

Supplementary Table 1: Numbers and proportions of people with MHO or MUO stratified by common BMI thresholds

BMI Threshold	N	MHO, n(%)	MUO, n (%)
$\geq 23.00 \text{ kg/m}^2$	297	100 (33.67)	197 (66.32)
$\geq 25.00 \text{ kg/m}^2$	246	69 (28.05)	177 (71.95)
$\geq 27.50 \text{ kg/m}^2$	174	40 (22.99)	134 (77.01)
$\geq 30.00 \text{ kg/m}^2$	109	16 (14.68)	93 (85.32)

Abbreviations: BMI, body mass index; MHO, metabolically healthy obesity; MUO, metabolically unhealthy obesity

Supplementary Table 2: Detailed data on parameters with missing data, and complete-case analysis of comparison between people with MHO and MUO

Factor	Missingness, n (%)	N	Overall	MHO	MUO	p
Systolic BP	2 (0.67)	295	128.00 (18.00)	120.00 (13.00)	133.00 (19.00)	<0.001
Diastolic BP	2 (0.67)	295	81.00 (14.00)	77.00 (10.00)	85.00 (14.00)	<0.001
LDL-c, mmol/L	2 (0.67)	295	3.27 ± 0.80	3.24 ± 0.74	3.28 ±0.83	0.681
Fasting plasma glucose, mmol/L	3 (1.01)	294	5.00 (0.60)	4.80 (0.50)	5.10 (0.60)	<0.001
HbA1c (%)			5.49 ± 0.58	5.21 ± 0.27	5.48 ± 0.67	
HbA1c (mmol/mol)	1 (0.33)	296	35.44 ± 6.39	33.48 ± 3.00	36.44±7.37	<0.001
Neck circumference	1 (0.33)	296	35.44 ± 0.24	33.90 ± 2.68	36.22 ± 3.26	<0.001

Abbreviations: BP, bloods pressure, LDL-c: low density lipoprotein cholesterol, HbA1c, glycated haemoglobin; MHO, metabolically healthy obesity; MUO, metabolically unhealthy obesity.

Supplementary Table 3: Sociodemographic, anthropometric, body composition and biochemistry factors associated with MUO of individuals participants with BMI ≥ 23 kg/m² using univariable logistic regression

N=297		Unadjusted Odds Ratio	95% Confidence Interval		p
			Lower limit	Upper limit	
Sociodemographic Parameters					
Age		1.02	0.99	1.06	0.113 [†]
Sex	Male vs Female	2.89	1.57	5.32	0.001 [*]
Marital Status	Married vs Single / Divorced	1.54	0.93	2.57	0.095
Occupation	Nurse vs Doctor / Allied Health	0.94	0.53	1.69	0.841
	Nonclinical vs Doctor / Allied Health	0.81	0.43	1.53	0.512
Education Level	Secondary vs Primary	1.68	0.41	6.89	0.474
	Tertiary vs Primary	1.57	0.41	6.01	0.512
Monthly Household Income, RM		1.00	1.00	1.00	0.186 [†]
Working Duration per week, Hours		1.02	0.98	1.06	0.244 [†]
Smoking	Yes vs No	3.46	0.77	15.65	0.107
Alcohol	Yes vs No	1.02	0.25	4.15	0.983
Physical Activity Level	Minimally Active vs Inactive	0.94	0.52	1.68	0.830
	HEPA Active vs Inactive	0.80	0.44	1.46	0.467
First degree family history of DM	Yes vs No	1.07	0.66	1.74	0.778
First degree family history of hypertension	Yes vs No	1.04	0.64	1.69	0.870
First degree family history of dyslipidemia	Yes vs No	1.20	0.72	2.01	0.488
Anthropometric Parameters					
BMI, kg/m ²		1.25	1.15	1.35	<0.001 [*]
Waist circumference, cm		1.09	1.06	1.12	<0.001 [*]
Hip circumference, cm		1.08	1.05	1.13	<0.001 [*]
Waist-hip ratio		1.05	1.01	1.08	0.010 [*]
Waist-height ratio		1.12	1.07	1.17	<0.001 [*]
Neck circumference, cm		1.31	1.19	1.43	<0.001 [*]
Systolic blood pressure, mmHg		1.11	1.08	1.14	<0.001 [*]

