

1 **Integrative genomic analysis implicates limited peripheral adipose storage capacity in the**  
2 **pathogenesis of human insulin resistance**

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41

1 **Abstract**

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Insulin resistance is a key mediator of obesity-related cardiometabolic disease, yet the mechanisms underlying this link remain obscure. Using an integrative genomic approach, we identify 53 genomic regions associated with insulin resistance phenotypes (higher fasting insulin adjusted for BMI, lower HDL cholesterol and higher triglycerides) and provide evidence that their link with higher cardiometabolic risk is underpinned by an association with *lower* adipose mass in peripheral compartments. Using these 53 loci, we show a polygenic contribution to familial partial lipodystrophy-type 1, a severe form of insulin resistance, and highlight shared molecular mechanisms between common/mild and rare/severe insulin resistance. Population-level genetic analyses combined with experiments in cellular models implicate CCDC92, DNAH10 and L3MBTL3 as previously unrecognised molecules influencing adipocyte differentiation. Our findings support the notion that limited storage capacity of peripheral adipose tissue is an important aetiological component in insulin-resistant cardiometabolic disease and highlight genes and mechanisms underpinning this link.

## 1 **Introduction**

2

3 Insulin resistance, usually defined as an impaired ability of insulin to maintain normal  
4 glucose metabolism and initially manifested by higher levels of circulating insulin, is positively  
5 associated with adiposity and is a key mediator of the link between obesity and its adverse  
6 impact on metabolic and cardiovascular disease.<sup>1-8</sup> Given the current global epidemic of  
7 metabolic disease, there is an urgent need for improved understanding of the mechanisms that  
8 link over-nutrition to insulin resistance in the general population.<sup>7-10</sup>

9 Among individuals stratified on the basis of overall adiposity, there is considerable  
10 variation in the extent of adverse metabolic sequelae,<sup>11</sup> demonstrating the importance of other  
11 factors in the aetiology of insulin resistance and its complications. Indeed, while insulin  
12 resistance often coexists with obesity, severe forms of insulin resistance develop without  
13 obesity or in association with generalized or regional lack of adipose tissue, i.e.  
14 lipodystrophy.<sup>12</sup> In lipodystrophies,<sup>13</sup> it has been proposed that the impaired capacity of  
15 peripheral adipose tissue to expand under the challenge of a positive energy balance leads to  
16 lipid accumulation at ectopic sites (e.g. liver, skeletal muscle, pancreas) and eventually to overt  
17 diabetes.<sup>12,14</sup> The notion of “adipose overflow” or “limited adipose tissue expandability”<sup>15-19</sup> is  
18 supported (i) by the metabolic disturbances seen in rare, monogenic lipodystrophies and their  
19 dramatic amelioration in response to dietary calorie restriction<sup>20</sup> or leptin replacement,<sup>21,22</sup> and  
20 (ii) by a series of elegant rodent studies including those in which adipose tissue capacity was  
21 expanded by fat transplantation in lipodystrophic mice<sup>23</sup> or by over-expressing adiponectin,<sup>24</sup>  
22 or where partially lipodystrophic mice were energetically challenged by rendering them leptin  
23 deficient.<sup>25,26</sup> However, the relevance of this model to the general population remains uncertain.

24 Some initial human genetic insights into more prevalent forms of insulin resistance are  
25 available. Genome-wide studies of gold-standard measures of insulin resistance have been  
26 limited by sample size,<sup>27</sup> but multiple genomic loci have been associated with fasting insulin

1 levels, a widely-measured marker of insulin resistance.<sup>28,29</sup> A subset of these loci were  
2 associated with higher triglycerides and lower high-density lipoprotein (HDL) cholesterol,<sup>28</sup>  
3 which are hallmarks of insulin resistance.<sup>13,30</sup> These loci were later validated for their  
4 association with insulin resistance,<sup>31</sup> suggesting that the combined association with this triad  
5 of phenotypes could help identify specific genetic determinants of insulin resistance.

6       Given the availability of large-scale genome-wide association data on lipid traits and  
7 fasting insulin,<sup>28,29,32</sup> we undertook an integrative genomic approach to characterise genetic and  
8 molecular mechanisms underpinning insulin resistance at a given level of adiposity and its role  
9 in cardiometabolic disease in the general population.

