, joint and segment angles were calculated using an *X, Y, Z* Euler angle rotation sequence. Joint moments and joint angular impulse were also calculated using Visual 3D.

Kinematic variables of interest included knee excursions in the sagittal and frontal plane during stance. Joint excursions were calculated from foot strike to peak values during early stance. Kinetic variables of interest included peak vertical force (maxFz), vertical impact peak (VIP), average and instantaneous vertical load rates (AVLR and

IVLR), sagittal and frontal plane moments at the knee, and knee angular impulse. MaxFz is defined as the peak force on the vertical ground reaction force curve. The local maximum between foot strike and maxFz is defined as VIP. AVLR was calculated as the slope of the curve between 20% to 80% from foot strike to VIP. IVLR was calculated as the maximum slope of the vertical ground reaction curve between 20% to 80% from foot strike to VIP (25). Joint moments were calculated as a product of the segment's moment of inertia and the joint's angular momentum. While peak joint moments provide information about a single time point during stance, angular impulse provides a description of the moment over the entire stance phase. All kinetic variables were reported in absolute values, as well as when scaled to bodyweight, scaled to tibial plateau surface area, and scaled to tibial plateau density. Variables of interest were averaged over five successful trials.

The temporal-spacial variables of interest included stance time, step length, and step width. Stance time was defined as the time the dominate foot is in contact with the ground during one gait cycle. The heel to heel distance between feet in the anterior-posterior direction and medial-lateral direction were defined respectively as step length and step width (11). Step length and step width were scaled by body height.

Body composition variables of interest included total body fat percentage, tibial plateau surface area, and tibial plateau density. DXA images were analyzed using Discovery Software (Hologic Inc., Marlborough, MA) provide by the manufacturer. Pediatric versions of the software were used because all participants were younger than 20 years old. The pQCT images were analyzed using ContMode2, Peel Mode 2, and a threshold of 400mg/cm^3 (Pforzheim, Germany) to obtain trabecular density.

Statistical Analysis

Data was run through a series of one-way ANOVAs to compare variables of interest between groups using SPSS (Version 22.0, IBM® SPSS® Statistics, Chicago, IL, USA). Level of statistical significance was set at $p \leq 0.05$. Cohen's *d* was calculated to determine effect sizes (large > 0.8, medium > 0.5, small > 0.2).

RESULTS

Ten children were classified as OW/OB with a BMI greater than the 85th percentile (n= 4 male, 6 female) and ten children were classified as HW with a BMI less than the 85th percentile (n= 5male, 5 female). Demographic and anthropometric data collected are found in Table 1.

TABLE 1. Demographic and Anthropometric Data of HW and OW/OB groups

	HW	OW/OB	*p*	Cohen's *d*
Age (years)	10.4±1.35	10.5±1.07	0.72	0.08
Height (m)	1.47±0.11	1.56±0.07	**0.05**	**0.98**
Mass (kg)	38.4±9.70	62.8±7.19	**<0.001**	**2.86**
BMI Percentile	52.7±21.5	96.6±2.72	**<0.001**	**2.86**
Waist Circumference (m)	0.63±0.09	0.81±0.54	<**0.001**	0.46
Body Fat %	21.3±2.51	35.3±4.49	**<0.001**	**3.85**

Values are mean±SD. HW: healthy weight, OW/OB: overweight/obese. Significant differences and large effect sizes are in bold $p \leq 0.05$, $d > 0.80$.

Vertical Ground Reaction Forces

Absolute vertical ground reaction forces as well as ground reaction forces scaled by bodyweight, tibia plateau area and tibial plateau density can be found in Figure 2.

Ground reaction force variables of interest and statistics can be found in Table 2. The OW/OB group had statically greater absolute VIP, MaxFz, IVLR and AVLR than the HW group. With the vertical ground reaction forces scaled to bodyweight, the HW group had statically greater MaxFz and AVLR. No difference was found between groups for VIP and IVLR when scaled to bodyweight. When scaled by tibial plateau density, the OW/OB group had significantly greater VIP, MaxFz, IVLR and AVLR. No differences were found between groups for VIP, MaxFz, IVLR and AVLR when scaled to tibial plateau area. All the significant differences were associated with a large effect.

TABLE 2. Ground reaction force variables of OW/OB and HW groups scaled by bodyweight, tibial plateau area and tibial plateau density

		HW	OW/OB	*p*	Cohen's *d*
VIP	Absolute (N)	68.6±19	107±22	**0.001**	**1.87**
	Scaled to Bodyweight (BWs)	1.81±0.4	1.71±0.3	0.55	0.28
	Scaled to Area (N/mm^2)	0.038±0.02	0.048±0.01	0.13	0.63
	Scaled to Dens ($N/mg/cm^3$)	0.27±0.08	0.43±0.1	**0.001**	**1.77**
MaxFz	Absolute (N)	99.3±26	147±13	**<0.001**	**2.32**
	Scaled to Bodyweight (BWs)	2.60±0.3	2.35±0.2	**0.02**	**0.98**
	Scaled to Area (N/mm^2)	0.053±0.02	0.067±0.02	0.09	0.27
	Scaled to Dens ($N/mg/cm^3$)	0.39±0.1	0.59±0.07	**<0.001**	**2.32**
IVLR	Absolute (N)	3546±1001	4804±1210	**0.02**	**1.13**
	Scaled to Bodyweight (BWs)	94.2±23	76.7±19	0.08	**0.83**
	Scaled to Area (N/mm^2)	1.95±0.8	2.10±0.5	0.27	0.22
	Scaled to Dens ($N/mg/cm^3$)	14.1±4.2	19.5±5.9	**0.03**	**1.05**
AVLR	Absolute (N)	3116±800	4085±993	**0.03**	**1.07**
	Scaled to Bodyweight (BWs)	83.0±20	65.1±15	**0.03**	**1.01**
	Scaled to Area (N/mm^2)	1.72±0.7	1.79±0.4	0.78	0.12
	Scaled to Dens ($N/mg/cm^3$)	12.9±3.5	16.6±4.7	**0.04**	**0.89**

Values are mean±SD. VIP: vertical impact peak, MaxFz: peak vertical ground reaction force, IVLR: instantaneous vertical load rate, AVLR: average vertical load rate, Dens: density, HW: healthy weight, OW/OB: overweight/obese. Significant differences and large effect sizes are in bold $p \leq 0.05$, $d > 0.80$.

Joint Kinematics

The comparison of joint kinematics can be found in Figure 1. In the sagittal plane, there was no significant differences between groups for peak knee flexion (OW/OB -

47.32±8.3, HW -46.97±3.5), knee flexion at FS (OW/OB -19.18±7.7, HW -17.19±6.7), knee flexion at VIP (OW/OB -28.66±6.9, HW -28.02±4.9), and knee flexion at MaxFz (OW/OB -46.48±8.6, HW -46.75±3.7). In the frontal plane, the OW/OB group had significantly greater peak knee abduction (OW/OB -6.75°±3.74°, HW -2.48±3.6, $p<0.05$, $d=1.16$), knee abduction at VIP (OW/OB -3.76°±4.48°, HW 1.03±3.6, $p<0.05$, $d=0.67$), and knee abduction at MaxFz (-4.17°±3.95°, HW 2.61±5.7, $p<0.05$, $d=0.31$), than the HW group. There was no difference of knee abduction at FS between groups (OW/OB -5.22°±3.94°, HW -1.92±3.4).

