Pilot Study of the Gait Deviation Index in Quantifying Overweight Children's Mobility

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Abstract

Childhood obesity in the United States has more than tripled in the past three decades. Differences in lower extremity kinematics between obese and nonobese children during walking have been investigated, but the validity of using the gait deviation index (GDI) for measuring gait in obese children has not been explored. Nine obese children (13.9 $\pm$ 2.4 years old) with a body mass index of 33.3 $\pm$ 3.5 participated in the study. Reflective markers were placed on all children in a widely used standard lower extremity marker configuration. All participants walked along a 20-foot walkway at a self-selected speed. The kinematic and kinetic measurements for all children were taken, and the GDI for each subject was calculated. The mean $\pm$ standard deviation (SD) GDI of the nine obese children was 88.5 $\pm$ 12, which was significantly lower than the GDI of the typically developing children (100 $\pm$ 10, $p < 0.002$). There were no statistically significant correlations between the GDI and the Pediatric Quality of Life (PedsQL) Total score or PedsQL Physical Functioning score. Obese children had a significantly increased anterior pelvic tilt, hip flexion, hip adduction, hip adduction moment, knee flexion, knee valgus, and plantar flexion in stance phase ($p < 0.05$). While in swing phase, obese children had increased hip adduction and knee varus. The kinematic differences may reveal lower limb mal-alignment in obese children during walking. Overall, the GDI can play a major role in evaluating gait pathology in obese children. Future studies will increase the sample size to further evaluate the correlation between the GDI and functional outcomes.

Keywords
- gait
- gait deviation index
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Introduction

Childhood obesity is known to be one of the main public health crises of the 21st century, with a 16.9% prevalence of adolescent and child obesity in the United States.[1] This is classified as a child's body mass index (BMI) being at or above the 95th percentile on the BMI-for-age growth charts, which is subject to change since the prevalence of child obesity is on the rise. Child obesity has been shown to lead to significantly decreased health-related quality of life.[2–4] Another known consequence of child obesity includes musculoskeletal problems, as childhood is a critical time for bone growth and development. Obese or overweight children report significantly more musculoskeletal problems than normal-weight children.[5] The excess mass of a child can increase the risk of fractures, cause pain in the lower extremities, and impair mobility.[6–9] Lower relative bone mass and reduced bone area have also been associated with childhood obesity, which has led to new developing studies that have found relationships between adipose and skeletal tissue.[10] This can reduce the strength of the bone relative to body weight of a child. Child obesity has been known to hold a decreased femoral anteversion,[7] which causes a child to display an externally rotated lower limb. The external rotation along with increased loading at the hip joint can further lead to a slipped capital femoral epiphysis, which can cause a patient hip pain and difficulty walking.[7,10–12] Finally, obese/overweight children have a higher prevalence for flat feet. There is a lower plantar arch height found in obese children, which suggests that this may be due to structural changes in foot anatomy exacerbated by an excess of weight bearing over an extended period of time.[13]

Several studies have also looked at how obesity affects the spatiotemporal, kinematics, and pressure distribution of gait in adults and children. When compared with normal subjects, obese subjects have a longer stance phase,[14–17] increased hip adduction, and wider stride lengths.[18,19] Butterworth et al[20] observed elevated pressure on the fore foot and mid foot in obese subjects. Though these studies have observed structural and limited functional differences between obese and typically developing (TD) children, an overall functional assessment measurement between obese and nonobese children has yet to be investigated.