## 1 **Results**

### 2 *Associations with insulin resistance phenotypes at 53 independent genomic regions*

3 We combined genome-wide association results for fasting insulin adjusted for body mass  
4 index,<sup>22,23</sup> HDL-cholesterol and triglyceride levels<sup>32</sup> from up to 188,577 individuals to identify  
5 loci associated with a phenotypic pattern indicative of insulin resistance (**Online Methods,**  
6 **Supplementary Figures 1-2 and Supplementary Table 1**). After aligning the association  
7 results of ~2.4 million single nucleotide polymorphisms (SNPs) to the insulin-raising allele,  
8 630 SNPs from 53 1Mb-genomic regions were associated with higher fasting insulin, higher  
9 triglycerides and lower HDL-cholesterol ( $p < 0.005$  for each phenotype, expected probability of  
10 association under null hypothesis  $p = 3.1 \times 10^{-08}$ ; **Online Methods, Supplementary Figures 3-**  
11 **4**). These 53 genomic regions included 10 loci previously implicated in insulin resistance,<sup>31</sup>  
12 and an additional 43 loci (**Supplementary Table 2**). A subset of 25 of the 53 loci had  
13 previously been associated with HDL cholesterol or triglyceride levels at genome-wide  
14 significance,<sup>32</sup> while 28 had not (**Supplementary Table 2**). We first investigated the  
15 associations of these loci in a completely independent sample of 6,101 individuals and found  
16 that genetic risk scores comprising the 53 lead SNPs were strongly associated with higher  
17 fasting insulin, higher triglycerides and lower HDL-cholesterol (**Supplementary Figure 5**).  
18 We next asked whether these variants were associated with “gold-standard” measures of insulin  
19 sensitivity. Having a greater number of risk-alleles from the 53-SNP, 43-SNP or 28-SNP  
20 (excluding loci previously implicated in insulin resistance and lipid traits, respectively) genetic  
21 scores was strongly associated with (a) lower insulin sensitivity measured by euglycemic clamp  
22 or insulin suppression test in 2,764 individuals<sup>27</sup> ( $p$ -value for 53-SNP genetic score =  $4.3 \times 10^{-$   
23  $06$ ; **Table 1**) and (b) lower insulin sensitivity index in 4,769 individuals with a frequently-  
24 sampled oral glucose tolerance test<sup>33</sup> ( $p$ -value for 53-SNP genetic score =  $7.3 \times 10^{-10}$ ; **Table**  
25 **1**).

1 *Genetic predisposition to insulin resistance via the 53 loci confers higher risk of*  
2 *cardiometabolic disease but lower levels of peripheral adiposity*

3 We next investigated associations of the 53 genomic regions with a range of continuous  
4 metabolic traits and disease outcomes. In 45,836 cases and 230,358 controls, the 53-SNP  
5 genetic score was associated with a higher risk of type 2 diabetes (odds ratio [OR] per standard  
6 deviation [SD] of the genetic score [i.e. ~4.5 alleles], 1.12; 95% confidence interval [CI], 1.11-  
7 1.14;  $p=9.2 \times 10^{-61}$ ; **Table 1**). In studies with available individual-level data, we saw no  
8 difference in associations across sex or body mass index (BMI) strata (**Supplementary Table**  
9 **3**). Genetically-predicted insulin resistance was also associated with a higher risk of coronary  
10 heart disease (**Table 1**). The associations with type 2 diabetes (OR, 1.10;  $p=9.0 \times 10^{-32}$ ) and  
11 coronary heart disease (OR, 1.04;  $p=9.7 \times 10^{-07}$ ) remained after removing 13 loci that were  
12 previously shown to be associated with either of the two diseases at genome-wide  
13 significance.<sup>34,35</sup> Association estimates were also consistent after removing the 25 loci  
14 previously associated with HDL cholesterol or triglyceride levels at genome-wide significance  
15 (**Table 1**). We also observed an association with coronary heart disease in 5,369 cases of  
16 coronary heart disease and 106,969 controls from the UK Biobank study not previously  
17 included in genome-wide discovery analyses of insulin or lipid traits (OR, 1.09;  $p=5.3 \times 10^{-09}$ ).  
18 Individually, 30 of the 53 lead SNPs were associated with higher type 2 diabetes risk ( $p<0.05$ ;  
19 **Supplementary Table 4**), including a novel association at genome-wide significance for  
20 rs718314 near *ITPR2* (OR per allele, 1.06;  $p=6.8 \times 10^{-09}$ ). We found an enrichment of loci  
21 associated with higher risk of both type 2 diabetes and coronary heart disease, including those  
22 encompassing the proximal insulin signalling *INSR*, *IRS1* and *PIK3R1* genes (11/53 loci  
23 associated with both diseases at  $p<0.05$ ; two-tailed binomial probability of observing this  
24 proportion of loci by chance  $p=8.5 \times 10^{-22}$ ; **Supplementary Table 5**).