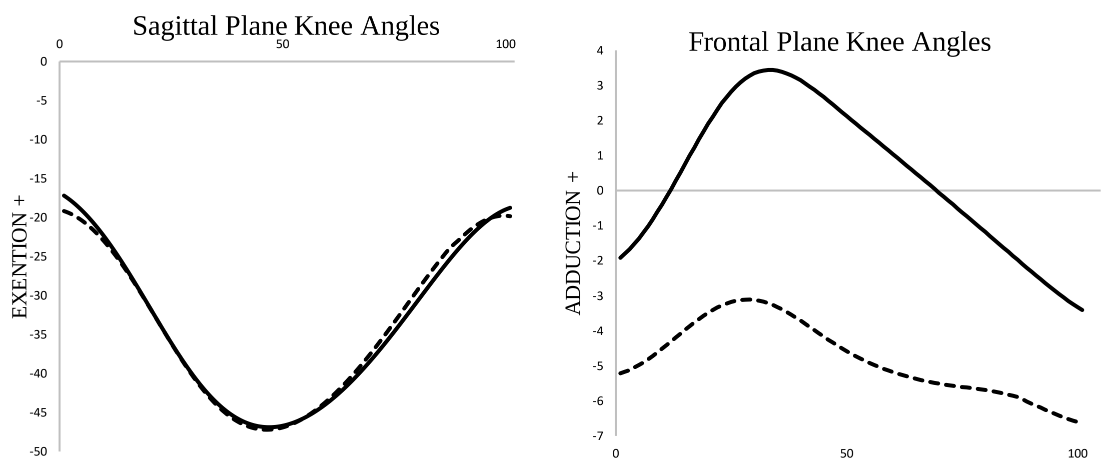

FIGURE 1. Comparison graphs of mean joint kinematics for each group. Sagittal and frontal planes are compared through the stance phase of running. Solid line indicates HW group. Dashed line indicates OW/OB group

Joint Moments and Angular Impulse

Sagittal Plane

Sagittal plane absolute joint moments and angular impulse variables of interest and statistics can be found in Table 3. The OW/OB group had statistically greater absolute peak knee extension moment, absolute knee extension moment at MaxFz, absolute knee extension angular impulse and absolute knee flexion angular impulse. No differences between groups were found for sagittal plane moments and impulses when scaled by bodyweight. When scaled by tibial plateau area, the OW/OB group had significantly greater knee extension angular impulse. The OW/OB group had significantly greater peak knee extension moment, peak knee flexion moment, knee extension at MaxFz, knee extension angular impulse and knee flexion angular impulse, all when scaled by tibial plateau density. All the significant differences were associated with a large effect.

Frontal Plane

Frontal plane absolute joint moments and angular impulse variables of interest and statistics can be found in Table 4. The OW/OB group had significantly larger absolute peak knee adduction moments and absolute knee adduction angular impulse than the HW group. When scaled by bodyweight, the HW group had significantly greater peak knee abduction moment, knee abduction moment at VIP and knee abduction moment at maxFz. The OW/OB group had significantly larger knee adduction angular impulse when scaled by tibial plateau area. When scaled by tibial plateau density, the OW/OB group had significantly greater peak knee adduction moment, and knee adduction angular impulse. All the significant differences were associated with a large effect. A comparison of group moments can be found in Figure 2.

TABLE 3. Sagittal plane joint moments of OW/OB and HW groups scaled by bodyweight, tibial plateau area and tibial plateau density

		HW	OW/OB	*p*	Cohen's *d*
Peak Knee Extension Moment	Absolute (N/m)	58.7±16	89.1±19	**0.001**	**1.70**
	Scaled to Bodyweight (BW/m)	1.53±0.14	1.41±0.19	0.15	0.72
	Scaled to Area (N/m*mm^2)	0.031±0.008	0.041±0.02	0.10	0.66
	Scaled to Dens (N*mg/m*cm^3)	0.229±0.06	0.353±0.05	**<0.001**	**2.25**
Peak Knee Flexion Moment	Absolute (N/m)	-12.8±7.6	-18.2±3.6	0.06	0.40
	Scaled to Bodyweight (BW/m)	-0.33±0.2	-0.29±0.06	0.54	0.27
	Scaled to Area (N/m*mm^2)	-0.007±0.004	-0.008±0.003	0.30	0.28
	Scaled to Dens (N*mg/m*cm^3)	-0.05±0.03	-0.07±0.02	**0.04**	**2.25**
Knee Extension Moment at VIP	Absolute (N/m)	8.92±10	13.4±13	0.39	0.39
	Scaled to Bodyweight (BW/m)	0.244±0.31	0.208±0.19	0.76	0.14
	Scaled to Area (N/m*mm^2)	0.005±0.007	0.006±0.006	0.79	0.15
	Scaled to Dens (N*mg/m*cm^3)	0.034±0.04	0.054±0.05	0.36	0.44
Knee Extension Moment at MaxFz	Absolute (N/m)	57.2±17	86.5±20	**0.002**	**1.58**
	Scaled to Bodyweight (BW/m)	1.49±0.2	1.37±0.2	0.18	0.60
	Scaled to Area (N/m*mm^2)	0.03±0.008	0.04±0.02	0.12	0.66
	Scaled to Dens (N*mg/m*cm^3)	0.224±0.06	0.343±0.06	**<0.001**	**1.98**
Knee Extension Angular Impulse	Absolute (N/m)	5.97±1.9	9.67±3.3	**0.004**	**1.37**
	Scaled to Bodyweight (BW/m)	0.146±0.01	0.152±0.04	0.66	0.21
	Scaled to Area (N/m*mm^2)	0.003±0.001	0.004±0.002	**0.05**	0.63
	Scaled to Dens (N*mg/m*cm^3)	0.022±0.007	0.038±0.01	**0.001**	**1.85**
Knee Flexion Angular Impulse	Absolute (N/m)	-0.345±0.013	-0.523±0.24	**0.05**	**1.05**
	Scaled to Bodyweight (BW/m)	-0.009±0.004	-0.009±0.004	0.71	0
	Scaled to Area (N/m*mm^2)	-0.0002±0.0001	-0.0002±0.001	0.44	0
	Scaled to Dens (N*mg/m*cm^3)	-0.001±0.0005	-0.002±0.01	**0.03**	0.14

Values are mean±SD. Dens: density, HW: healthy weight, OW/OB: overweight/obese. Significant differences and large effect sizes are in bold $p \leq 0.05$, $d > 0.80$.

