Biomechanical characteristics of lower limb gait waveforms: Associations with body fat in children

Abstract

Background

Childhood obesity is associated with musculoskeletal dysfunction and altered lower limb biomechanics during gait. Few previous studies have explored relationships between childhood obesity measured by body fat and lower limb joint waveform kinematics and kinetics.

Research question

What is the association between body fat and hip, knee and ankle joint angles and moments during gait and in 7 to 11 year-old boys?

Methods

Fifty-five boys participated in the study. Body fat was measured by air displacement plethysmography. Hip, knee and ankle 3D waveforms of joint angles and moments were recorded during gait. Principle component analysis was used to reduce the multidimensional nature of the waveform into components representing parts of the gait cycle. Multiple linear regression analysis determined the association between the components with body fat.

Results

Higher body fat predicted greater hip flexion, knee flexion and knee internal rotation during late stance and greater ankle external rotation in late swing/early stance. Greater hip flexion and adduction moments were found in early stance with higher body fat. In mid-stance, greater knee adduction moments were associated with high body fat. Finally, at the ankle, higher body fat was predictive of greater internal rotation moments.

Significance

The study presents novel information on relationships between body fat and kinematic and kinetic waveform analysis of paediatric gait. The findings suggest altered lower limb joint kinematics and kinetics with high body fat in young boys. The findings may help to inform research in to preventing musculoskeletal comorbidities and promoting weight management.

Word count 249

Introduction

Childhood obesity is associated with a greater incidence of musculoskeletal pain and dysfunction. Studies have reported links between orthopaedic conditions (e.g. Slipped Capital Femoral Epiphysis), increased musculoskeletal pain, foot problems, lower limb joint osteoarthritis and aberrant lower limb biomechanics and obesity [1,2,3]. Excessive and misplaced forces across lower limb joints may predispose to joint dysfunction resulting in increased stress, joint pathology and pain [4,5]. Greater understanding of the biomechanical impact on childhood obesity is important to fully understand the impact of musculoskeletal structure and function, to inform rehabilitation strategies for obesity related joint and soft-tissue dysfunction, and prevent musculoskeletal co-morbidities.

The impact of childhood obesity on clinical gait characteristics has been documented; obese children are reported to walk slower, with a greater base of support and longer stance phase duration [6,7]. To date, five studies have described associations between childhood obesity and three-dimensional (3D) kinematic/kinetic changes in the lower limb [8,9,10,11,12] with conflicting findings. Both significantly greater [9] and lower [11] hip abduction moments have been reported when comparing obese/overweight (OW/OB) children with healthy-weight controls. McMillan et al [10] reported less hip flexion at initial contact, whereas Cimolin et al [12] reported greater hip flexion at the same gait event. Three studies have reported reduced knee flexion angle in OW/OB participants [8,11,12] yet all reported conflicting findings for frontal plane knee moments; Gushue et al [8] reported greater knee abduction moments, McMillan et al [11] reported reduced knee abduction moment and Cimolin et al [12] reported no significant difference. Three studies report reduced ankle plantarflexion moments in OW/OB children [8,10,11] and one study reported no significant differences [12].

Conflicting findings in previous studies may result from two methodological factors; (1) The definition of obesity used to define groups and, (2) the method of analysing gait data. Earlier studies have used BMI Z-Scores to define OW/OB groups which are based on arbitrary cut-offs (e.g >99%, >97%, >95%) rather than fat measurements as a continuous variable. Furthermore, defining OW/OB by BMI Z-Scores has low sensitivity meaning some OW/OB children are grouped as healthy-weight whereas measures of body fat provide greater confidence in the degree of obesity in children [13]. Previous work by the authors has utilised waveform analysis to determine relationships between foot motion and body fat in the same cohort as that reported in the current article [14]. Analysis of complete waveforms does not rely on the selection of peak or event data to describe gait (commonly reported in previous studies), but instead enables examination over the entirety of the gait cycle.

Looking at the evidence to date, the overall impact of obesity on paediatric gait biomechanics is not understood. However, to the authors' knowledge, no study has used complete waveform analysis to provide a detailed lower limb kinematic and kinetic analysis in children. The aim of this study was to identify relationships between percentage body fat and lower limb gait waveforms in in young boys.