1 While insulin resistance is often considered secondary to higher adiposity, at the 53 loci  
2 we observed associations with *lower* body fat percentage, BMI and hip circumference (**Figure**  
3 **1A, Supplementary Figures 6 and 7**). The larger magnitude of association with measures of  
4 body fat rather than with glycaemic phenotypes is consistent with a primary effect of many  
5 variants on adipose tissue mass (**Figure 1A, Supplementary Figures 6 and 7**).

6 By follow-up studies using dual-energy X-ray absorptiometry (DEXA) measures in  
7 12,848 individuals, we found that the most marked association of the genetic score was with  
8 lower levels of gynoid and leg fat mass (**Figure 1B**). Individuals in the highest quintile of the  
9 53-SNP genetic score had an average of 712 grams *less* leg fat mass compared to individuals  
10 in the bottom quintile (**Figure 1C**), which accounted for the majority of the overall body fat  
11 association (**Supplementary Figure 8**). The association with lower levels of leg fat was  
12 accompanied by a higher hazard of incident type 2 diabetes (**Figure 1C**). In 9,150 participants  
13 from the EPIC-Norfolk cohort who gained weight during a median follow-up of 3.7 years,  
14 carrying a greater number of the 53 risk alleles was inversely associated with change in hip  
15 circumference, adjusted for the amount of weight gained (i.e. individuals carrying more alleles  
16 were less likely to deposit extra mass in their gluteal region for a given increase in body mass;  
17  $\beta$  in cm of hip circumference per SD of genetic score, -0.07;  $p=0.027$ ; **Supplementary Note**).  
18 Overall, these association analyses suggest that individuals genetically predisposed to insulin  
19 resistance via the 53 loci have a relative inability to expand their peripheral fat compartment  
20 when challenged by a positive energy balance and that this incapacity results in higher  
21 cardiometabolic disease risk. We also found that the 53-SNP genetic score was associated with  
22 higher levels of alanine aminotransferase and gamma-glutamyl transferase (**Supplementary**  
23 **Table 6**), which suggests that the failure to store lipid in gluteofemoral adipose tissue may be  
24 accompanied by hepatic lipid deposition.

1 The 53-SNP genetic score was associated with greater waist circumference (**Figure 1A**),  
2 but not with trunk adipose tissue (**Figure 1B**), indicating that the association with body fat  
3 distribution and cardiometabolic disease was largely driven by the association with lower levels  
4 of peripheral adipose tissue (**Figure 1 and Supplementary Figures 6-8**). Among the 53 lead  
5 SNPs, 17 were within 500kb of a waist-to-hip ratio (WHR) associated SNP<sup>36</sup> (**Supplementary**  
6 **Figure 6**). Consistent with DEXA analyses, the associations with WHR at this subset of  
7 overlapping loci were largely driven by an association with lower hip circumference, rather  
8 than higher waist circumference (**Supplementary Figure 6 and Supplementary Table 4**).

9 Our large-scale meta-analyses allowed the investigation of individual-SNP associations  
10 with both adiposity and metabolic risk. At eight of the 53 loci, the lead SNP was associated  
11 with *lower* total body fat percentage or hip circumference at genome-wide significance ( $p < 5 \times$   
12  $10^{-08}$ ), including a novel association of the insulin-raising G allele of rs4976033 near *PIK3R1*  
13 with lower body fat percentage ( $p = 3.0 \times 10^{-09}$ ; see **Figure 1D and Supplementary Figure 9**).  
14 Seven of the eight adiposity-lowering alleles at these loci were associated with a higher risk of  
15 type 2 diabetes ( $p < 0.05$ ; **Figure 1D**).