TABLE 4. Frontal plane joint moments of OW/OB and HW groups scaled by bodyweight, tibial plateau area and tibial plateau density

		HW	OW/OB	*p*	Cohen's *d*
Peak Knee Adduction Moment	Absolute (N/m)	4.54±3.4	12.1±9.0	**0.02**	**1.11**
	Scaled to Bodyweight (BW/m)	0.133±0.2	0.194±0.2	0.32	0.31
	Scaled to Area (N/m*mm^2)	0.003±0.003	0.005±0.004	0.13	0.57
	Scaled to Dens (N*mg/m*cm^3)	0.018±0.01	0.05±0.04	**0.03**	**1.10**
Peak Knee Abduction Moment	Absolute (N/m)	-17.8±8.1	-16.2±8.1	0.69	0.20
	Scaled to Bodyweight (BW/m)	-0.442±0.2	-0.259±0.1	**0.01**	**1.16**
	Scaled to Area (N/m*mm^2)	-0.009±0.003	-0.008±0.005	0.47	0.24
	Scaled to Dens (N*mg/m*cm^3)	-0.07±0.04	-0.064±0.3	0.67	0.03
Knee Abduction	Absolute (N/m)	-6.97±5.4	-2.18±8.0	0.13	0.70
	Scaled to Bodyweight (BW/m)	-0.177±0.1	-0.035±0.1	**0.02**	**1.42**
	Scaled to Area (N/m*mm^2)	-0.004±0.003	-0.001±0.004	0.16	**0.85**

Moment at VIP	Scaled to Dens (N*mg/m*cm^3)	-0.027±0.02	-0.007±0.03	0.11	0.78
Knee	Absolute (N/m)	-14.0±10	-6.19±14	0.18	0.64
Abduction	Scaled to Bodyweight (BW/m)	-0.337±0.21	-0.097±0.23	**0.03**	**1.09**
Moment at	Scaled to Area (N/m*mm^2)	-0.007±0.004	-0.003±0.007	0.21	0.70
MaxFz	Scaled to Dens (N*mg/m*cm^3)	-0.056±0.04	-0.022±0.06	0.14	0.67
Knee	Absolute (N/m)	0.221±0.2	0.914±0.9	**0.02**	**1.06**
Adduction	Scaled to Bodyweight (BW/m)	0.006±0.006	0.015±0.01	0.10	**0.83**
Angular	Scaled to Area (N/m*mm^2)	0.0001±0.001	0.0004±0.0003	**0.05**	0.41
Impulse	Scaled to Dens (N*mg/m*cm^3)	0.001±0.004	0.004±0.004	**0.03**	0.75
Knee	Absolute (N/m)	-1.57±1.1	-1.24±1.3	0.54	0.27
Abduction	Scaled to Bodyweight (BW/m)	-0.038±0.02	-0.020±0.02	0.07	0.13
Angular	Scaled to Area (N/m*mm^2)	-0.001±0.004	-0.001±0.001	0.59	0
Impulse	Scaled to Dens (N*mg/m*cm^3)	-0.006±0.004	-0.005±0.005	0.45	0.22

Values are mean±SD. Dens: density, HW: healthy weight, OW/OB: overweight/obese. Significant differences and large effect sizes are in bold $p \leq 0.05$, $d > 0.80$.

Temporal Parameters

Step width of the OW/OB group (0.092m/bh±0.04m) was significantly wider ($p<0.01$, $d=1.21$) than the HW group (0.037m/bh±0.05m). Stance phase time of the OW/OB group (0.26s±0.01s) was significantly longer ($p<0.005$, $d=1.26$) than the HW group (0.24s±0.02s). There was no difference between step length of the OW/OB (1.22m/bh±0.06m) and HW (1.27m/bh±0.07m) groups. Also, there was no difference between running speeds of the OW/OB (3.46m/s±0.06m/s) and HW (3.44m/s±0.4m/s) groups. All the significant differences were associated with a large effect.

Tibial Plateau Dimensions

Tibial plateau data and statistics can be found in Table 5. No difference was found between groups for total area and density of the tibial plateau. Mass normalized by tibial plateau density was significantly different between groups. Mass normalized by tibial plateau area was also found to be significantly different. All the significant differences were associated with a large effect.

TABLE 5. Tibial plateau data of HW and OW/OB groups

	HW	OW/OB	*p*	Cohen's *d*
Total Density (mg/cm^3)	258.7±47.9	251.1±27.6	0.67	0.19
Total Area (mm^2)	1950±575	2330±475	0.13	0.72
Mass Density Ratio (kg/mg/cm^3)	0.151±0.04	0.251±0.03	**<0.001**	**2.83**
Mass Area Ratio (kg/mm^2)	0.02±0.004	0.03±0.008	**0.01**	**1.58**

Values are mean±SD. HW: healthy weight, OW/OB: overweight/obese. Significant differences and large effect sizes are in bold $p \leq 0.05$, $d > 0.80$.

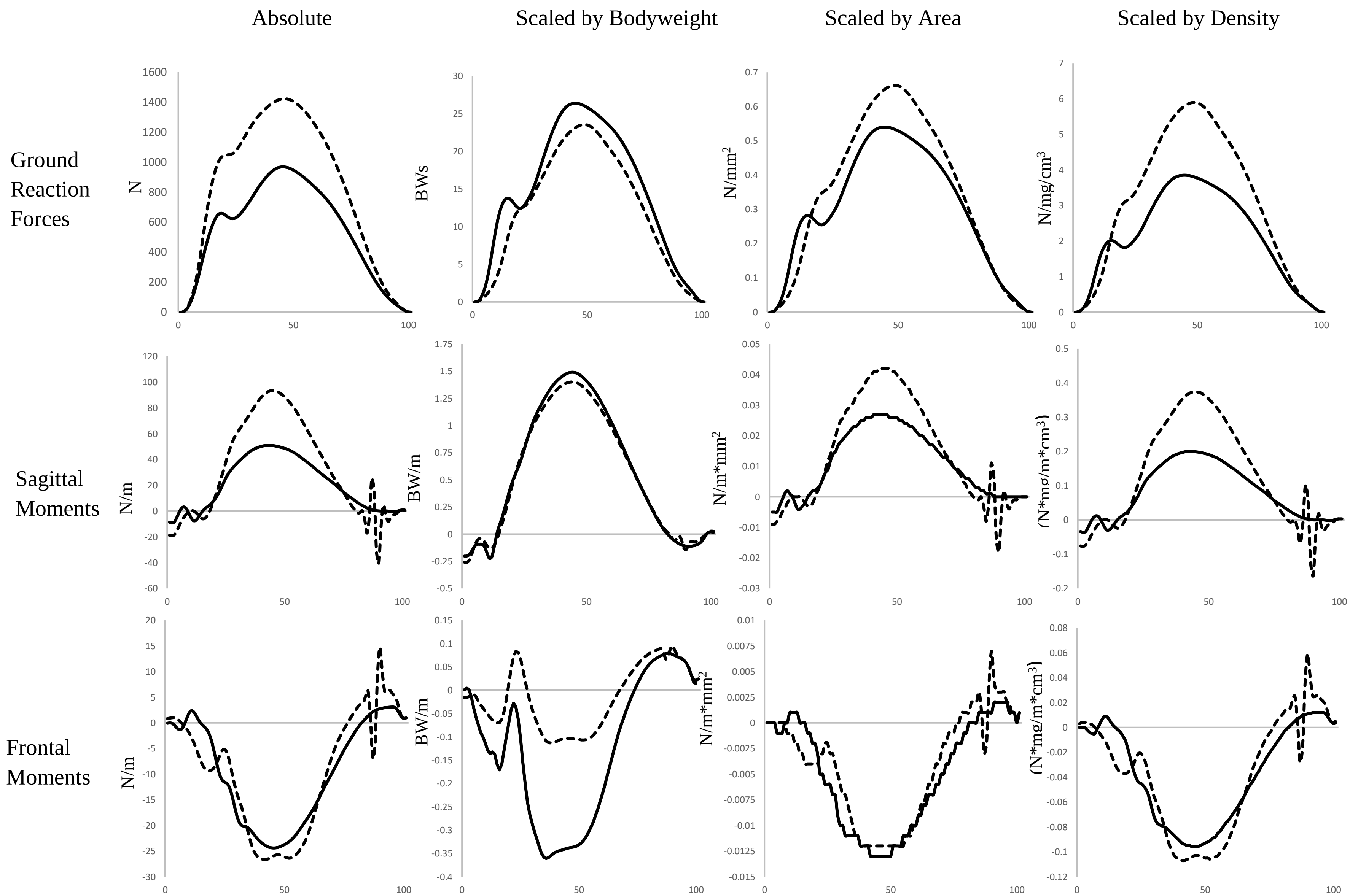

FIGURE 2. Comparison graphs of mean ground reaction forces and joint moments for each group. Ground reaction forces and moments are compared through the stance phase of running in absolute, scaled to bodyweight, scaled to tibial plateau area and scaled to tibial plateau density. Solid line indicates HW group. Dashed line indicates OW/OB group.