Methods

Selection and description of participants

Fifty-five boys, aged 7 to 11 years, participated in the study (Table 1). Ethical approval was obtained (Ref No. ETH/13/11). Participants were recruited from a convenience sample of local schools and clubs. Parental consent and child assent was obtained prior to testing. Participants were excluded from participating if any medical conditions affecting neuromuscular and orthopaedic integrity or any complications contributing to altered foot posture and/or gait disturbance were identified from a health screening questionnaire.

Instrumentation and procedures

Measures of anthropometrics and body fat

Body fat was measured by air displacement plethysmography using a Bodpod (Life Measurement, Inc, Concord, CA, USA). Procedures for this study have been described in our previous study [14]. Estimates of body volume were derived from pressure measures within the Bodpod chamber and converted to body fat percentage (relative to body mass) using age- and gender-specific equations. Weight was measured to the nearest 0.1 kg using Bodpod scales and height measured to the nearest 0.5 cm using a portable Leicester stadiometer (Seca Vogel, Hamburg, Germany). Body Mass Index (BMI) score was calculated as height/weight^2 and reported as an age and sex specific z-score (UK90 data set) [15].

Measures of spatiotemporal and 3D biomechanics of the lower limb during gait

An eight-camera Vicon Nexus motion capture system (Vicon Motion Systems Ltd, Oxford, UK) was used to track and record the motion of skin mounted reflective markers at 200 Hz during barefoot walking. All participants walked at self-selected speed.

Fifteen 12 mm retro-reflective markers were attached (by one operator, RM) to the right and left legs of each participant in line with the Plug-in Gait protocol. An 'instrumented pointer device' was used to create virtual markers representing the ASIS landmarks to reduce skin-mounted displacement by adipose tissue [16]. The location of the ASIS virtual markers were tracked using skin-mounted markers attached to each iliac crest. Seven segments were reconstructed from marker trajectories from which joint relative angular motion and moments were calculated (Visual 3D, C-Motion Inc., MD, USA). Two floor mounted force plates (Bertec, Model MIE Ltd, Leeds, UK) recorded ground reaction forces during gait trials at 1000 Hz. Joint moments were filtered using a low-pass Butterworth filter with a cut-off off frequency of 10 Hz. The gait cycle was defined from initial contact (determined as an increase in vertical force above 20 N) through foot-off and the subsequent initial contact of the same foot. Sagittal, frontal and transverse angular motion and moments were described for the hip, knee and ankle joints. 3D angles and moments from each participant were extracted as 51 data points normalised over the entire gait cycle for angular data, and over the stance phase for moment data. Joint moments are presented as external joint moments. For each participant mean and standard deviations were calculated from six successful gait cycles across the 51 data points forming the waveforms.

Statistical analysis

Principal component analysis

Principal component analysis (PCA) was employed to reduce the major modes of variation in the data to fully explore angular motion and moments over the entire gait cycle. Previous research on paediatric gait has employed PCA to analyse multiple waveforms utilising separate matrices and further information on its application to the gait data is presented [14]. A brief overview of PCA is included in this paper and readers are referred to recent work [17,18] for a detailed overview. The four PCA steps were applied as follows: (1) generation of a co-variation matrix containing 55 participants and 51 data points, (2) retention of components that cumulatively explained 90% of the variation in the waveform, (3) application of a Varimax orthogonal rotation to maximally explain variability in the original waveforms, (4) identification of the part of the gait cycle represented by the component [18]. The output of PCA is a regression score (estimated coefficient representing a participant's score on a component) which was calculated for each participant based on their 3D angular motion or moments within each principal component. Positive regression scores indicated dorsiflexion, eversion and abduction and negative regression scores indicated plantarflexion, inversion and adduction. This regression score was used for subsequent analysis by multiple linear regression.