Developed by Schwartz and Rozumalski, the gait deviation index (GDI) is a comprehensive index of gait pathology, based on multivariable measurement of the overall gait cycle.[21] This value is calculated from nine different kinematic angles obtained from the pelvis, hip, knee, and ankle using a reduced order approximation of data, and was originally validated using 6,702 sides from patients with no abnormalities in gait. Pelvis and hip angles in all three planes are used in the calculation of the GDI, while only knee flexion/extension and ankle dorsi/plantarflexion and foot progression angle are used.[21] The knee coronal and transverse angles were not used in the calculations by Schwarz due to artifact and less clinical relevance, respectively.[21] A GDI is a convenient clinical tool and its score is standardized, such that a value of 100 or above indicates the average gait of a TD child, and every 10 points below a score of 100 are one standard deviation away from the mean.[21] In addition, the GDI has even been validated in multiple studies[22,23] and has been used as an evaluation tool in studies involving patients with CP.[24,25] The GDI has also been used as an evaluation of a patient's gait pre- and post total hip arthroplasty.[26] The goal of this study was to identify differences in kinetic and kinematic function, as well as differences in the GDIs between obese and TD children.

Methods

Study Participants

Nine obese children were recruited for a study designed to examine the benefits of yoga for obsess youth (unpublished). The average age and BMI for the subjects were 13.9 ± 2.4 years and 33.3 ± 3.5, respectively. Motion data were collected for both the right and left limbs for each participant. Existing data from Schwartz and Rozumalski were used for the TD children.[21] This study was approved by the Institutional Review Board at the Children's Hospital of Wisconsin (Milwaukee, Wisconsin, United States).

Data Collection

Upon arrival, subject consent was obtained, which explains what would be done during the study, possible risk or benefits of the study, and data de-identification and protection. Participants also completed the Pediatric Quality of Life Inventory (PedsQL).[27] This measure consists of 21 items that rate the extent to which functioning in various domains is affected by one's current state of health. For this study, the total score and physical functioning scores were computed.

After consent, anthropometric measurements were taken of the children for computer model input and BMI calculations, which include weight (kg), height (cm), leg lengths (cm), knee diameters (cm), inter anterior superior illiac spine (ASIS) distance (cm), and ankle diameters (cm). The marker set used was the lower limb Plug-in-Gait (PiG) (Vicon Systems, Oxford, United Kingdom) model, which consists of 18 reflective makers placed on the pelvis (4), thighs (2), knees (2), shanks (2), and feet (8) (►**Fig. 1**). As increased adipose tissue present on obese individuals can result in additional soft tissue artifact, particularly on the belly and pelvis, it is important that markers are placed as close as possible to firm bony landmarks, while still being visible to the cameras. If the anterior pelvis were obscured, the markers were moved 1 cm laterally as guided by the Vicon PiG model (Plugin Gait Manual Vicon Systems, Oxford, United Kingdom).

Before the children begin walking, a static calibration trail was performed to standardize the orientation planes. During the static trial, the knee makers are replaced with knee alignment devices (KAD). The KADs are used only in the static trial to determine the flexion axis for the model. After the static trial, the KADs are removed and the knee markers are put in their place (Plugin Gait Manual). The children were then asked to walk along a 20-foot walkway at a self-selected pace. The children's motion and ground reaction force were captured using a Vicon motion capture system (Vicon

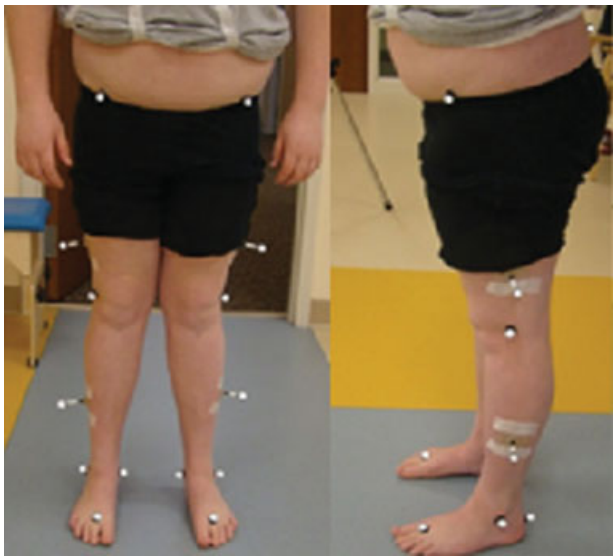

Fig. 1 Lower limb Plug-in-Gait marker set. Markers are placed bilaterally on the ASIS, PSIS, thigh, knee, shank, lateral malleolus, medial malleolus, heel, and second toe. If the ASIS markers are obstructed, they are moved 1 cm laterally. ASIS, anterior superior illiac spine; PSIS, posterior superior illiac spine.