DISCUSSION

The primary goal of this study was to compare running mechanics between OW/OB and HW children. The results revealed that OW/OB children have significant differences in running mechanics compared to HW children. The secondary goal of this study was to compare tibial plateau dimensions between groups and determine the relationship between tibial plateau dimensions and running kinetics. The results revealed no statistical group differences between raw tibial plateau dimensions. However, significant group differences were found when tibial plateau dimensions were used to scale kinetic variables of interest.

Tibial Plateau Dimensions

To provide context for the following variables, a discussion of the differences in tibial plateau dimensions is necessary. No difference was found between tibial plateau surface area and density between the OW/OB and HW groups (Table 5). These results lead us to reject our hypothesis that OW/OB children would have larger tibial plateau surface area and density than HW children. The effect size does support that OW/OB children's tibial plateau area is clinically larger than HW children. Due to the weight discrepancies between groups, the similarities of tibial plateau dimensions suggest altered force distribution at the knee. Contrary to the current results, other studies have found that OW/OB children do have larger and more dense proximal tibias than their HW counterparts (26, 27). Though previous studies found differences between OW/OB and HW children's tibial plateau dimensions, the differences are not proportionate to the increase in mass. Vanderwalle and colleagues found the mass scaled to tibial plateau area ratio of OW/OB children was 0.09, while the mass to area ratio of HW children was 0.05. The OW/OB mass to tibial plateau density ratio was 0.3 while the HW children's ratio was 0.2 (26). These findings suggest that though tibial plateau dimensions between groups may be different, the bones of OW/OB children are not responding sufficiently to excess loading due to the increase in mass.

A significant group difference with large effect sizes, was found for mass to tibial plateau surface area and mass to density ratios (Table 5). This finding supports our hypothesis that tibial plateau dimensions would not be proportional to the mass of the OW/OB group. The OW/OB group had greater ratios for each condition indicating greater mass per unit of area and per unit of density compared to the HW group. Despite having the similar tibial surface areas and densities, the increased mass of the OW/OB group will subsequently increase the forces at the knee joint. Our results are similar to Ding and colleagues who found that OW/OB adults had larger tibial plateau surface area than HW adults, but the OW/OB tibial plateau surface area was not proportionate to the increase in mass (18). The density of the tibial plateau of OW/OB children is also not proportionate to mass. If the OW/OB children's bones were responding correctly, the density would increase as mass increases. This is not observed by the present data. The inappropriate bone remodeling response to increased weight has been understood to be related to the relationship between obesity and bone metabolism. Obesity has been associated with the increase of bone metabolism, which decreases bone density (28). Tibial plateau dimensions that are not proportionate to mass may lead to poor distribution of forces on the tibial plateau. This poor distribution of forces could lead to increased loading at the knee which may contribute to an increased likelihood of experiencing an

ACL tear, stress fractures, or increasing the future risk of osteoarthritis (28, 29). Considering the mass to density and mass to area ratios, scaling the kinetic data to tibial plateau area and density will provide greater insight into loading at the knee joint without measuring the joint forces directly through modelling. The present study did not directly measure the loading at the tibial plateau, but instead measured loading at the knee indirectly, using tibial plateau dimensions.

Temporal Parameters

Compared to HW children, OW/OB children have a longer stance time. These results are consistent with Rubinstein and colleagues who also found greater stance time in OW/OB children during running (11). It has been suggested that OW/OB children spend greater time in stance to avoid an increase in metabolic cost and mechanical work because of excess resistance due to heavier limbs (40). Another possible explanation of increased stance time is the reduced postural stability of OW/OB children and their inability to control the fall of center of gravity (41). Although a difference in step length was not found, which could also be an explanation for an increase in stance time, OW/OB children did have greater step width. The wider step width could increase stance time because OW/OB children had a farther distance between footfalls, which means the time to transition during swing could be elongated.

OW/OB children were found to have almost triple the step width of HW children. Significantly larger step width while walking has been found in obese adults when compared to healthy weight adults (30, 40). The increase in step width for obese participants has been suggested to result from increased thigh diameter, and the reduction of postural stability (30). Increased step width has also been associated with decreasing knee abduction moments during walking (30, 37). The decrease of knee abduction moments due to increased step width can be observed in the present study. The OW/OB group had larger step width as well as significantly lower knee abduction moments during the stance phase of running when compared to the HW group.

Vertical Ground Reaction Forces

As hypothesized, mass influences the vertical ground reaction forces during the stance phase of running. When examining absolute ground reaction forces, OW/OB children had significantly greater VIP, Max Fz, IVLR and AVLR (Table 2). The results had large effect sizes that confirmed the findings. These results are consistent with other articles that state that OW/OB adults and children display greater absolute vertical ground reaction force than their HW counterparts during the stance phase of walking (30,31). Absolute vertical ground reaction force values do not provide the most accurate comparison between groups due to weight differences. However, absolute values are important when examining joint loading because of the similarities of the articulating tibial surface area and densities between groups (30). The OW/OB and HW groups have the similar size tibial plateau dimensions, which indicates that the OW/OB group experienced excess force on similar size bone structure and densities.

Contrary to our hypothesis, when vertical ground reaction forces were scaled to bodyweight, HW children were found to have statically greater MaxFz and AVLR, as well as clinically greater IVLR. Such a difference was not found by Pamukoff and colleagues who stated there was no difference in Max Fz and AVLR during the stance phase of walking between OW/OB and HW young adults (32). The discrepancies in results from the two studies could be attributed to the differences between young adults and children as well as the differences between walking and running speeds. The OW/OB children in our study may be better at dispersing the force after foot contact due to a self-preserving mechanism, but the weight of absolute loading is excessive. The excessive weight counteracts their attempts of dispersing the excess force, resulting in the absolute AVLR and Max Fz to be higher in OW/OB children. Ultimately, absolute values, as well as the tibial plateau ratios will provide more insight on vertical loading at the knee during running.

Confirming our hypothesis, the results of our study revealed that scaling vertical ground reaction forces to tibial plateau density provide further insight on loading at the knee joint. When scaled by tibial plateau density, all vertical ground reaction force variables of the OW/OB children were significantly greater, with large effect size, than the HW children. This suggests that tibial plateau density may not be responding and remodeling sufficiently to distribute forces at the knee during running. The OW/OB children's tibial plateau density may not be remodeling appropriately because obesity has been related to the increase in bone breakdown (28). This insufficient remodeling may lead to an overload of forces on the tibial plateau. The overload of forces could be related to the increased risk of ACL tears, stress fractures and osteoporosis that OW/OB children and adults are predisposed to (15, 28).

