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Body size and walking cadence affect lower extremity joint power in children's gait

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Abstract

Obese children move less and with greater difficulty than normal-weight counterparts but expend comparable energy. Increased metabolic costs have been attributed to poor biomechanics but few studies have investigated the influence of obesity on mechanical demands of gait. This study sought to assess three-dimensional lower extremity joint powers in two walking cadences in twenty-eight obese and normal-weight children. 3D-motion analysis was conducted for five trials of barefoot walking at self-selected and 30% greater than self-selected cadences. Mechanical power was calculated at the hip, knee, and ankle in sagittal, frontal and transverse planes. Significant group differences were seen for all power phases in the sagittal plane, hip and knee power at weight acceptance and hip power at propulsion in the frontal plane, and knee power during mid-stance in the transverse plane. After adjusting for body weight, group differences existed in hip and knee power phases at weight acceptance in sagittal and frontal planes, respectively. Differences in cadence existed for all hip joint powers in the sagittal plane and frontal plane hip power at propulsion. Frontal plane knee power at weight acceptance and sagittal plane knee power at propulsion were significantly different between cadences. Larger joint powers in obese children contribute to difficulty performing locomotor tasks, potentially decreasing motivation to exercise.

Introduction

Physical inactivity is a significant public health problem [1] and obese children are more sedentary than normal-weight counterparts [2]. Cross-sectional studies have not demonstrated a significant association between body fat and energy cost of physical activity [3-6], yet time spent in physical activity is inversely related to fat mass [7,8]. In short, obese children spend less time in physical activity but expend comparable energy. Studies have consistently reported similarity between obese and normal-weight children in flexibility and absolute muscle strength tasks, but worse performance in the obese in whole body movements [9-11]. Difficulty completing such tasks could influence physical activity participation however little research has addressed the effects of excess mass on lower extremity biomechanics.

Greater attention has been paid to metabolic cost of activity compared to biomechanical consequences of obesity [12-16]. Nantel et al. [15] reported changes in sagittal plane hip power during gait, suggesting obese children develop a mechanically easier walking strategy but with higher energy costs. Peyrot et al. [17] reported similar external work between weight categories but a higher energy cost of walking in obese children suggested greater mechanical efficiency in normal-weight children. No research to date has investigated individual joint power in sagittal, frontal, and transverse planes. Faster walking speeds have been associated with higher energy costs of walking in the obese; however, the effect of walking cadence on lower extremity joint power has not been reported. This study aimed to determine if significant differences existed in the lower extremity joint powers across all planes in obese and normal-weight children during self-selected (SSP) and fast (FP) walking cadences.

Materials and Methods

Participants

Twenty-eight children, aged 8-12 y, were recruited at two locations using identical methodologies. Participants were categorized as normal-weight (N = 14) or obese (N = 14), based on body mass index (BMI) using international cut-off points [18] (see Table 1). Exclusion criteria included proxy-reported history of non-insulin dependent diabetes mellitus], neuromusculoskeletal disease, lower extremity surgery or injury six months prior to the study. Participants and parents/guardians gave written informed assent and consent prior to commencement and methods were approved by the University Institutional Review Board and Ethics Research Committee.

Walking Cadence

SSP was determined for all participants during five walking trials without reference to walking speed. Number of right footfalls and time spent walking were recorded and cadence (steps/min) calculated. A metronome was used to control SSP throughout subsequent biomechanical analyses. Time constraints at one study location resulted in twenty participants (10 obese, 10 normal-weight) completing walking trials at FP. FP was calculated as 130% of participants' SSP based on previous research in this population [13]. Spatial and temporal parameters were monitored at each cadence for changes that could alter joint biomechanics.

Biomechanical Analysis

Three-dimensional kinematic and kinetic measures were calculated according to the protocol by Shultz et al. [16] (see supplementary material). In the sagittal plane, phases were defined as power generation of hip extensor (H1-S), hip flexor (H3-S), knee extensor (K2-S), and ankle plantarflexor (A2-S) moments, as well as power absorption of hip flexor (H2-S), knee extensor (K1-S; K3-S), knee flexor (K4-S), and ankle plantarflexor (A1-S) moments [19]. Power curves for the frontal plane joint powers at the hip and knee differed from reference data [19]; however, specific phases were identifiable during power absorption of hip abductor (H1-F), knee abductor (K1-F), knee adductor (K2-F), ankle inverter (A1-F) moments and power generation of hip abductor (H2-F) and ankle everter (A2-F) moments. Power absorption of the hip external rotator (H1-T), knee internal rotator (K1-T), and ankle external rotator (A1-T) moments were defined in the transverse plane.