Systems, Oxford, United Kingdom) consisting on 12 T-40S cameras and 4 force plates (Bertec Corp, Columbus, OH and AMTI, Watertown, Massachusetts, United States).

Data Analysis

During the processing, the data were filtered through a fourth-order zero-lag low-pass Butterworth digital filter with a cut-off frequency of 15 Hz. Once three trials of kinetic and kinematic were obtained, standardized to one gait cycle, and averaged, peak kinematics during stance and swing phase were calculated. The kinematic data were calculated only for the stance phase.

Statistical Analysis

A descriptive analysis for three-dimensional motion and moments at the pelvis, hip, knee, and ankle joint was performed, and the GDI was calculated. Comparison of those kinematic and kinetic data in obese children with 83 TD children was made using two sample *t*-test and a Welch's t-test of unequal variances. Pearson correlation between GDI and functional outcome measurements was performed in obese children. The *p*-values < 0.05 were considered significant.

Results

Our study participants had a cadence of 112.9 ± 10.6 steps/minute, stride length of 1.1 ± 0.1 m, and walking velocity of 1.0 m/second. Significant differences in kinematics and kinetics of the lower extremity between TD and obese children are displayed in ►**Table 1**.

At the pelvic level, there was no statistical difference in the coronal or transverse planes ($p > 0.05$). In the sagittal plane, the obese group displayed an increased maximum anterior tilt as compared with TD children during the stance phase (obese = 22.3° ± 6.6, TD = 12.5° ± 4.9) and swing phase (obese = 21.9° ± 6.5, TD = 12.4° ± 5.0).

The hip kinematic values exhibited statistical significance in all three planes (►**Table 1**). In the sagittal plane of obese children, hip extension was measured at 6.4° ± 11.5 and 17.2° ± 11.9 for stance and swing phase, respectively.

Table 1 Statistically significant maximal kinematic and moment values (mean ± SD, $p < 0.05$)

Joint	Variable	Phase	Typical[2] Mean ± SD	Obese Mean ± SD	*p*-Value
Pelvis	Anterior tilt	Stance	12.5° ± 4.9	22.3° ± 6.6	0.0001
		Swing	12.4° ± 5.0	21.9° ± 6.5	0.0001
	Flexion	Swing	36.7° ± 5.5	44.1° ± 10.2	0.0008
Hip	Extension	Stance	−5.8° ± 6.8	6.4° ± 11.5	0.0001
		Swing	−0.9° ± 6.7	17.2° ± 11.9	0.0001
	Adduction moment (Nm/kg)	Stance	0.49 ± 0.14	0.95 ± 0.12	0.0001
	Adduction	Stance	5.2° ± 3.4	9.5° ± 2.1	0.0004
		Swing	−1.6° ± 3.4	2.9° ± 1.8	0.0002
	Internal	Swing	1.2° ± 9.9	14.0° ± 10.0	0.0004
Knee	Flexion	Stance	27.9° ± 6.4	37.7° ± 10.7	0.0001
	Valgus	Stance	−1.0° ± 4.5	−7.8° ± 2.0	0.0001
	Varus	Swing	4.7° ± 6.6	15.1° ± 7.8	0.0001
Ankle	Plantar flexion	Swing	−19.8° ± 8.9	−10.5° ± 4.1	0.0001
Foot progression angle	External	Stance	−8.2° ± 6.4	−13.7° ± 5.4	0.0001
		Swing	−14.2° ± 6.9	−21.6° ± 4.9	0.0001

Abbreviation: SD, standard deviation.