16

### 17 *Role of common variants in the genetic basis of a severe form of lipodystrophy*

18 Given the strong association with insulin resistance but lower levels of peripheral  
19 adiposity, we hypothesized that the polygenic predisposition to insulin resistance imparted by  
20 the 53 loci might contribute to the pathogenesis of familial partial lipodystrophy-type 1  
21 (FPLD1). When compared to women from the population-based Fenland study, women  
22 diagnosed with FPLD1 displayed markedly lower levels of leg fat mass for a given fat mass in  
23 the rest of the body (**Figure 2A**). Whilst the name of the condition implies Mendelian  
24 inheritance, using exome sequencing in 9 FPLD1 cases we did not identify likely candidate  
25 causal genes (**Online Methods and Supplementary Table 7**). When compared with 5,296

1 unrelated women from the UKHLS study in a case-control analysis, 37 patients with FPLD1  
2 had a higher burden of the 53 risk alleles (OR per SD of genetic score in logistic regression  
3 analyses adjusted for age and the first 10 genetic principal components, 1.70; 95% CI, 1.21-  
4 2.39;  $p=0.0021$ , **Figure 2B**;  $p_{\text{permutation}}=0.0020$ , see **Online Methods**). Also, the phenotypes  
5 observed in FPLD1 patients in comparison to obese women from the Fenland study mirrored  
6 the association pattern of the 53-SNP genetic score (**Supplementary Table 8**). FPLD1 women  
7 had a more severe leg fat phenotype compared to that expected from the relationship between  
8 the 53 SNP score and leg fat mass in the Fenland study (**Figure 2C**), suggesting that additional  
9 genetic and environmental factors contribute to determining this extreme phenotype.

10

#### 11 *Prioritisation of putative effector genes, cell-types and tissues*

12 We prioritised putative effector genes at the 53 loci by integrating data about physical  
13 proximity, expression quantitative trait locus (eQTL) mapping, functional annotation and  
14 previous knowledge about genes causing monogenic forms of insulin resistance (summarised  
15 in **Supplementary Table 2**; see also **Supplementary Tables 9-11** for details). Putative  
16 effector genes included five with well-established roles in proximal insulin signalling  
17 (**Supplementary Table 2 and Figure 3A**). Other candidates included *LPL*, encoding the key  
18 lipolysis regulator lipoprotein lipase (**Supplementary Table 2 and Figure 3B**). The insulin-  
19 lowering, minor allele of rs1011685 (near *LPL*) is on the same haplotype ( $r^2=1$ ) as a gain-of-  
20 function,<sup>37</sup> protein-truncating allele in *LPL* (p.Ser447\*; rs328; minor-allele frequency [MAF],  
21 9.9%). The p.Ser447\* gain-of-function variant was recently reported to be associated with  
22 lower risk of coronary heart disease,<sup>38</sup> while an independent loss-of-function missense variant  
23 of *LPL*<sup>39</sup> (p.Asp36Asn; rs1801177; MAF, 1.9%) was associated with higher risk.<sup>38</sup> Here, we  
24 found that the p.Ser447\* gain-of-function variant is associated with greater insulin sensitivity,  
25 lower fasting glucose, lower levels of liver markers and protection from type 2 diabetes (OR

1 per allele, 0.93;  $p=1.6 \times 10^{-05}$ ; **Figure 3B and Supplementary Figure 10**). Conversely, the  
2 p.Asp36Asn loss-of-function variant in *LPL* is associated with a higher risk of type 2 diabetes  
3 (OR per allele, 1.11;  $p=0.0086$ ; **Figure 3B and Supplementary Figure 10**). Thus, recent  
4 findings of an allelic series of *LPL* variants implicating lipoprotein lipase as a putative  
5 therapeutic target in heart disease<sup>38</sup> are now complemented by a directionally consistent  
6 observation for type 2 diabetes, compatible with a role for impaired lipoprotein lipase-mediated  
7 lipolysis in insulin resistance and type 2 diabetes.