Diastolic blood pressure, mmHg	1.14	1.10	1.18	<0.001 [*]
Body Composition Parameters				
Body fat percentage, %	1.02	0.99	1.05	0.228 [†]
Body fat mass, kg	1.08	1.04	1.12	<0.001 [*]
Truncal fat mass, kg	1.20	1.18	1.29	<0.001 [*]
Upper limb fat mass, kg	1.34	1.18	1.55	<0.001 [*]
Lower limb fat mass, kg	1.20	1.08	1.32	<0.001 [*]
Fat free mass, kg	1.10	1.16	1.14	<0.001 [*]
Truncal fat free mass, kg	1.26	1.16	1.37	<0.001 [*]
Upper limb fat free mass, kg	2.10	1.62	2.73	<0.001 [*]
Lower limb fat free mass, kg	1.28	1.15	1.42	<0.001 [*]

^{*}Statistically significant at $p < 0.05$

[†] $p < 0.25$

Factors with $p < 0.25$ were selected for multiple logistic regression

Abbreviations: BMI, Body mass index; HEPA, Health-Enhancing Physical Activity; MUOO, Metabolically unhealthy overweight/obesity

Supplementary Table 4: Diagnostic details for primary multivariable logistic regression model (Model 3) for anthropometric and body composition factors associated with MUOO status among participants with BMI ≥ 23 kg/m²

	Collinearity tolerance	VIF	Box-Tidwell Test P-value
Age	0.96	1.04	0.67
Sex	0.29	3.44	-
BFP	0.23	4.36	0.75
LFFMI	0.28	3.58	0.66
WC	0.32	3.15	0.62
HC	0.28	3.64	0.35
NC	0.42	2.36	0.75

Abbreviations: BFP, body fat percentage; BMI, Body mass index; HC, hip circumference; LFFMI, Lower Limb fat-free mass index; MUO, Metabolically unhealthy obesity; NC, Neck circumference; TyGI, Triglyceride-glucose Index; WC, waist circumference; VIF, variance inflation factor.

All VIF values were <5 and collinearity tolerance values were >0.20 , indicating no significant multicollinearity in either model. Box-Tidwell testing (all $p>0.05$) indicated linearity of the logit for all continuous predictors

Supplementary Table 5: Sensitivity analyses including other lifestyle factors in predicting MUOO status

	Adjusted Odds Ratio	95%CI	p-value
Age	1.025	0.99-1.06	0.200
Sex (Male vs Female)	2.54	0.79-8.19	0.118
Smoking (Yes vs No)	0.55	0.11-2.88	0.75
Working hours	1.03	0.98-1.07	0.29
BFP	1.05	0.97-1.13	0.23
LFFMI	1.39	0.64-3.04	0.41
WC	1.01	0.96-1.06	0.751
HC	1.05	0.99-1.11	0.108
NC	1.15*	1.01-1.32	0.048

Abbreviations: 95% CI, 95% Confidence Interval; BFP, body fat percentage; BMI, Body mass index; HC, hip circumference; LFFMI, Lower Limb fat-free mass index; MUOO, Metabolically unhealthy overweight/obesity; NC, Neck circumference;

*Statistically significant at $p < 0.05$

Supplementary Table 6: Sensitivity analyses of the association with neck circumference with MUOO using alternative lean mass measures

Model variant	VIF	Lean mass metric aOR (95%CI)	p	Neck Circumference aOR (95%CI)	p-value
Final Model (LFFMI)	4.36	1.43 (0.66-3.11)	0.368	1.15 (1.01-1.32)*	0.047
Sensitivity 1 (LFFM)	5.11	1.03 (0.83-1.26)	0.834	1.16 (1.02-1.33)*	0.026
Sensitivity 2 (FFM)	6.51	1.06 (0.97-1.16)	0.176	1.14 (1.00-1.31)	0.050
Sensitivity 3 (FFMI)	4.46	1.35 (1.01-1.79)*	0.042	1.11 (0.97-1.28)	0.143
Sensitivity 4 (SMI)	4.45	1.55 (0.97-2.78)	0.138	1.13 (0.98-1.29)	0.096

Abbreviations: 95%CI, 95% confidence Interval, aOR, adjusted odds ratio; FFMI, fat-free mass Index; LFFMI, lower limb fat-free mass index; LFFM, lower limb fat-free mass; MUOO, metabolically unhealthy overweight/obesity; SMI, Skeletal Muscle Index, VIF, variance inflation factor

*Statistically significant at $p < 0.05$

Other factors in the models were maintained as per Model 3 (final model): Age, sex, body fat percentage, waist circumference, hip circumference, and neck circumference (all of which were non-statistically significant after adjustment).