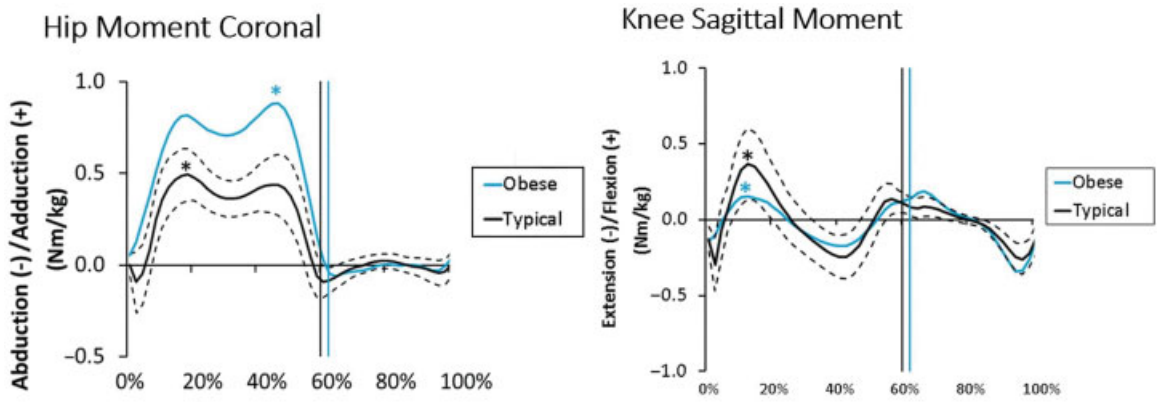

Fig. 2 Mean hip and knee moments of obese (blue line) and typically developing children (black line) is increased throughout the stance phase. Vertical lines indicate toe off, and black dashed lines indicate ± 1 standard deviation from mean typical motion. *means $p < 0.05$.

Showing increased hip flexion ($p < 0.05$), these measurements are larger than those of TD children. The same was presented for hip flexion during swing phase with the obese group at 44.1° ± 10.2 versus TD at 36.7° ± 5.5. Increased adduction was observed in the coronal plane of the hip during stance (obese = 9.5° ± 2.1, TD = 5.2° ± 3.4) and swing (obese = 2.9° ± 1.8, TD = –1.6° ± 3.4) phase ($p < 0.05$). Significance was also seen in the hip adduction moment during stance phase (obese = 0.95 ± 0.12 Nm/kg, TD = 0.49 ± 0.14 Nm/kg; ►**Fig. 2**). During swing phase in the transverse plane of the hip, the obese group had an increase in internal rotation (14.0° ± 10.0 vs. 1.2° ± 9.0; ►**Fig. 3**).

The knee joint had no statistical significance in the transverse plane. During the stance phase, the obese group experienced increases in knee flexion (37.7° ± 10.7 vs. 27.9° ± 6.4) and in knee valgus (–7.8° ± 2.0 vs. –1.0° ± 4.5) in the sagittal and coronal planes, respectively ($p < 0.05$). In the coronal plane during swing phase, knee varus was significantly increased in the obese group (obese = 15.1° ± 7.8, TD = 4.7° ± 6.6, $p = 0.0001$).