Joint Moments

The joint moment results from this study provides further evidence that OW/OB children have increased loading at the knee during running. Joint moments and joint angular impulse provide further insight on joint loading than other variables (6). When comparing absolute peak knee adduction moments during the stance phase of running, OW/OB children display significantly greater values than HW children (Table 4). Our findings are consistent with previous studies who reported OW/OB adults have greater knee adduction moments during the stance phase of walking and running (3, 7, 30, 33-35). The OW/OB group also had greater absolute knee adduction angular impulse. Greater knee adduction angular impulse was also found in OW/OB adult women during walking (35). Excessive knee adduction moments and angular impulse have been found to increase the medial compartment loading at the knee (35, 36). Excessive medial compartment loading may increase the risk of knee osteoarthritis and alter frontal plane alignment to a more varus alignment (4, 35, 36).

HW children had greater peak knee abduction moments than OW/OB children when knee moments were scaled to bodyweight. OW/OB children had clinically greater knee adduction angular impulse when scaled to bodyweight. These findings lead us to reject our hypothesis which states that OW/OB children would have greater peak knee abduction moments during running. Contrary to these results, McMillan and colleagues determined that OW/OB children had greater knee abduction moments than HW children (4). The discrepancy can be explained by the difference in step width. Yocum and colleagues found that increased step width decreases knee abduction moment in OW/OB adults. The results of this study show that OW/OB children have significantly greater step width than HW children, potentially explaining the decreased knee abduction moments observed in OW/OB children (37).

Scaling knee moments by the tibial plateau dimensions provides further evidence for increased loading at the knee for OW/OB children. When scaled by tibial plateau surface area, OW/OB children had significantly larger, with large effects, knee extension angular impulse and knee adduction angular impulse. When scaled by tibial plateau surface density, OW/OB children had significantly larger knee extension moment and angular impulse, flexion moment and angular impulse and adduction moment and angular impulse. By examining both the peak moment and angular impulse, our data suggests that not only the peak moment is greater, but the overall moment throughout the phase is greater as well. Creaby and colleagues reported that excessive knee adduction moments are associated with increased medial tibial plateau bone surface area in adults with OA (38). Also, Hudson and colleagues found that knee abduction moments are related to increases in bone mineral density in the knee of healthy adults (39). These findings suggest that the tibial plateau surface area and density are not increasing proportionally to the increased moments and impulses that occur during running. The disproportionality may cause the OW/OB children to have excessive knee moments, which could exacerbate risk of knee injuries like ACL tears and osteoarthritis (4).

Joint Kinematics

Group differences in knee angles were found only in the frontal plane. Consistent with our hypothesis, OW/OB children displayed greater peak knee abduction during the stance phase of running compared to HW children (Figure 1). Our findings are consistent with McMillan et al who reported that OW/OB children also display greater peak knee abduction during walking (4). However, Lai and colleagues observed that OW/OB adults display less peak knee abduction during walking (33). Finally, Shultz et al found no difference in peak knee abduction in obese children during walking (3). One possible explanation for the inconsistent findings among these studies is the different gait speeds used. The previous studies examined knee kinematics of OW/OB children and adults during walking, while the present study examined children while running. The average running speeds of this study were around two meters per second faster than the walking speeds of previous studies (3, 4, 33). The faster speeds may contribute to a more abducted position of the knee due to shorter stance times. During stance, the knee may have less time to compensate for the load being placed on it and fall to a more abducted position.

In the sagittal plane, no differences were found in peak knee flexion during running. In contrast, during walking, OW/OB children have previously been found to have decreased knee flexion during walking when compared to HW children (6, 7). Decreased knee flexion has been shown to be related to a stiffer landing and increased vertical loading. In adults, studies have found no difference of knee flexion between OW/OB and HW groups during walking (30, 33).

Temporal Parameters

Compared to HW children, OW/OB children have a longer stance time. These results are consistent with Rubinstein and colleagues who also found greater stance time in OW/OB children during running (11). It has been suggested that OW/OB children spend greater time in stance to avoid an increase in metabolic cost and mechanical work because of excess resistance due to heavier limbs (40). Another possible explanation of increased stance time is the reduced postural stability of OW/OB children and their inability to control the fall of center of gravity (41). Although a difference in step length was not found, which could also be an explanation for an increase in stance time, OW/OB children did have greater step width. The wider step width could increase stance time because OW/OB children had a farther distance between footfalls, which means the time to transition during swing could be elongated.

OW/OB children were found to have almost triple the step width of HW children. Significantly larger step width while walking has been found in obese adults when compared to healthy weight adults (30, 40). The increase in step width for obese participants has been suggested to result from increased thigh diameter, and the reduction of postural stability (30). Increased step width has also been associated with decreasing knee abduction moments during walking (30, 37). The decrease of knee abduction moments due to increased step width can be observed in the present study. The OW/OB group had larger step width as well as significantly lower knee abduction moments during the stance phase of running when compared to the HW group.

Limitations

A potential limitation of this study is that the forces at the tibial plateau were not directly measured. Future studies should model joint contacts forces of OW/OB children during running. The physical activity level of the children in the study was not measured. There could be a relationship with physical activity level and tibial bone dimensions. Future studies should measure the participants physical activity levels. Because of the cross-sectional research design of the study, a direct causal relationship between mass, running biomechanics and tibial plateau dimensions is difficult to determine. To determine this relationship, a longitudinal study following children into adulthood would be beneficial.

CONCLUSION

In conclusion, running mechanics are different between OW/OB and HW children, especially when considering the tibial plateau surface area and density. The results of mass, vertical ground reaction force and joint moments scaled by tibial plateau dimensions suggest that OW/OB children experience excessive loading at the knee during the stance phase of running when compared to HW children. The excessive loading may be contributing to the increased risk of ACL injuries and osteoporosis that OW/OB children and adults are prone to. Future research investigating the indirect relationship between mass, ground reaction forces, moments and tibial plateau dimensions is necessary to confirm these findings.

LITERATURE REVIEW

The literature review consists of five sections: the kinematics differences between obese and non-obese children during walking and running (Table 1), the kinetic differences between obese and non-obese children during waking and running (Table 2), the kinematic and kinetic differences of running in adults (Table 3), information on collection biomechanical data on obese participants (Table 4), and previous research on knee contact forces (Table 5). Table 1 and Table 2 identify the already known kinematic and kinetics differences between obese and non-obese children during walking and running. Table 3 provides deeper understanding of running mechanics in adults that can aid in understanding children's running mechanics. Table 4 provides information of how to best collect data on participants that are overweight or obese. Table 5 is a summation of previous studies that looked at knee contact forces in relation to gate and other lower body movements.

Table 1 summarizes the kinematic differences between obese and non-obese children during both walking and running. This table shows that temporally, obese children choose to walk slower and have wider step width. Kinematically, this table shows that there is little evidence for children during running. Current evidence on walking is somewhat contradictive due to varying methodology, but obese children seem to present decreased knee flexion and increased knee abduction during stance.