8       Among the 53 loci, three contained genes at which rare mutations have been previously  
9 implicated in severe monogenic forms of insulin resistance (i.e. *PPARG*, *PIK3R1*, *INSR*;  
10 **Figure 3C**), which is more than what expected by chance given the prevalence of monogenic  
11 insulin resistance genes in the genome (observed percentage 0.54% [3 out of a total of 553  
12 genes in the 53 loci], expected percentage 0.064%, two-tailed binomial  $p=0.0056$ ). The *PIK3R1*  
13 gene encodes regulatory subunits of a critical kinase involved in proximal insulin signalling  
14 and rare, loss-of-function mutations in this gene are associated with SHORT syndrome, a  
15 dysmorphic condition characterised by short stature, partial lipodystrophy and insulin  
16 resistance.<sup>40-43</sup> To date, such mutations have been identified in few families worldwide and  
17 data from Exome Aggregation Consortium show this gene to have decreased tolerance of  
18 missense variation ( $Z=2.42$ ) and to be particularly intolerant of loss-of-function mutations  
19 ( $pLI=1$ ; Exome Aggregation Consortium, Cambridge, MA, URL:  
20 <http://exac.broadinstitute.org> accessed 22<sup>nd</sup> March 2016). Here, we provide evidence that a  
21 common variant near *PIK3R1*, which accounts for almost half of all alleles in the general  
22 population ( $MAF=49\%$ ), is associated with subtle effects on insulin resistance, lower body fat  
23 percentage, higher risk of type 2 diabetes and coronary heart disease (**Supplementary Figure**  
24 **9**). This association pattern partially overlaps with that reported for *PIK3R1* mutations and  
25 SHORT syndrome (**Supplementary Table 12**). We also found that the common rs8101064

1 allele T in *INSR*, encoding the insulin receptor, was associated with insulin resistance and  
2 higher risk of type 2 diabetes (OR per allele, 1.08;  $p=0.020$ ), but not with body fat percentage  
3 ( $p=0.16$ ), consistent with the fact that patients with heterozygous loss-of-function mutations in  
4 the *INSR* are frequently insulin resistant but are not commonly lipodystrophic.<sup>13</sup>

5 We assessed the overlap of lead SNPs and their proxies ( $r^2>0.8$ ) with functional  
6 regulatory annotations across 98 cell types from the NIH Epigenome Roadmap (**Online**  
7 **Methods**) and, consistent with phenotypic associations, identified substantial overlap with  
8 adipose tissue active enhancer elements (31 of 53 loci overlapped adipose tissue active  
9 enhancer elements; observed percentage=58.4% of loci, expected=30.1%, binomial  $p=2.1 \times$   
10  $10^{-05}$ ; **Online Methods and Figure 3D**). Furthermore, combined pathway analyses with  
11 integration of large-scale gene expression data<sup>44</sup> implicated adipocytes as likely effector cell-  
12 type underlying observed associations (**Figure 3E**). In subcutaneous adipocyte eQTL data from  
13 1,064 individuals of the EUROBATs and GTex projects (**Online Methods and**  
14 **Supplementary Table 10**), we observed evidence of eQTL associations with nearby genes  
15 ( $p<10^{-06}$ ) at 21 loci including 14 with supportive evidence of co-localisation of lead phenotypic  
16 and eQTL associations (**Online Methods and Supplementary Table 10**).

17

### 18 *Experimental validation of putative effector genes in cellular adipogenesis models*

19 We sought to experimentally validate the role of five putative effector genes (*IRS1*,  
20 *CCDC92*, *DNAH10*, *L3MBTL3* and *FAM13A*) across four loci which showed associations with  
21 (a) expression of nearby transcripts in subcutaneous adipocytes, (b) lower peripheral adiposity  
22 and (c) higher metabolic disease risk (**Supplementary Note, Supplementary Figure 11,**  
23 **Supplementary Tables 10 and 13**). We used short interfering RNA (siRNA) to reduce mRNA  
24 levels for these five genes in OP9-K cells, an adipocyte model which shows rapid  
25 differentiation in response to adipogenic stimuli.<sup>45</sup> Knockdown of the *IRS1*, *CCDC92*,

1 *DNAH10* and *L3MBTL3* genes significantly reduced both mRNA of the target gene (**Figure**  
2 **4A** top graph) and lipid accumulation (**Figure 4A** bottom graph and **Figure 4B**). These results  
3 were directionally consistent with the association of the insulin-raising alleles at these loci with  
4 lower expression of these genes in subcutaneous adipocytes and with lower levels of peripheral  
5 fat (**Figure 4C**). Knockdown of *FAM13A* reduced mRNA (**Figure 4A** top graph), but did not  
6 significantly affect pre-adipocyte lipid accumulation (**Figure 4A** bottom graph and **Figure 4B**).  
7 In contrast to the other four genes, the risk allele at *FAM13A* was associated with higher mRNA  
8 expression of this gene in subcutaneous adipocytes (**Figure 4C**).