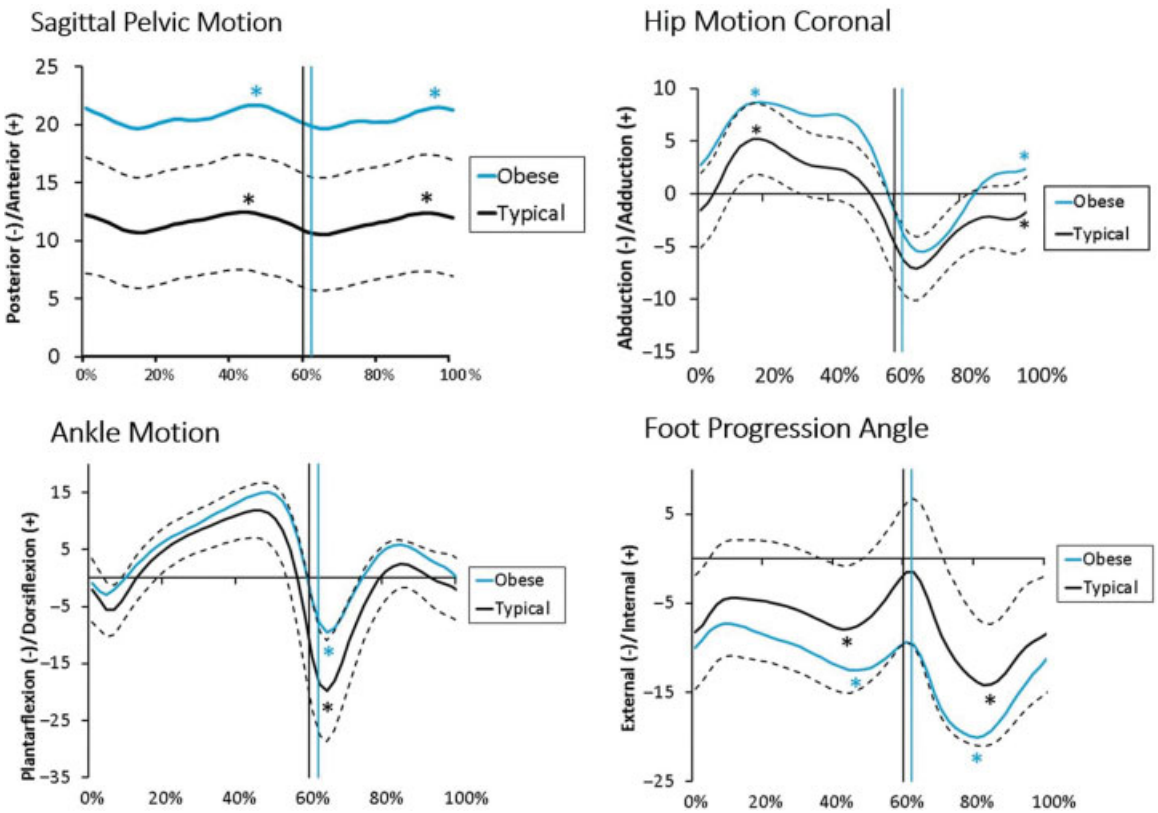

Fig. 3 Mean pelvic, hip, and angle kinematics and foot progression angles of obese (blue line) and typically developing children (black line) are increased throughout the stance phase. Vertical lines indicate toe off, and black dashed lines indicate ± 1 standard deviation from mean typical motion. *means $p < 0.05$.

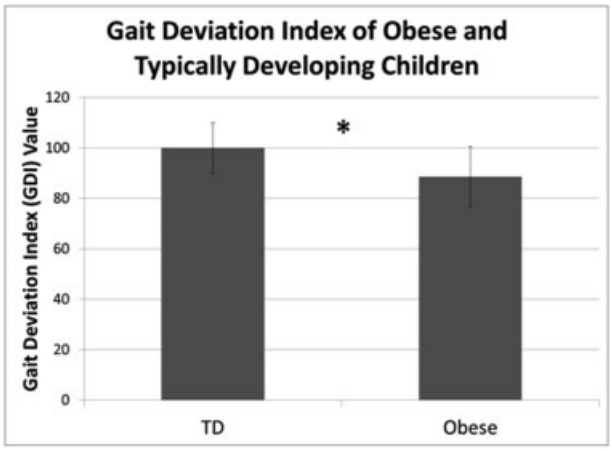

Fig. 4 Significant difference of averaged gait deviation index (GDI) between typically developing (TD) and obese children ($^*p < 0.0002$).