Table 1: Kinematic differences between obese and non-obese children during walking and running

Study	n	Participant Characteristics	Walking/ Running	Instruments	Methods	Findings	Pedro
Lerner et al. 2014 (22)	18	9 OW/OB -8 F -av BMI: 35.0 9 HW -5 F -av BMI: 22.1	Walk	Dual Belt Treadmill Surface EMG Markers	1.25m/s 0 deg	OW/OB had ↓ peak hip flex in stance	3
Rubinstein et al. 2017 (11)	41	31 OW/OB Av age: 9.9 yr OW= BMIP>85 HW= BMIP<85	Walk and Run	Motion capture Portable insole system Treadmill	80%, 100%, 120% of normal walking velocity 80%, 100% of running velocity Collection for 15 sec, 5 strides analyzed	OW/OB had ↑ cycle length ↑ cycle time ↑ stance phase time ↑ relative double support phase ↑relative swing phase	5
Dufek et al. 2012 (5)	111	55 OW/OB -BMIP>=85 12-17yrs	Walk	Motion capture with IREDs Force plates	Walked at two speeds: av: 1.2m/s, 1.7 m/s	OW/OB had ↑knee flexion angle ↑axial knee force ↑ankle plantarflexion moment ↑knee abduction moment	4
Shultz et al. 2009 (3)	20	10 OW/OB -BMI 30.47 10 HW -matched by age and sex -BMI 16.85	Walk	Motion capture Force plates	Barefoot walking on 15.25m walkway	OW/OB had ↑absolute peak joint moments at hip, knee, and ankle ↑ankle dorsiflexion moments with weight accounted for	5

		Av age: 10.4					
Hills et al. 1991 (42)	20	10 OW/OB -BMIP>95 Age: 8.5-10.9	Walk	10m gait track Photosonics camera at 50 f/s	Walked at normal speed, 10% slower, 30% faster	OW/OB had ↑cycle duration Mean cycle ↓ as speed ↑ ↓cadence ↓relative velocity	3
Nantel et al. 2006 (43)	20	10 OW/OB -BMIP>95 -av age: 9.7 10 HW -av age: 9.4	Walk	Optoelectric cameras Force plates	Self-selected pace on 10m walkway	OW/OB had ↓single support phase duration	4
Lerner et al. 2015 (9)	20	10 OW/OB -4 F -BMIP 98 -age 9.5 10 HW -5 F -BMIP 34 - age 9.6	walk	DXA Instrumented treadmill Motion capture Digitized pointer	walked for 20 min at 1.0 m/s	OW/OB had ↑knee adduction moment	4
Lerner and Browning. 2016 (44)	20	10 OW/OB -4 F -BMIP 98 -age 9.5 10 HW -5 F -BMIP 34 - age 9.6	walk	Motion capture Digitizing pointer Instrumented treadmill	1 m/s 1 min collection	OB/OW had ↓peak hip extension	4
McMillan et al. 2010 (4)	12	All male 6 OW/OB -BMIP>=95 6 HW -BMIP<85 Age: 10-12	walk	Motion capture Force plate	6 in platform drop landing	OW/OB had ↑knee valgus on landing ↑hip adduction on landing	3

Study	n	Participant Characteristics	Walking/ Running	Instruments	Methods	Findings	Pedro
Song-hua et al. 2017 (13)	40	20 OW/OB -age: 10.69 -BMI: 28.13 20 HW -age: 11.02 -BMI: 17.44	walk and run	2 m footscan plantar pressure plate	Natural walking, slower running/jogging, fast running	OW/OB had -longer midstance phase -shorter propulsion phase	4

Legend: OW/OB: overweight/obese, HW: normal weight, EMG: Electromyography, ↑: increase/more, ↓:decrease/less, F: female, av: average, BMI: body mass index, BMIP: body mass index percentile, DXA: dual energy X-ray absorptiometry, GRF: ground reaction forces, BW: body weight, ML: mediolateral, IREDS: infrared light emitting diodes, CT: computed tomography, MRI: magnetic resonance imaging, PA: physical activity

Table 2 summarizes the kinetic differences between obese and non-obese children during walking and running. This table shows that obese children have greater absolute ground reaction forces during walking than non-obese children. It also shows that during running, obese children have greater foot pressures than non-obese children. The research comparing running mechanics between obese and non-obese children has been limited to examining plantar pressure. Plantar pressure can provide meaningful data on loads placed on the foot but does not provide information on lower extremity joint kinematics and kinetics

Table 2: Kinetics differences between obese and non-obese children during walking and running

Study	n	Participant Characteristics	Walking/ Running	Instruments	Methods	Findings	Pedro
Lerner et al. 2014 (22)	18	9 OW/OB -8 F -av BMI: 35.0 9 HW -5 F -av BMI: 22.1	walk	Dual Belt Treadmill Surface EMG Markers	1.25m/s 0 deg	OW/OB had ↓1st peak rectus femoris forces ↓1st peak axial hip and knee contact forces	3
Villarrasa-Sapina et al. 2017 (31)	16	-6 F -av age: 11.5 yrs	walk	DXA Force plate	Self-selected speed	OW/OB children have	4

		-av mass: 69.8 kg -av height: 1.56 m -av BMI: 28.36				-positive relationship with impact force and weight -inverse relationship with impact force and lean mass	
Browning and Kram. 2007 (30)	20	10 OW/OB -5 F -av BMI:35.5 10 HW -5 F -av BMI:22.1 Av age:28.8	walk	Dual belt treadmill Footswitches Motion capture	0.5, 0.75, 1.0, 1.25, 1.5, 1.75 m/s Measured for 2 min	OW/OB had ↑ Absolute GRF ↓ GRF scaled to BW at 1.00m/s ↑ absolute peak GRF at faster walking speeds ↑peak ML GRF for all speeds	4
Nantel et al. 2006 (43)	20	10 OW/OB -BMIP>95 -av age: 9.7 10 HW -av age: 9.4	walk	Optoelectric cameras Force plates	Self-selected pace on 10m walkway	OW/OB had ↓mechanical work done by hip extensor ↑mechanical work done by hip flexors	4
Shultz et al. 2014 (45)	40	20 OW/OB -BMI: 24.3 - av age: 10.4 Age and gender matched HW -BMI: 17.2	walk	Force plate Motion capture	2 sessions: normal, added 10% body mass Walked on 6m walkway at self-selected speed	OW/OB had During weight acceptance: ↑power absorption of hip abductors, hip external rotators, knee extensors, and knee abductors ↑generation of hip flexors, abductors and ankle plantar flexors	4
Lerner et al. 2015 (46)	20	10 OW/OB -4 F -BMIP 98 -age 9.5 10 HW -5 F -BMIP 34 - age 9.6	walk	DXA Instrumented treadmill Motion capture Digitized pointer	walked for 20 min at 1.0 m/s	OW/OB had ↑peak medial force ↓peak lateral force ↑medial load share ↑medial loading rate	4