Supplementary Table 7: Receiver operating curve statistics for neck circumference and body fat percentages to predict metabolically unhealthy overweight/obesity among males and females with BMI ≥ 23 kg/m²

Marker	AUROC (95% CI)	Cutoff	Sensitivity	Specificity
Female (n=211)				
Neck circumference (unadjusted)	0.667 (0.593-0.742)	≥ 33.35 cm	70.90%	56.00%
Neck circumference (adjusted)*	0.745 (0.679-0.812)	≥ 33.00 cm	81.10%	57.10%
Body fat percentage (unadjusted)	0.679 (0.606-0.751)	$\geq 42.05\%$	71.70%	61.90%
Male (n=86)				
Neck circumference (unadjusted)	0.654 (0.517-0.790)	≥ 38.90 cm	44.30%	87.50%
Neck circumference (adjusted)*	0.709 (0.578-0.840)	≥ 38.80 cm	54.30%	81.20%
Body fat percentage (unadjusted)	0.694 (0.557-0.831)	$\geq 30.65\%$	60.00%	75.00%

Abbreviations: 95% CI, 95% Confidence Interval; AUROC, Area Under Receiver Operating Characteristics Curve; BMI, Body Mass Index;

*Neck circumference measures were adjusted for factors in Model 3 (Age, sex, body fat percentage, lower-limb fat-free mass index, waist circumference, and hip circumference)

Supplementary Table 8: Mediation of body composition parameters on anthropometric parameters, by body segments, and the effects on MUOO status

N=297 AM / BC Parameters	Direct effect of AM or BC Parameter on MUO	Direct effect of AM on BC parameter	Indirect Effect of BC on MUO	Proportion mediated	Mediation Effect
Upper Body					
Neck circumference	0.13 (-0.01-0.27)				
Upper limb fat mass	0.30* (0.14-0.47)	0.18* (0.10-0.26)	0.05* (0.02-0.10)	41.18%	0.19* (0.08-0.33)
Upper limb fat free mass	0.47* (0.12-0.81)	0.29* (0.26-0.32)	0.1364* (0.03-0.26)	102.71%	
Trunk					
Waist circumference	0.02 (-0.03-0.06)				
Truncal fat mass	0.13* (0.03-0.24)	0.30* (0.27-0.33)	0.04* (0.01-0.07)	250%	0.08* (0.04-0.12)
Truncal fat free mass	0.18* (0.09-0.28)	0.22* (0.18-0.25)	0.04* (0.02-0.06)	243%	
Lower body					
Hip Circumference	0.06* (0.01-0.11)				
Lower limb fat mass	0.03 (-0.15-0.22)	0.23* (0.22-0.25)	0.01 (-0.04-0.05)	12.97%	0.02 (-0.02-0.07)
Lower limb fat-free Mass	0.21* (0.10-0.33)	0.07* (0.03-0.10)	0.01* (0.01-0.03)	23.29%	

Data are presented in effect size (95% Confidence Interval)

Mediation analysis was done using PROCESS Macro package on SPSS

Collinearity was ruled out (Supplementary Table 7)

Homoscedasticity was visually assessed via residual plots for each independent variable-mediator path; no violations were observed