Multiple linear regression

To determine the association between body fat (predictor variable) and 3D angular motion and moments (predicted variables), multiple linear regression was undertaken. Based on potential confounding effects of size and gait patterns, eight potentially confounding predictor variables (age, height, BMI Z-Score, walking speed, step length, step width, stance phase duration and total single support phase duration) were entered into our modelling. To account for the possibility of a curvilinear relationship between the predictor variables and the regression score, a second order polynomial was fitted to each predictor variable (Linear variables were denoted by the $_{linear}$ suffix, quadratic variables were denoted by the $_{quad}$ suffix). Regression scores that were significantly associated with obesity are presented. Assumptions of normality and homoscedasticity were checked by plotting the standardised predicted values against the standardised residuals; the residuals were found to be normally distributed, and there was no association between the residuals and fitted values. All statistical analysis was carried out in SPSS version 20. Statistical significance was set to p<.05.

Results

Demographic, anthropometric and spatiotemporal characteristics of the participants

Participant's demographic, anthropometric and spatiotemporal characteristics are presented (Table 1). Eight participants were classified as obese, 12 participants were classified overweight, 29 as ideal weight and 6 were underweight [16].

Principal component analysis

Mean and standard deviation of joint angular waveforms are presented (Figure 1). Table 2 presents the results of PCA for the three lower limb joint angles, each joint in three planes of motion. From the hip angular waveform two sagittal, five frontal and three transverse plane PCs were extracted explaining 80.73%, 90.22% and 87.19% of the variance respectively. At the knee joint five sagittal, two frontal and three transverse plane PCs were extracted from the angular waveform explaining

96.74%, 80.18% and 96.11% of the variance, respectively. Five sagittal, three frontal and three transverse plane joint angular PCs were extracted from the ankle waveform respectively, explaining 93.78%, 94.24% and 95.90% of the variance.

Mean and standard deviation of joint moment waveforms are presented (Figure 2). Table 3 presents the results of PCA of the three lower limb joint moments, each joint in three planes of motion. Six sagittal, five frontal and five transverse plane joint moment PCs were extracted from the hip moment waveform explaining 92.78%, 95.75% and 94.63% of the variance, respectively. At the knee joint, four sagittal, four frontal and five transverse plane PCs were extracted respectively explaining 93.72%, 87.03% and 95.31% of the variance. From the ankle moment waveform, four sagittal, four frontal and five transverse plane PCs were extracted explaining 95.89%, 95.74% and 94.68% of the variance, respectively.

Multiple linear regression analysis

Significant relationships between joint 3D angles and body fat from the regression analysis are presented in Table 4. Body fat_{linear}, $height_{linear}$, step $distance_{linear}$ and $velocity_{linear}$ were significant in predicting hip sagittal angle PC2 (F=27.25, *p*<.000). Higher body fat and height as well as lower step length and velocity were associated with less hip extension during the second half of the stance phase. Body fat_{linear} and $velocity_{linear}$ were significant predictors of knee sagittal motion in PC1 (F=8.38, *p*=.001). Higher body fat was positively associated and velocity was negatively associated with greater knee flexion during the second half of stance phase. Greater internal rotation of the knee in PC2 was predicted by body fat_{linear} (F=11.76, *p*=.001). Significant associations between greater external rotation of the ankle joint during the beginning and end of the gait cycle motion in PC3 (F=5.26, *p*=.026) and body fat_{linear} were found.

Significant relationships between joint 3D moments and body fat from the regression analysis are presented (Table 4). Significant associations between greater hip extension moments from PC3 with body fat_{linear} (F=11.50, *p*=.001) were identified. Hip moments in the frontal plane in PC3 were significantly associated with body fat_{linear}, stance phase $duration_{quad}$, step $width_{linear}$ and step $width_{quad}$ (F=20.23, *p*<.000). Greater adduction hip moments during the first half of stance were positively associated with obesity, stance phase duration and step width. A regression model containing body fat_{linear} and $height_{linear}$ was significant in predicting knee frontal plane moments in PC1 (F=8.24, *p*=.001). Higher body fat and height were positively associated with greater knee adduction moments during the middle of stance. A regression model of age_{linear}, body fat_{linear} and body fat_{quad} were significant in predicting transverse ankle joint moments in PC1 (F=16.77, *p*<.000).