Statistical Analysis

One investigator undertook data collection and intra-tester reliability determined for all dependent variables, resulting in moderate to high correlation (see supplementary material). The exceptions were frontal plane ankle joint powers [20], which was considered unreliable and excluded from subsequent analyses.

Because no significant group differences existed in walking speed during SSP, speed was not considered a covariate. However, a significant difference between SSP and FP ($p < 0.001$) suggested increased cadence produced a greater locomotor demand. Step length was not significantly different between walking cadence or group.

Data for all joint power phases were analyzed for normality and considered suitable for parametric statistical analysis. Analyses of variance [2 (group) x 2 (walking cadence)] with repeated measures on walking cadence were performed for the pre-determined power phases at each joint. Power phases were normalized to body weight using additional repeated measures analyses of covariance [2 (group) x 2 (walking cadence)]. All statistical analysis was performed using SAS 9.1 with significance set at $p < 0.05$.

Results

Means, standard deviations, and test statistics for all joint phases are presented in Table 2. Sagittal, frontal, and transverse plane power curves for each joint are in Figure 1.

Hip Joint Power

Significant differences in group and walking cadence seen at the H1-S power phase remained when body weight was accounted for. Normal-weight ($p = 0.0025$) and obese children ($p < 0.0001$) had significantly greater joint power during FP than SSP, with obese children generating more power during FP ($p = 0.0137$). Significant differences existed for group and walking cadence at the H2-S phase with obese children displaying greater power absorption during FP (Figure 1; $p = 0.0232$). Despite the lack of group differences when accounting for body weight, obese children showed greater power absorption during FP ($p = 0.0239$). Significant differences between group and walking cadence were seen for the H3-S power phase. When body weight was a covariate, obese children increased power generation during FP ($p = 0.0073$). Greater power absorption was also seen at the H1-F phase during FP and SSP ($p < 0.0001$) and at the H2-F power phase but the latter failed to reach significance ($p = 0.0693$). No significant differences for group or speed were seen at H1-T; except for a trend towards greater power absorption in the obese during FP ($p = 0.0678$).

Knee Joint Power

Despite no group differences in walking cadence at the K1-S phase; obese children displayed greater power absorption at a faster cadence ($p = 0.0008$) until body weight was a covariate. Obese children generated greater energy at the K2-S phase for both SSP ($p = 0.0146$) and FP ($p = 0.0139$) but not after adjusting for body weight. Significant differences for group and walking cadence were seen at the K3-S phase with greater joint powers at FP than SSP in the obese ($p < 0.0001$). After accounting for body weight no group differences remained but significant differences persisted for walking cadence. Significant group and walking cadence differences were seen at the K1-F phase and remained after accounting for body weight. Conversely, no differences in group or walking cadence were observed at the K2-F power phase. Significant group differences at K1-T did not remain after accounting for body weight. There were no significant differences in walking cadence at the K1-T phase.

Ankle Joint Power

Significant differences for group, but not walking cadence, at the A1-S phase did not remain after accounting for body weight. Obese children had significantly greater joint powers at the A2-S phase during SSP ($p = 0.0024$) and FP ($p = 0.0001$), however not after accounting for body weight. There were no significant differences in walking cadence at the A2-S phase nor differences in group or walking cadence for the A1-T phase, despite a trend towards significantly greater power absorption in the obese during SSP ($p = 0.0615$).

Discussion

To our knowledge, this is the first study of three-dimensional characteristics of lower extremity joint powers in obese children. We confirmed that body mass and walking cadence affect hip, knee, and ankle joint powers in all planes and could place increased demands on locomotion with negative implications on children’s gait.