*Statistically significant at $p < 0.05$

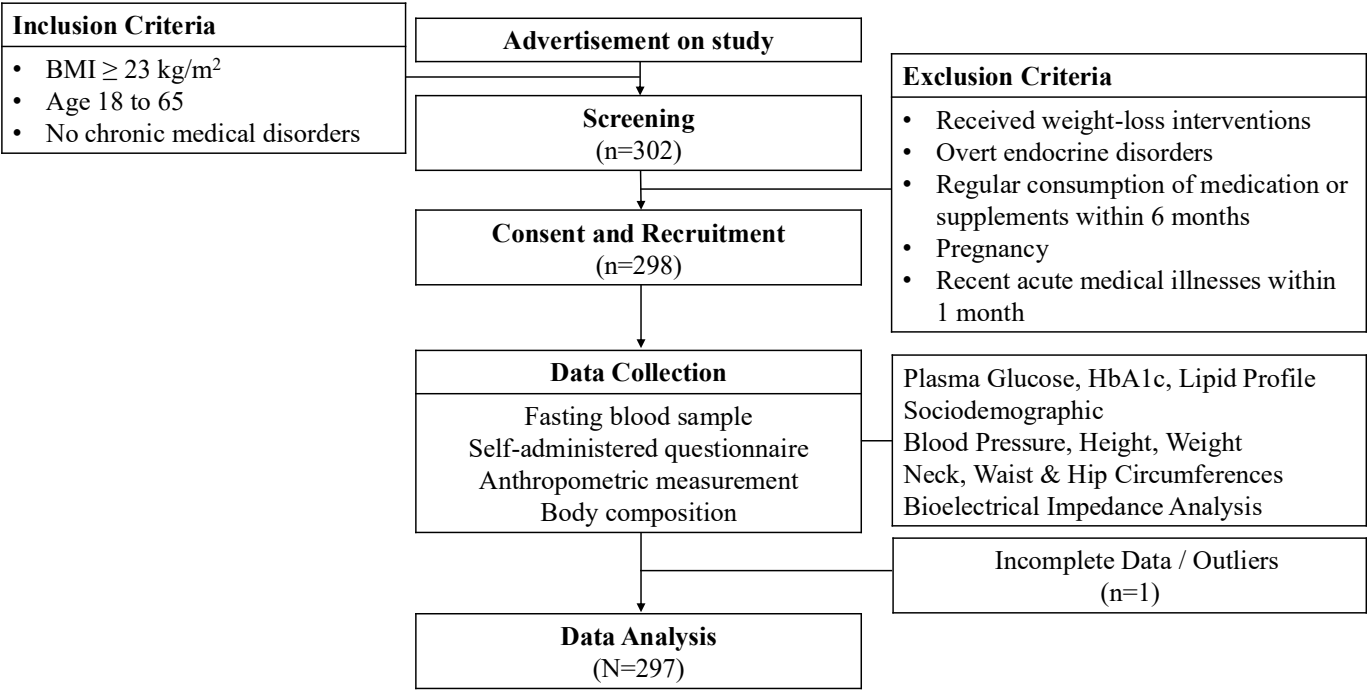
Abbreviations: AM, Anthropometric parameters; BC, Body composition parameters; MUO, Metabolically Unhealthy Obesity

Supplementary Table 9: Collinearity diagnostic details for mediation analysis models for body composition predictors associated with MUOO status among participants with BMI ≥ 23 kg/m²

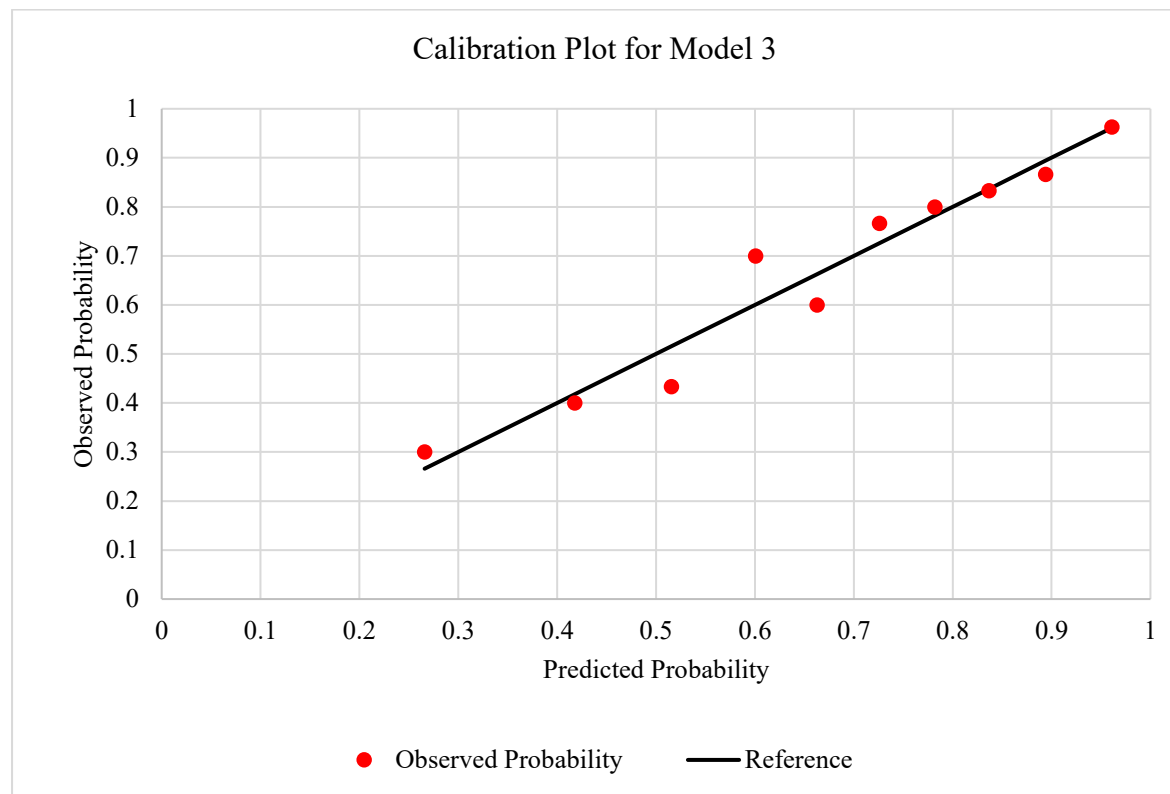
	Collinearity tolerance	VIF
Upper Body		
Upper limb FM	0.96	1.04
Upper limb FFM	0.96	1.04
Trunk		
Truncal FM	0.90	1.12
Truncal FFM	0.90	1.12
Lower Body		
Lower limb FM	0.99	1.00
Lower limb FFM	0.99	1.00