Statistical significance was only seen in one parameter in the ankle joint. The obese group had a plantar flexion measurement of $-10.5° \pm 4.1$ during swing phase, while the TD group had a measurement of $-19.8° \pm 8.9$.

The foot progression angle of the obese displayed external rotation relative to the line of walking during stance ($-13.7° \pm 5.4$) and swing ($-21.5° \pm 4.9$) phase. The TD group also displayed negative external rotation during both phases (stance $=-8.2° \pm 6.4$, swing $=-14.2° \pm 6.9$).

From Schwartz and Rozumalski, TD children have a mean GDI of 100 ± 10.[21] The mean GDI of the nine obese children in this study was significantly lower than the GDI of TD children (88.5 ± 12, $p < 0.002$; ►**Fig. 4**). No statistically significant correlations were found between the GDI and PedsQL Total score, or the PedsQL Physical Functioning score ($p > 0.05$).

Discussion

The overall goal of this study was to provide initial validation of the GDI for obese children, by first examining differences in kinematics and kinetics between obese and TD children. At every joint level in gait analysis, there were statistically significant differences between TD and obese children. Obese children had an increased anterior pelvic tilt, hip flexion, hip adduction, hip adduction moment, knee flexion, knee valgus, and plantar flexion in stance phase. While in swing phase, obese children had increased hip adduction and knee varus. As compared with TD children, obese children also had a significantly reduced GDI.

The kinematics observed in this study are comparable to several other studies. Our results demonstrate an increase in hip adduction throughout the entire stance phase (►**Fig. 3**). Lai et al showed the same trend and similar recordings for obese subjects, with a hip adduction of 7.5° during terminal stance phase and 4.9° during preswing phase.[14] McMillan et al and Huffman et al had higher values of hip adduction than the current study (16.4° and 14.3°, respectively), but also followed the trend of increased hip adduction in obese participants.[19,28] Finally, Shultz et al showed obese subjects had increased hip adduction, but their results were not statistically significant.[18] Overall, hip adduction findings are consistent across studies, supporting the validity of our gait results.

Huffman et al showed an increase in obese hip adduction moment normalized to a subject height and weight.[28] Although our study did not normalize the hip adductor moments, a similar result was seen. Normally, obese participants have a greater ground reaction force compared with TD participants, especially at slow walking speeds.[29] This would result in an increased moment load throughout many joints in the body, including hip adduction moment. In addition, it is known that obese participants take wider strides during gait,[19] which is done to increase base support during standing and gait. Moreover, a wider stance will compensate for an overall loss of balance. Since the patient's leg support will be further deviated from the patient's center of mass in the coronal plane, it may also result in an increase in the moment arm in obese patients during gait. This could cause the increase in hip adduction moment seen in our study. Finally, we have found that obese participants have an increased peak knee flexion during mid-stance phase, which may be an additional compensatory method to maintain balance due to a shifted center of mass in the sagittal plane.

In addition, while studies agree on most kinetic and kinematic trends between TD and obese groups, a confounding factor may be the walking speed of the participants. For example, during early stance phase, Gushue et al experienced a decrease in obese participant knee flexion compared with nonobese participants (obese: 14.5°, nonobese: 21.1°).[30] Spyropoulos et al demonstrated that obese participants walked significantly slower, but had the same knee flexion as normal weighted people.[31] Lelas et al found that peak knee flexion during early stance phase increases with increased walking speed.[32] When TD participants were required to walk the same speed as obese participants, some gait parameters' statistical significances were eliminated.[33] Overall, findings between studies may be more consistent if participants walked at the same walking speed. In this study, participants were asked to walk at a self-selected, natural speed, and spatiotemporal data was recorded. Future studies should evaluate whether the GDI of obese children is affected by walking speed.