Group Differences

Obese children had significantly greater sagittal plane power phases throughout stance. During heel-strike, increased mass requires larger joint powers from the anti-gravity musculature to maintain an upright posture, with additional power generation at the H1-S phase to control the trunk at heel-strike and throughout weight transference. The corresponding power absorption, followed by power generation phase, of knee extensors is also increased in the obese, indicating a need for greater control of knee flexion. Significant group differences in H1-S and K1-S phases remained after accounting for body weight, suggesting alteration of locomotor strategy. A larger trunk may cause the center of mass to decelerate faster when approaching mid-stance, consistent with greater power absorption by hip flexors to decelerate thigh extension at the H2-S phase. Corresponding to deceleration through mid-stance is increased power absorption of ankle plantarflexors, which control the larger leg mass as it rotates over the foot. At propulsion, obese children required greater power generation of hip flexors and ankle plantarflexors to prepare for swing phase and propel the body forward, as well as increased power absorption of knee extensors to control limb collapse. Increased power generation for hip propulsion at H3-S phase indicates greater demand on hip musculature and supports previous findings of poor performance in the obese when moving total body weight [9-11]. Increases in knee joint power phases may also predispose trauma and injury to soft tissue around the knee. Similarly, increased force to the foot at propulsion can promote pain in the triceps surae mechanism, including the Achilles tendon. Increased joint powers in the sagittal plane [19] suggests a change in locomotor strategy by obese children and reduced mechanical efficiency [15].

Greater frontal plane power phases in the obese could be due to greater step width [13,14]. Despite lack of significant differences in frontal plane hip kinematics [16], increased step width creates a larger power absorption phase to control for pelvic drop during weight acceptance. Concurrently, obese children have increased power absorption of knee abductor moments to control increased external adductor forces [16] and would also need to generate more hip power prior to swing to elevate the pelvis and allow for foot clearance without increased circumduction. Increased frontal plane joint powers were anticipated, however it is unclear if this increases risk for soft tissue injury.

Despite no significant differences in the transverse plane, a trend towards greater power absorption by hip and knee external rotators moments was evident in obese children during FP. The H1-T phase occurs during weight acceptance as a mechanism for decelerating the forward rotation of the pelvis simultaneously with the K1-T phase to resist internal rotation of the knee. The larger trunk and limb mass of obese children requires greater control at heel-strike in all three planes and could explain the trend in absolute joint powers in the transverse plane.

Walking Cadence

Increased walking cadence created greater hip power in all sagittal plane phases, emphasizing the joint's importance in propulsion and stability. Larger ground reaction forces at heel-strike require greater control of the trunk and lower extremity in the H1-S phase. Acceleration of the center of mass is greater at increased walking cadences, as is the associated deceleration, evidenced by increased joint powers at the H2-S phase. With body weight as a covariate, obese children had significantly greater hip flexor power absorption at FP, suggesting that the combination of excess mass and increased speed requires additional control. Greater power generation by hip flexors at the H3-S phase created greater propulsive force and a faster moving swing limb enabled the maintenance of increased walking cadence. Greater propulsive force also required coincidental control of the collapsing limb through increased power absorption at K3-S. Additionally, the obese children had considerably greater differences between walking cadences than normal-weight children. Increased muscular power to maintain a faster cadence may cause obese children to fatigue more quickly and have difficulty managing faster paced walking.

Previous research has shown that knee angular displacements decrease at faster walking cadences [16]. Decreased joint movement diminishes the absorption of power by active and passive stabilizers in the frontal plane during weight acceptance, resulting in a decreased K1-F phase. Conversely, higher cadence increases power generation by hip abductors during swing phase preparation, which raises the pelvis to allow toe clearance and maintenance of speed through the concurrent increased power in the sagittal plane. Obese children have less knee flexion and a flatter foot, reducing toe clearance during walking [13,14]. Increased power generation by the abductors in obese children is identifiable at toe-off. This may be a strategy for maintaining toe clearance after the kinematics have been altered.

After accounting for body weight, obese children had significantly, or trend towards, greater joint powers at all positive hip power phases during FP. These differences did not occur in all negative hip power phases. The increase in power generation without a subsequent decrease in power absorption has implications for energy expenditure in the obese. Results are similar to earlier work [15], with significant increases at the hip in the energy transfer ratio (generation-to-absorption) of obese compared to normal-weight children. This supports other research suggesting mechanical inefficiency is partially responsible for the increased energy cost of walking in obese children at faster speeds [17,21].