Older children with higher body fat were positively associated with greater internal rotation moments of the ankle during the second half of stance.

Discussion

The aim of this study was to analyse complete 3D waveforms of lower limb joint angular motion and joint moments to examine the impact of body fat on gait in young boys. The findings offer novel information about the relationships between angular motion of the lower limb joints and body fat and demonstrates that body fat was associated with altered joint angle and moments of the lower limb during gait.

Our data demonstrated reduced hip extension during the second half of the stance phase with higher body fat, slower walking velocity and lower step distance. According to Gage [19], adequate step length is an attribute of normal gait and therefore a reduction is likely to compromise. Reduced hip extension, resulting in lower step distance, has been shown to be significantly affected by slower walking speed in children [20] and obesity [6]. Shultz et al [10] found (non-significant) greater hip flexion in obese children, but McMillan et al [11] reported significantly greater hip extension which contrasts with the current findings. It is worth noting that McMillan et al [11] used greater trochanter markers which can be displaced due to soft tissue artefact and Shultz et al [10] used functional hip joint centres. The use of a pointer device has been previously shown to reduce errors in soft tissue artefact and reduce hip flexion [21, 22] which may account for the differences between studies.

Greater hip flexion in participants with higher body fat may relate to greater hip flexion moments, both occurred in the second half of the stance phase. Sheehan & Gormley [23] found greater hip flexion in OW/OB adults, attributing greater hip flexion to hip extensor weakness and reducing their role as anti-gravity muscles. In the current study, greater hip external moments in mid- to late stance concurs with the finding of McMillan et al [11] who attributed this to a compensatory action to pull the limb into swing rather than utilise the plantarflexors to push it through. Weaker hip flexors may contribute to greater external hip extensor moments effecting the ability to propel the body forward [24].

During the first half of stance, greater hip adduction moments in boys with higher body fat were also found. In the regression model, reduced step width and longer stance phase were also associated with body fat and have previously been suggested as a gait strategy to decrease instability in OW/OB

[7]. A reduction in step width likely results from the foot being placed closer to the mid-line of the body meaning the ground reaction vector may pass more medial to the hip joint centre, thus, causing higher adduction moments. Greater hip adduction moments found in the current study is comparable with McMillan et al [9], but in contrast to McMillan et al [11]. Differences in hip frontal plane forces suggests OW/OB boys alter medial-lateral forces placing them at risk of musculoskeletal injury and reduce physical activity.

Boys with higher body fat demonstrated greater knee flexion, similar to previous work in OW/OB adults [23], but contrasting other reports [8,10]. The discrepancies between studies are likely due to experimental methods including OW/OB classifications, differences in marker sets and walking speed and the need to account for soft-tissue artefact [16]. There is a need to define appropriate methods of 3D motion analysis to account for soft tissue artefact errors (including bony landmark identification and tracking) and across different populations, but particularly in paediatric populations with high body fat. Walking velocity was also associated with greater knee flexion indicating that boys with higher body fat may be utilising knee flexion to achieve comparable velocity to boys with health body fat.

Boys with higher body fat demonstrated greater external peak knee adduction moments in the stance phase, consistent with Gushue et al., [8]. These authors attributed greater external knee adduction moments to increased adipose tissue between the thighs of obese children. Greater external knee adduction moments could reflect the distribution of larger compressive forces across the medial compartment of the tibiofemoral joint [25]. In adults, external knee adduction moments have been positively correlated with osteoarthritis severity and progression [26] and obesity is a strong biomechanical risk factor for knee osteoarthritis due to increase knee joint loading [27]. Therefore, childhood obesity may impart a risk for the development of knee osteoarthritis [8] if obesity continues through to adulthood.

Greater knee internal rotation in boys with greater body fat found in the current study may relate to excessive flattening of the foot causing the tibia to rotate internally [28]. The current authors previously found midfoot pronation and a flattening of the medial arch in boys with greater body fat. This may arise from relative weakness of lower limb muscle strength in OW/OB children [14].