Abbreviations: BMI, Body Mass Index; FFM, Fat-free Mass; FM, Fat Mass; MUOO, Metabolically unhealthy overweight/obesity; VIF, variance inflation factor.

All VIF values were <5 and collinearity tolerance values were >0.20 , indicating no significant multicollinearity.

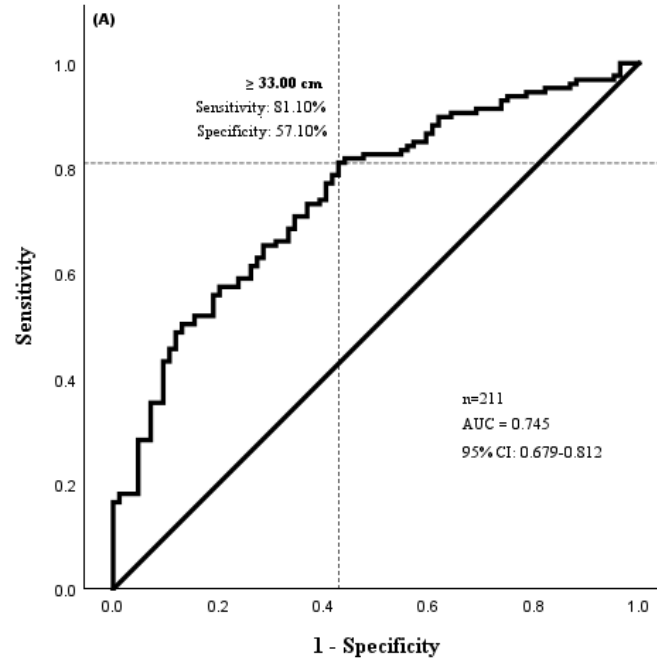


Supplementary Figure 1: Study flow diagram

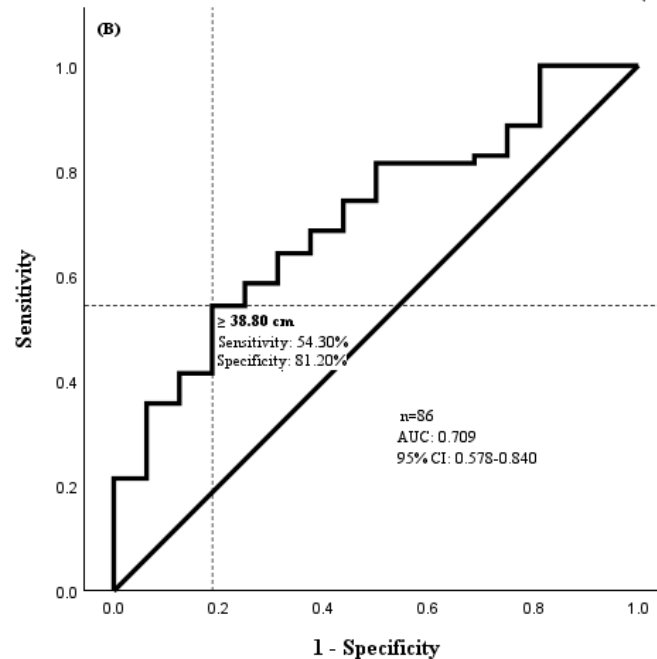


Supplementary Figure 2: Calibration Plots for Model 3

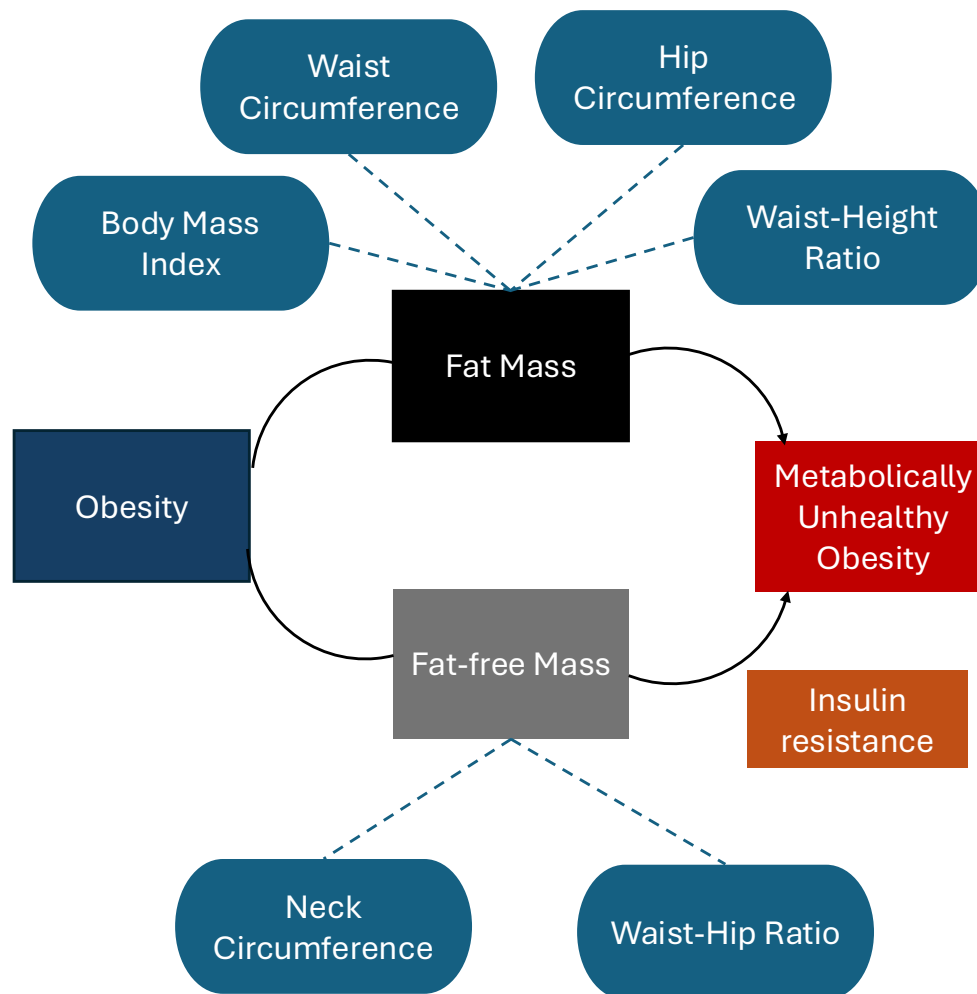
Adjusted ROC Curve for Neck Circumference to Predict MUOO Status (Females)



Adjusted ROC Curve for Neck Circumference to Predict MUOO Status (Males)



Supplementary Figure 3: Adjusted receiver operating curve (ROC) for neck circumference (NC) for predicting metabolically unhealthy obesity (MUOO) status among (A) females, NC ≥ 33.00 cm, with 81.00% sensitivity and 57.10% specificity; and (B) males, NC ≥ 38.80 cm with 54.30% sensitivity and 81.20% specificity.



Supplementary Figure 4: Proposed Pathways Linking Anthropometry, Body Composition, and Metabolic Unhealthy Obesity

Anthropometric measures reflect underlying FM and FFM compartments that influence metabolic status: body mass index, waist circumference, hip circumference and Waist-to-height ratio reflect fat-mass-related pathways, whereas neck circumference and waist-to-hip map more closely to fat-free-mass-related pathways, which is likely mediated by insulin resistance, together contributing to metabolically unhealthy obesity.