## 1 **Discussion**

2 Our data implicate the impaired capacity to adequately expand the peripheral adipose  
3 tissue compartments in human insulin resistance and related disease at the population level.  
4 These results substantially augment existing evidence<sup>31,36,46-49</sup> by clarifying the extent and  
5 relevance of adipose tissue dysfunction to cardiometabolic disease and by providing novel  
6 mechanistic insights into its underpinning biology.

7 Our results are consistent with the existence of dozens of genomic regions at which  
8 common genetic variation affects cardiometabolic disease risk via subtle “lipodystrophy-like”  
9 mechanisms. While these common genetic mechanisms have individually small effects, their  
10 cumulative effect is large and relevant to a large fraction of the population. For instance, we  
11 observed ~700 grams difference in leg fat mass between the top and bottom 20% of the  
12 population distribution of risk alleles. We also show a polygenic contribution to an extreme  
13 phenotype, referred to as FPLD1 or Köbberling-type lipodystrophy, illustrating the  
14 contribution of common alleles to severe forms of insulin resistance. At given loci (e.g.  
15 *PIK3R1*), we found that genetic variants at the two extremes of the allele frequency spectrum  
16 result in corresponding consequences at the extremes of the phenotypic severity spectrum.  
17 These findings strongly concur with the notion that molecular and pathophysiologic  
18 mechanisms first described in severe forms of lipodystrophic insulin resistance are relevant to  
19 the general population. While a centripetal distribution of body fat is a well-recognised risk  
20 factor for metabolic and cardiovascular disease,<sup>50-54</sup> there is considerable confusion about the  
21 underlying mechanisms and relative importance of lower peripheral fat versus higher central  
22 adiposity. Whilst supportive of a role for central fat accumulation, different lines of evidence  
23 from this study suggest a role for impaired peripheral fat deposition in insulin-resistant  
24 cardiometabolic disease in the general population. These include strong associations with  
25 gluteo-femoral adiposity, overlap with regulatory regions in adipose tissue and with genomic

1 loci known to cause lipodystrophies, as well as functional characterisation in adipocytes. These  
2 findings provide evidence from large-scale human genetics studies which add to a body of  
3 research about the links between subcutaneous and lower-body adipocyte phenotypes and a  
4 favourable metabolic profile.<sup>19,55-57</sup>

5 By combining population-scale association studies with eQTL data from adipose tissue  
6 and experimental evidence from murine cellular models, we provide evidence that specific risk  
7 loci influence adipose gene expression resulting in impaired adipogenesis, reduced peripheral  
8 fat depots and ultimately increased cardiometabolic disease risk. For the *L3MBTL3*, *DNAH10*  
9 or *CCDC92* genes, evidence presented in this study provides the first link with impaired  
10 adipocyte differentiation capacity. *L3MBTL3* recognises methylated lysine residues on histone  
11 tails<sup>58</sup> and previous genome-wide anthropometric studies have implicated this locus in adult  
12 height and length at birth.<sup>59-61</sup> At the chromosome 12q24 locus, our analyses are consistent  
13 with the implication of both *CCDC92* and *DNAH10* in impaired adipogenesis. *CCDC92* is a  
14 coiled coil domain protein which interacts with proteins in the centriole/ciliary interface.<sup>62</sup>  
15 *DNAH10* encodes one of the heavy chains of the dynein arms of the motile cilia and it is,  
16 therefore, surprising that its product appears to have cell autonomous effects on adipocyte  
17 biology. However, an essential splice site mutation in *DNAH10* has previously been reported  
18 to co-segregate with abnormal circulating HDL-cholesterol levels in a family,<sup>63</sup> while the locus  
19 containing both *CCDC92* and *DNAH10* has been associated with circulating levels of large  
20 HDL particles,<sup>64</sup> further supporting an unexpected role for these proteins in metabolism.