The ankle joint of boys with higher body fat was more externally rotated and demonstrated greater internal rotation moments at the end of swing and beginning of stance. An externally rotated limb, or out-toe gait has been reported in obese adults [29]. Less internal rotation of the foot about the ankle at the start of the stance phase may reduce lateral body motion enhancing stability during gait. Furthermore, external rotation of the foot is likely to increase internal rotation moments around the ankle by placing more mass of the foot lateral to the joint centre. Appropriate positioning of the foot at the end of swing is a requirement of a smooth transition to stance and is important for effective progression and efficiency of gait [19].

The findings from this study must be considered in light of the limitations. One of the key limitations from this work was the low amount of variance in lower limb angular motion and moments explained in some regression models despite the model being significant. It is likely that other factors such as; lower limb and foot structure, muscle strength and physical activity may influence the relationship between gait kinematics and kinetics and body fat [30]. Future studies should consider the relationships between structure, muscle strength, physical activity and body composition to understand the impact of paediatric obesity on musculoskeletal function.

Summary

The current study presents novel information on the associations between hip, knee and ankle kinematic and kinetic gait waveforms with body fat in 7-11 year-old boys. Utilising the entire kinematics and kinetics waveforms pattern may provide insight into the effects of obesity on gait biomechanics and help to inform further research into preventing musculoskeletal co-morbidities and promoting weight management. The findings of this study have clinical implications for allied health professionals seeking to deliver optimal gait based interventions to improve physical functioning and reduce body fat in OW/OB children.

<u>Word count 2968</u>

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Highlights

	PC1	PC2	PC3	PC4	PC5

- Few studies have explored associations between childhood obesity and gait waveforms
- Body fat predicted hip and knee flexion, knee internal and ankle external rotation
- Greater hip flexion and adduction moments were associated with higher body fat
- At the ankle, higher body fat was predictive of greater internal rotation moments
- These novel findings suggest altered gait kinematics and kinetics with high body fat

Table 1. Mean, SD and range of age, anthropometric and spatiotemporal characteristics of sample population (n=55)

	Mean	SD	Range
Age (years)	9.55	1.18	7 - 11
Height (m)	1.40	0.08	1.19 - 1.59
Weight (kg)	37.69	10.67	22.32 - 68.67
BMI (kg/m^2)	18.41	4.00	12.34 - 29.62
BMI Z-score	0.55	1.58	-2.87 - 3.54
BMI Centile (%)	59.99	36.08	0.21 - 99.98
Body fat mass (%)	23.78	9.33	9.46 - 42.06
Walking velocity ($m{\cdot}s^{-1}$)	1.33	0.19	0.95 - 1.81
Cadence (steps/min)	131.69	15.66	105.77 - 171.52
Stance Phase duration (%)	57.29	2.32	52.60 - 65.16
Total single support duration (%)	49.86	1.85	41.59 - 56.70
Step Width (mm)	81.59	28.18	29.47 - 156.38
Step length (m)	0.60	0.06	0.41 - 0.79

Joint	Plane	% Variance explained	% of gait cycle	% Variance explained	% of gait cycle	% Variance explained	% of gait cycle	% Variance explained	% of gait cycle	% Variance explained	% of gait cycle
Hip	sagittal	41.75	95 to 23	38.98	33 to 61						
	frontal	25.92	17 to 39	17.17	49 to 61	16.67	81 to 93	16.16	65 to 77	14.30	1 to 11
	transverse	34.83	61 to 81	34.42	87 to 5	27.94	49 to 51				
Knee	sagittal	26.46	27 to 51	25.85	1 to 23	19.87	69 to 85	14.12	53 to 65	10.44	89 to 97
	frontal	44.38	23 to 53 93 to 99	35.80	57 to 81						
	transverse	42.18	7 to 13 57 to 85	37.16	23 to 53	16.71	91 to 99				
Ankle	sagittal	24.49	7 to 25	20.66	31 to 45	19.78	89 to 3	18.09	61 to 73	10.76	51 to 57
	frontal	38.91	57 to 85	37.81	21 to 53	17.92	89 to 99				
	transverse	35.66	57 to 83	31.12	19 to 51	29.12	91 to 3				