Conclusion

There were limitations to this study (see supplementary material). However, this is the first study to examine three-dimensional lower extremity joint powers at varying walking cadences. Differences in group and walking cadences were commonly seen at the hip, an expected result as the joint is responsible for 74% of work completed during locomotion [19]. Obese children require larger sagittal plane joint powers to control the trunk and prevent the collapse of the lower limb, while promoting locomotion through greater propulsion. The result may include greater difficulty performing locomotor tasks and decreased motivation to exercise. Obese children also required greater frontal plane joint powers at the hip and knee to control external adductor moments during weight acceptance and raise the pelvis quickly for adequate toe-clearance [13]. Greater mass and walking cadence create a gait cycle that requires more mechanical power. Further research is needed to better understand the implications of this increased power, specifically as it relates to difficulty performing movement tasks and hesitation participating in physical activities.

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Figure Captions

1. *Average joint power (W) curves for group and walking cadence*. Solid black line indicates normal-weight group at SSP, dashed black line indicates normal-weight group at FP. Solid gray line indicates obese group at SSP, dashed gray line indicates obese group at FP. Significant differences ($P < .05$): ^{A}Group differences (ANOVA), ^{B}Cadence differences (ANOVA), ^{C}Group differences (ANCOVA), ^{D}Cadence differences (ANCOVA).

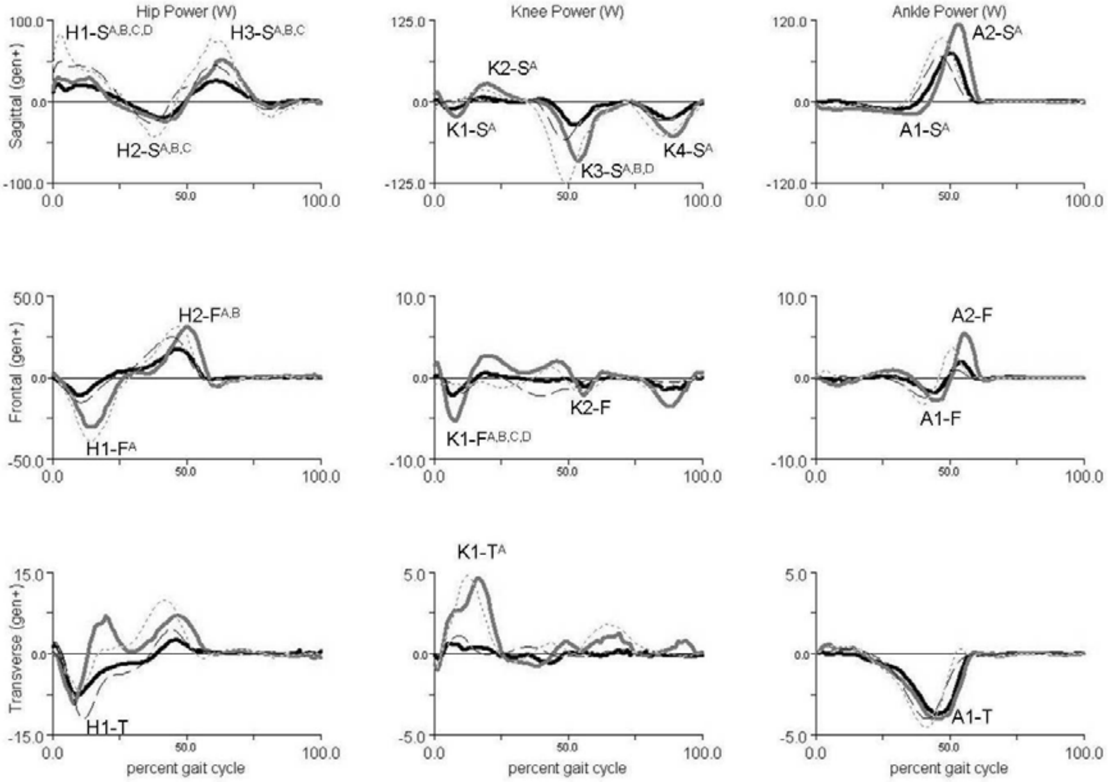

Table 1. Descriptive characteristics of obese and normal-weight groups

Parameter	Obese (n=14)	Normal-weight (n=14)
Age (years)	10.43±1.51	10.79±1.37
Weight (kg)	72.20±19.34*	36.54±6.61
Height (m)	1.55± 0.13$^{\#}$	1.46±0.09
Body Mass Index (kg/m^2)	29.74± 4.91*	17.03±1.26
Walking speed (m/s)	1.18±.16	1.23±.16

Note. Values are the mean ± standard deviation. $^{\#}p < 0.05$; $*p < 0.001$.