Lerner and Browning. 2016 (47)	20	10 OW/OB -4 F -BMIP 98 -age 9.5 10 HW -5 F -BMIP 34 - age 9.6	walk	Motion capture Digitizing pointer Instrumented treadmill	1 m/s 1 min collection	-Total and lean body mass were both significant predictors of hip joint contact forces -Total body mass has strong positive correlations with compressive and vertical shear forces	4
Mesquita et al. 2017 (12)	42	23 OW/OB 19 HW -av age: 7.3	run	Emed pressure platform	Run at self-selected speed over platform	-BMI was correlated to peak pressure at whole foot, midfoot and forefoot -peak plantar pressure is positively associated with obesity at mid and forefoot OW/OB had -↑whole foot forces except at hallux	4
Song-hua et al. 2017 (13)	40	20 OW/OB -age: 10.69 -BMI: 28.13 20 HW -age: 11.02 -BMI: 17.44	walk and run	2 m footscan plantar pressure plate	Natural walking, slower running/jogging, fast running	OW/OB had -↑peak pressures during walking other than Toe II-V -↑peak pressures during jogging other than T2-T5 -↑peak pressures during running other than T2-T5	4
Cousins et al. 2013 (14)	100	44 OW/OB -age: 9.68 -BMI: 21.66 56 HW -age: 9.16 -BMI:15.63	walk	Matscan pressure distribution platform Photo electric timing gates	Barefoot walking over platform at self-selected speed	OW/OB had -↑peak pressure at midfoot and 2-5 metatarsals -↑peak force at midfoot and 2-5 metatarsals -↑peak pressure at lateral heel midfoot and 2-5 metatarsals -↑peak force at lateral heel, medial heel,	4

					midfoot and 2-5 metatarsals -↑loading at midfoot and 2-5 metatarsals after normalizing to mass	

Legend: OW/OB: overweight/obese, HW: normal weight, EMG: Electromyography, ↑: increase/more, ↓:decrease/less, F: female, av: average, BMI: body mass index, BMIP: body mass index percentile, DXA: dual energy X-ray absorptiometry, GRF: ground reaction forces, BW: body weight, ML: mediolateral, IREDS: infrared light emitting diodes, CT: computed tomography, MRI: magnetic resonance imaging, PA: physical activity

Table 3 summarizes the kinematics and kinetics of running in adults. Due to the little evidence of obese children while running, a in depth study of running in adults was necessary. The studies in this table state that clinical populations have larger temporal variables, greater hip range of motion and larger instantaneous and average loading rates than healthy adults.

Table 3: Kinematic and Kinetics of running in adults

Study	n	Participant Characteristics	Instruments	Methods	Findings	Pedro
Schepens et al. 1998 (48)	57	51 children -2-16yr 6 adults -23-31yr	Force plate Photocells at neck	Subject needed to be running at constant mean height and speed	In children ↑step frequency ↓mass specific power sent against gravity	2
Arndt et al. 2007 (49)	4	Healthy male 28-55yrs	Motion capture -tibia skin markers -inserted foot marker arrays Force plates	10 running tails at self-selected pace before and after insertion	No differences seen in stance phase times	3

Bischof et al. 2010 (50)	24	All F 18-35yrs Ran at least 10 mi/week 9 experimental -had previous foot fracture	Motion capture -23 markers Force plates	Running at 3.3m/s on runway	No differences found between groups	5
Clark et al. 2017 (51)	42	19 F Regular PA 18-37yrs	Instrumented treadmill Motion capture	Running from 3.0m/s to max speed 3.46s of motion capture video	values were nearly identical for force data and vertical GRF Model R^2 was significant for predictions	4
Crowell and Davis. 2011 (52)	10	Rearfoot strike runners Run 16km/wk Av age: 26 6 F	Accelerometer Force plate	Ran 3.7m/s over force plate Gate trained and retested	From pre to post: ↓peak positive acceleration ↓vertical impact peak ↓vertical loading rate	4
Silvernail et al. 2015 (53)	28	Recreational runners 14 YA -13-35yrs 14 OA -45-65yrs Matched on gender, height, weight and weekly mileage	Questionnaires Force plate Motion capture	5 running trials at 3.5m/s	OA had ↑extended hip position at stance ↑hip ROM YA had ↑max hip flexion	4

Rubinstein et al. 2017 (11)	41	31 OW/OB -BMI>85 Av age: 9.9	Motion capture Portable insole system Treadmill	80%, 100% running Collection for 15 sec, 5 strides analyzed	OW/OB had ↑ cycle length ↑ cycle time ↑ stance phase time ↑ relative double support phase ↑relative swing phase	5
Schmitz et al. 2014 (54)	48	32 F Av age: 25 Healthy active	Instrumented treadmill Motion capture -27 markers	Ran at 3.3m/s for 2 min	Impact peak predictors -vert acc of foot -position of foot -vert vel of shank mid-swing Loading rate predictors -thigh position at mid swing	4
Milner et al. 2006 (36)	40	All F Exp: 20 -rearfoot strikers -history of tibial stress fracture -av age: 26 Con: 20 -no history of injuries -age and milage matched to experience -av age: 25	Motion capture Force plate Uniaxial accelerometer	5 running trials at 3.7m/s	Exp had ↑instantaneous loading rates ↑average loading rates	4

Legend: OW/OB: overweight/obese, HW: normal weight,↑: increase/more, ↓:decrease/less, F: female, YA: young adults, OA: older adults, av: average, BMI: body mass index, BMIP: body mass index percentile, DXA: dual energy X-ray absorptiometry, GRF: ground reaction forces, BW: body weight, PA: physical activity

Table 4 summarizes data collection techniques on obese participants. The table shows that surface EMG and motion capture can be affected by excess subcutaneous fat. The main options of correcting for excess error were a subject specific marker set, and a spring-loaded pointer.

Table 4: Collecting data on obese participants

Study	n	Participant Characteristics	Instruments Used	Methods	Findings	Pedro
Minetto et al. 2012 (55)	28	14 OW/OB -mean BMI 44.9 -av age 37.4 14 HW -mean BMI 23.7 -av age 35.0	Surface EMG	Voluntary and electrically elicited contractions of quad muscles Bioelectric impedance Surface EMG placement Stimulation of programmable neuromuscular stimulator	Significant negative correlations between subcutaneous tissue thickness and RMS estimates for both groups	3

Lerner et al. 2014 (22)	18	9 OW/OB -BMI 35 -8 F 9 HW -BMI 22.1 -5 F adults	Subject specific marker set	Walked on instrumented treadmill at 1.25m/s with EMG on legs and motion capture	OW/OB method measured smaller -peak hip flexion -pelvis tilt angles -first peak rectus femoris forces - axial hip and knee contact forces	5
Horsak et al. 2018 (56)	10	2 F Age: 14.6 BMI: 34.2	Motion capture	Comparing a calculated hip joint center and a functional hip joint center	-both are accurate representations of hip joint center in OW/OB children	4
Horsak et al. 2017 (57)	11	2 F Age: 14.6 BMI: 33.4	Motion capture	Determining the test-retest reliability of kinematic data in OW/OB children	-There are acceptable error margins in sagittal and frontal plane -pelvic tilt had low reliability	4
Horsak et al. 2018 (58)	10	2 F Age: 14.6 BMI: 34.2	Motion capture	Test-retest reliability of inverse kinematics and direct kinematics in OW/OB children	-clinically acceptable error margins between the models	3

Legend: OW/OB: overweight/obese, HW: normal weight, f: female, BMI: body mass index, EMG: electromyography, RMS: root mean squared

Table 5 highlights the previous research on knee contact forces. Most studies used a modeling system to determine the loads on the knee. Important findings were that BMI is associated with tibial plateau bone area, as well as bone distribution was associated with knee adduction moment.