While most studies choose to focus on individual kinematic, kinetic, or spatiotemporal parameters to study gait deviations between obese and TD patients, few examine the overall biomechanics.[21] There are no previous studies that investigate the GDIs between obese and TD participants, which will give a holistic measurement of a patient's gait via multivariable measurement of the overall gait cycle of a patient that uses multiple kinematic parameters for its overall calculation. Furthermore, the GDI has been especially important in investigating participants for other disorders that lead to a deviation in gait, particularly in children with CP. Aligning with previous studies which established the presence of statistically significant differences in kinematic data, the current study found seven statistically significant kinematic parameters that contributed to the calculation of

the GDI between obese and TD children. This corresponded to the significantly reduced GDI calculated for the obese compared with TD children. While there is no validated cutoff for a "normal" GDI, the significantly lower GDI of obese children observed in this study suggests that the GDI may be a useful tool for clinicians to evaluate gait pathology in obese youth. Overall, the GDI may give clinicians an additional objective measurement to assess gait pathology in obese patients and may serve as a novel assessment of treatment outcomes for obese children who receive different interventions.

Study Limitations

While Gorton et al found significant variability both within and between motion laboratories,[34] 75% of the resultant error was due to examiner variability in marker placement. Furthermore, Gorton found that an error reduction of 20% in marker placement when examiners implemented a standardized gait analysis protocol. To decrease interlaboratory error, for this study all markers, for all subjects, were placed by a single examiner, thus eliminating interexaminer error. The examiner for our study employed the GCMAS standardized protocol for patient evaluation and marker and KAD placement resulting in a further reduction in marker placement error. As interlaboratory variability can still result in some error, in the future, collecting a normal population with the same examiner and laboratory as the obese population could further decrease error.

With an increase in adipose tissue in the abdomen area, obese patients have an increased anterior pelvic tilt to compensate the forward translation of the center of mass, which has been demonstrated in static positions.[35] Our results further support these conclusions, finding an increase in anterior pelvic tilt during dynamic trials in the swing and stance phases. However, these results may also be partially explained by the lateral movement of the ASIS markers due to significant adipose tissue covering the front of the pelvic. This lateral ASIS movement can result in the erroneous calculation of increased anterior pelvic tilt and increased hip flexion. Lerner et al found that when comparing the kinematic results of obese patients using the PiG model versus an obese patient-specific-markermodel, a difference of 13.3° of anterior pelvic tilt and 10° of hip flexion was observed between the two marker sets.[36] These differences are consistent with the differences observed in our study (9.8° anterior pelvic tilt during stance, 9.5° during swing phase, and a hip flexion difference of 7.4°). Therefore, we have to be careful in the interpretation of kinematic results, especially in regard to pelvic and hip sagittal plane motion obtained from the PIG model. Lerner's model would be recommended for future use with an obese population.

As indicated, walking speed may have been a confounding factor, which may be a limitation of the study. To eliminate this as a variable, other studies have used multiple walking speeds.[15,31,34] In addition, only nine children participated in this study; future studies should use an increased sample size to increase statistical power. A larger sample size would also allow for further validation of the GDI as index of gait pathology in obese youth. Future plans include validation of the GDI using other outcomes affected by gait in obese youth, including functional disability. Finally, although the correlation between GDIs and PedsQL Total or Physical Functioning scores was not extensively examined for this study, it is plausible that the GDI may still be an index of functional outcomes. It may be that these measures are not sensitive to the gait abnormalities in obese youth.

Conclusion

Significant kinematic differences emerged at the lower extremity joints when comparing normal with obese children. The kinematic differences may reveal lower limb malalignment in obese children during walking. These kinematic differences also make it unsurprising that the GDI for obese children was significantly different from TD children. This study suggests that the GDI may serve as a useful tool with which to examine gait pathology in obese youth.

Conflict of Interest
None.

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