Table 2. Significant Means and Standard Deviations for Hip Power Phases

Power Phase	Group	SSP (n = 28)	FP (n = 20)	P_{group} ANOVA (*ANCOVA*)	P_{cadence} ANOVA (*ANCOVA*)
H1-S (W)	OW	45.61±19.36	90.98±35.57	**0.0017 (*0.0092*)**	**<0.0001** ***(<0.0001)***
	NW	24.87±10.16	53.33±17.77		
H2-S (W)	OW	-37.86±18.75	-56.15±38.94	**0.0103** (*0.6731*)	**0.0308** ***(0.0315)***
	NW	-20.64±9.26	-25.01±11.65		
H3-S (W)	OW	52.51±25.19	86.30±40.60	**0.0019** *(0.6463)*	**0.0020** ***(0.0022)***
	NW	26.85±8.05	43.41±14.32		
H1-F (W)	OW	-38.56±20.54	-46.49±24.55	**<0.0001** *(0.1943)*	0.2982 *(0.2685)*
	NW	-12.92±7.72	-13.97±8.85		
H2-F (W)	OW	36.38±10.94	45.57±16.11	**0.0005** *(0.1926)*	**0.0345** *(0.0552)*
	NW	19.57±6.77	22.15±12.98		
H1-T (W)	OW	-21.00±16.55	-23.04±21.49	0.0775 *(0.6044)*	0.0637 *(0.1202)*
	NW	-10.06±6.05	-13.00±7.55		
K1-S (W)	OW	-27.65±24.99	-28.43±14.58	**0.0055** (*0.1335*)	0.5197 *(0.5227)*
	NW	-14.21±5.39	-8.14±7.47		
K2-S (W)	OW	27.57±25.94	32.29±29.81	**0.0047** (*0.9587*)	0.4483 *(0.4639)*
	NW	8.47±21.30	7.66±4.02		
K3-S (W)	OW	-100.31±46.39	-148.20±86.88	**0.0004** *(0.6840)*	**<0.0001** ***(0.0002)***
	NW	-43.64±44.40	-60.69±30.43		
K4-S (W)	OW	-63.86±34.09	-63.67±26.75	**0.0001** *(0.8500)*	0.8645 *(0.8806)*
	NW	-29.83±31.27	-45.56±27.05		
K1-F (W)	OW	-7.60±6.32	-1.88±1.03	**0.0249** ***(0.0473)***	**0.0013** ***(0.0013)***
	NW	-3.39±5.28	-1.58±1.04		
K2-F (W)	OW	-9.70±16.03	-3.46±5.24	0.2887 *(0.0861)*	0.1048 *(0.1415)*
	NW	-3.57±11.96	-2.82±2.41		
K1-T (W)	OW	-1.63±1.12	-1.55±0.62	**0.0207** *(0.2806)*	0.9907 *(0.9953)*
	NW	-0.82±1.12	-0.79±0.78		
A1-S (W)	OW	-30.40±13.83	-22.96±15.45	**0.0026** (*0.5350*)	0.2086 *(0.4599)*
	NW	-14.85±7.35	-11.19±8.28		
A2-S (W)	OW	141.42±64.83	125.40±39.03	**0.0002** (*0.1566*)	0.0801 *(0.0805)*
	NW	80.37±21.63	66.40±22.46		
A1-T (W)	OW	-6.37±3.82	-6.05±4.19	0.0910 *(0.6941)*	0.5681 *(0.5321)*
	NW	-4.21±1.56	-4.18±2.33		

Note. SSP = self-selected walking cadence and FP = 130% of SSP. OW = obese (N = 14) and NW = normal-weight (N = 14).

Significant differences ($p < 0.05$) are highlighted in bold font.