Joint	Plane	PC1		PC2		PC3		PC4		PC5		PC6	
		% Variance explained	% of gait cycle	% Variance explained	% of gait cycle	% Variance explained	% of gait cycle	% Variance explained	% of gait cycle	% Variance explained	% of gait cycle	% Variance explained	% of gait cycle
Hip	sagittal	40.90	27 to 45	16.65	12 to 15	15.53	6 to 9	8.40	1 to 4	6.29	47 to 48	5.01	49 to 50
	frontal	44.38	10 to 34	24.12	37 to 46	11.94	4 to 7	9.83	47 to 51	5.48	1 to 2		
	transverse	33.21	6 to 22	29.24	32 to 46	15.53	25 to 30	8.72	48 to 51	7.93	1 to 4		
Knee	sagittal	35.24	28 to 44	24.05	16 to 24	23.21	4 to 12	11.22	49 to 50 1 to 2				
	frontal	40.42	24 to 42	30.99	5 to 19	9.67	48 to 51	5.950	1 to 3				
	transverse	44.54	26 to 48	26.38	11 to 23	10.31	6 to 9	8.24	1 to 4	5.84	50 to 51		
	sagittal	35.83	26 to 43	26.07	12 to 23	19.25	1 to 9	14.74	45 to 51				

Table2. Summary of principle component analysis of 3D lower limb joint angles.

Ankle	frontal	33.96	10 to 27	25.76	30 to 41	18.26	43 to 51	17.76	1 to 8		
	transverse	45.34	25 to 47	22.17	12 to 21	11.14	6 to 10	9.48	1 to 4	6.55	49 to 51

Predictor variables β (Std Error), *p* value

Table 3. Summary of principle component analysis of 3D lower limb joint moments.

Table 3. Summary of multiple regression analysis of regression score from PCA with predictor variables (only significant results are shown).

Joint	Plane	Principle component (% gait cycle)	%FM Linear	%FM quad	Age Linear	Height Linear	Velocity Linear	Step distance Linear	Step width Linear	Step width quad	Stance duration Linear	Model R^2	Model *p* value
Joint angles													
Hip	sagittal	PC2 (33 to 61)	0.025 (.010) *p* 0.014			6.669 (1.287) *p* 0.000	-0.002 (.001) *p* 0.016	-0.009 (.003) *p* 0.001				.690	.000
Knee	sagittal	PC1 (27 to 51)	0.031 (.014) *p* 0.027				-0.003 (.001) *p* 0.004					.247	.001
Knee	transverse	PC2 (23 to 53)	0.048 (.014) *p* .001									.184	.001
Ankle	transverse	PC3 (91 to 3)	-0.034 (.015) *p* 0.026									.092	.026
Joint moments													
Hip	sagittal	PC1 (27 to 45)	-0.047 (.014) *p* 0.001									.181	.001
Hip	frontal	PC1 (10 to 34)	0.055 (.012) *p* 0.000						-0.072 (.034) *p* 0.041	0.000 (.000) *p* 0.017	0.179 (.083) *p* 0.035	.583	.000
Knee	frontal	PC1 (24 to 42)	0.030 (.014) *p* 0.048			4.267 (1.604) *p* 0.010						.229	.001
Ankle	transverse	PC1 (25 to 47)	-0.229 (.065) *p* 0.001	0.005 (.001) *p* 0.000	0.247 (.090) *p* 0.008							.501	.000

Figure 1. All participant mean angular gait cycle waveform (solid line) with standard deviation (shaded area) for the hip (top row), knee (middle row) and ankle (bottom row) in sagittal (left column), frontal (middle column) and transverse planes (right column). Waveforms normalised 51 data points over complete gait cycle (stance and swing). Vertical lines define the portion of the gait cycle captured in each principal component. * denotes significant relationship with relative fat mass