Table 5: Previous research on knee contact forces

Study	n	Participant characteristics	Methods	Model Type	Findings	Pedro
Ding et al. 2004 (18)	372	Age: 45 BMI: 27.9	x-ray MRI	Knee cartilage volume and thickness measurement Cartilage defect assessment Knee bone size measurement	BMI was associated with knee cartilage defect, patellar cartilage thickness, tibial plateau bone area	3
Hurwitz et al. 1998 (59)	26	8 F Age: 32	DXA Optoelectronic system Force plate	Walked at 3 self-selected speeds: slow, normal and fast	-Best predictor of bone distribution was adduction moment	3
Taylor et al. 1998 (60)	1	41 Female	Instrumented distal femoral replacement	Level walking at four speeds, stair ascending and descending, rising from a chair, standing on one leg	-data produced matched a normal subject -walking peak axial force was between 2.2-2.5 BW	3
Kutzner et al. 2010 (61)	5	1 F with osteoarthritis	Instrumented knee implant Force plate	Level walking, ascending stairs descending stairs	-peak forces were highest during stair descending -resultant forces acted almost vertically on the tibial plateau	3
Lerner et al. 2015 (46)	1	Male with knee replacement 83yrs	Used Knee Load Grand Challenge to compare 4 types of models	-Fully informed -uninformed -alignment informed -contact point informed	-Fully informed had the best prediction accuracy -fully informed was statically similar to *in-vivo* measurements	4
Wehner et al. 2008 (62)	N/A	N/A	A computes model of hip contact force and axial force on the tibial plateau were compared to in vivo data from literature	7 rigid bodies to represent the lower extremities	-highest internal loads occurred in late stance - the model calculated hip contact force and axial tibial force within range	4

Winby et al. 2009 (63)	11	Av age: 44 No knee joint injury history	Walking at self-selected pace, fast pace, and slow run Force, motion capture and EMG data	EMG-driven model	-peak medial and lateral tibial compartment forces occurred during early stance - compartment loads were mainly generated by muscles	4
Knarr and Higginson 2015 (64)	3	2 male 1 female	Compared four models to an instrumented knee implant	-standard static optimization -uniform muscle coordination weighting - subject specific muscle coordination weighting -subject specific strength adjustments	-models with subject specific information were more accurate -using weight created the most accurate model	3
Gerus et al. 2013 (65)	1	Male Age:83 Instrumented total knee replacement	-Walked on an instrumented treadmill -Walking over ground at self-selected speed	EMG-driven neuromusculoskeletal modeling	-subject specific models more accurately calculate knee contact forces	2

Legend: MRI: magnetic resonance imaging, BMI: body mass index, DXA: dual energy X-ray absorptiometry, BW: body weight

In summary, the literature review identified the known kinematic and kinetics differences between obese and non-obese children during walking and running. It also identified that there is contradicting evidence for some kinematic and kinetic variables, and a lack of kinetic evidence specifically during running. Because of the lack of running evidence in obese children, the kinematics and kinetics of adults, specifically clinical populations, gives insight to the possible results found in children. To obtain good data, accurate data collection is important. Understanding the limitations of data collection of obese participants and learning how to correct them will aid in superior data collection. Lastly, the connection of movement kinematics and kinetics, and knee contact forces is important for creating a full picture of the effects of movement on the lower body.

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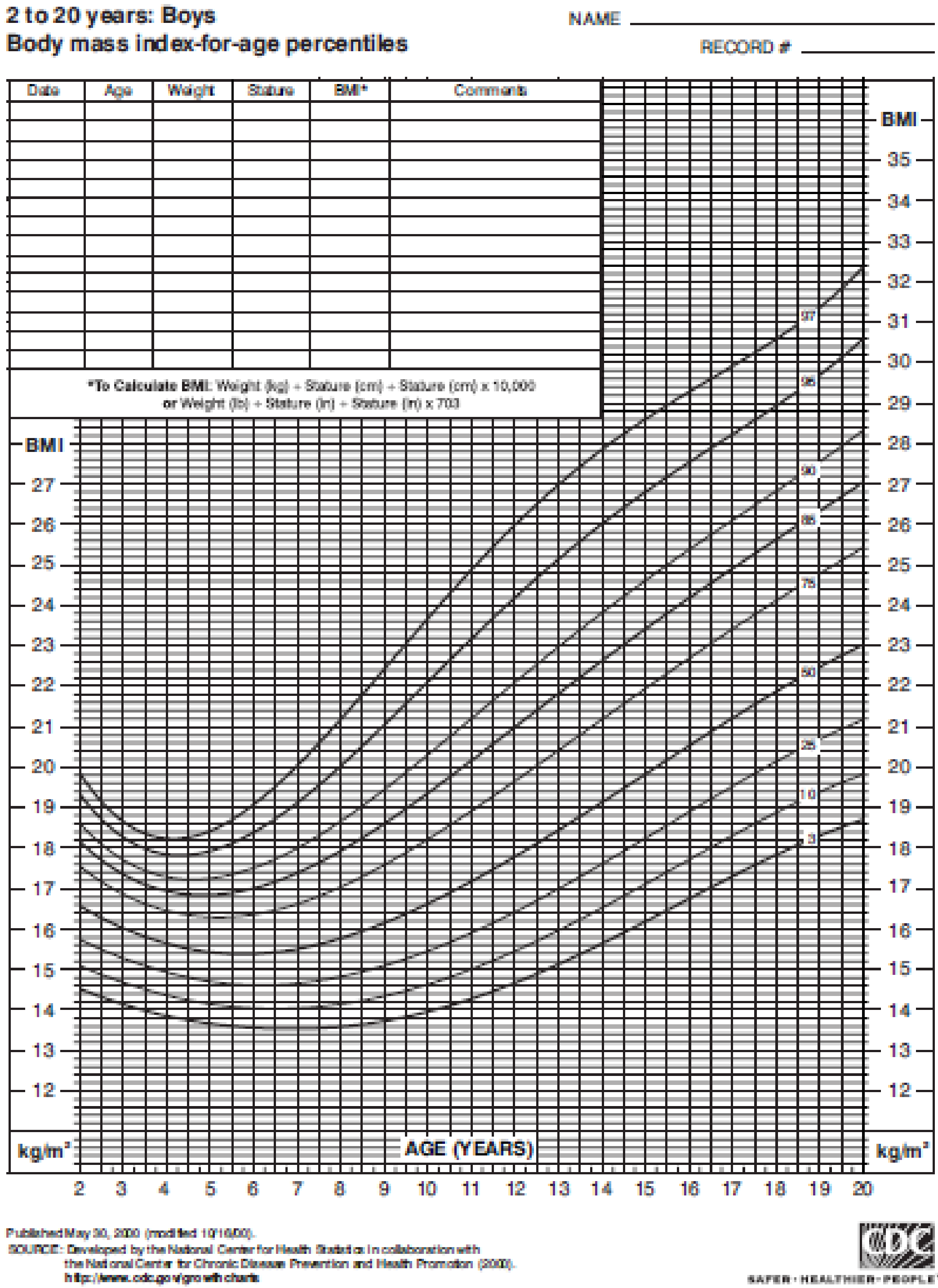
APPENDIX 1 CDC Boys BMI for Age Percentile Chart



APPENDIX 2 CDC Girls BMI for Age Percentile Chart