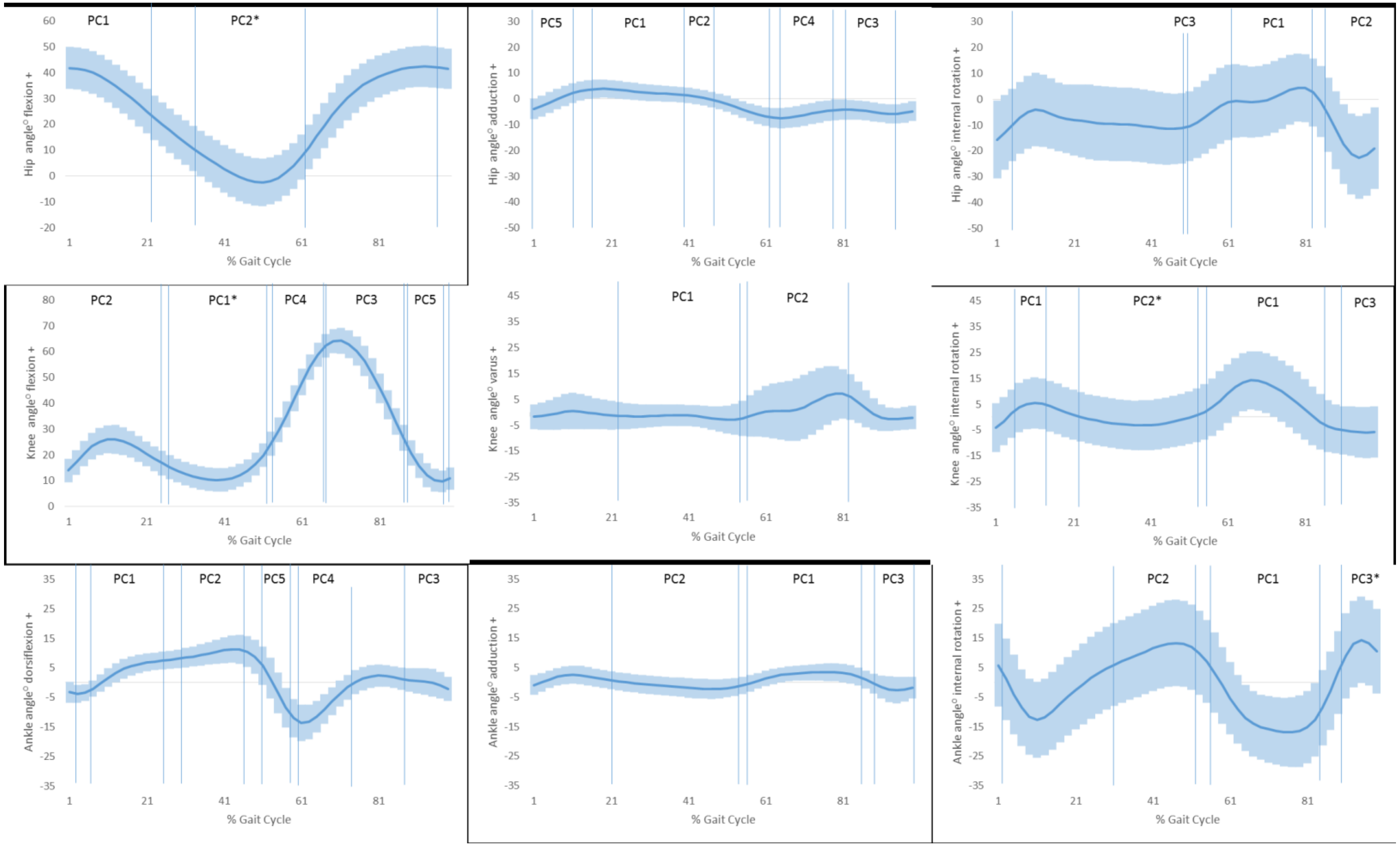

Figure 2. All participant mean moment gait cycle waveform (solid line) with standard deviation (shaded area) for the hip (top row), knee (middle row) and ankle (bottom row) in sagittal (left column), frontal (middle column) and transverse planes (right column). Waveforms normalised to 51 data points over the stance phase. Vertical lines define the portion of the gait cycle captured in each principal component. * denotes significant relationship with relative fat mass