21 Our results have preventive and therapeutic implications for cardiovascular and metabolic  
22 disease. First, they suggest that attempts to develop pharmacological agents acting on the  
23 molecular mechanisms of obesity are likely to reduce cardiometabolic risk if they reduce  
24 calorie intake (e.g. by acting on appetite) or reduce ectopic fat deposition in tissues such as the  
25 liver, muscle and pancreas, but not if they impair adipogenesis or peripheral fat deposition.

1 Agents that promote adipocyte differentiation and increase peripheral adipose mass via action  
2 on the peroxisome proliferator-activated receptor gamma have powerful antidiabetic  
3 actions,<sup>65,66</sup> and in some cases have a beneficial effect on cardiovascular outcomes,<sup>67,68</sup>  
4 although some of these agents have been reported to have an adverse cardiovascular safety  
5 profile.<sup>69</sup> An early but vital challenge in the translation of genetic findings towards therapeutic  
6 insight is the ability to identify likely effector transcripts underlying genetic associations. In  
7 the current study, we identify putative effectors of genetic associations and the tissues in which  
8 they operate. We also demonstrate that these genetic variants often affect the risk of type 2  
9 diabetes and coronary disease in a consistent direction, which suggests that targeting these  
10 pathways may satisfy current regulatory requirements that anti-diabetic agents should not be  
11 associated with unacceptable cardiovascular risk.<sup>70</sup> This is particularly true of findings from  
12 both gain- and loss-of-function variants in the *LPL* gene and risk of type 2 diabetes, which are  
13 directionally consistent with those previously reported for the same mutations and risk of heart  
14 disease.<sup>38</sup> Notably, the directional concordance for risk of heart disease and type 2 diabetes is  
15 in contrast to genetic evidence for other lipid-lowering agents (e.g. cholesterol-lowering  
16 variants near the molecular target of statins).<sup>71</sup> In the context of a growing body of evidence  
17 linking lipolysis and heart disease risk,<sup>38,72-75</sup> these data suggest that enhancing lipoprotein  
18 lipase activity may also become a viable preventive or therapeutic strategy in type 2 diabetes.

19 In interpreting the results of this study, it is important to note that combining multiple  
20 genetic-association analyses to gain insights about a latent unmeasured phenotype (i.e. insulin  
21 resistance) is not immediately comparable with a univariate genome-wide association study of  
22 a trait (e.g. fasting insulin). However, we validated these genetic variants as being strongly  
23 associated with “gold-standard” measures of insulin sensitivity, with multiple insulin-  
24 resistance related diseases, including a severe form of insulin-resistant partial lipodystrophy,  
25 and showed overlap with monogenic insulin resistance genes. Thus, approaches to leverage

1 additional sources of evidence to prioritise genomic variation (such as multiple phenotypes or  
2 putative functional class<sup>76</sup>) represent a powerful use of extant genetic association results to  
3 advance understanding of biology previously intractable to conventional strategies.

4 Our results were based on genome-wide analyses of fasting insulin adjusted for BMI,<sup>28,29</sup>  
5 and we did not identify loci with a primary effect on higher adiposity and secondary association  
6 with insulin resistance (e.g. *FTO*). Our approach was more likely to identify loci influencing  
7 insulin resistance at a given level of adiposity. Prompted by the strong association pattern of  
8 the genetic scores and variants, we focused on evaluation of mechanisms linking lower levels  
9 of peripheral adiposity with insulin resistance. The importance of adipose function as a  
10 prominent driver of common insulin resistance is highlighted by the observation that half of all  
11 variants associated with fasting insulin at genome-wide significance (without adjustment for  
12 BMI) in a previous study<sup>28</sup> were included in our genetic score. However, our results do not  
13 preclude the presence nor diminish the importance of other mechanisms underlying insulin  
14 resistance.<sup>5,77</sup> Indeed, the associations we observe of the genetic score with central fat, visceral  
15 fat and liver enzymes would be further strengthened after adjustment for overall adiposity.  
16 While we conclude that our findings implicate a primary effect on impaired adipose function  
17 and a secondary effect on insulin resistance, we cannot entirely exclude the possibility of the  
18 reverse, nor that there are pleiotropic contributions to the associations.

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20

1 **Conclusions**

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3 Collectively, our findings support the notion that limited capacity of peripheral adipose

4 tissue to store surplus energy is implicated in human insulin resistance and related

5 cardiometabolic disease in the general population. Furthermore, we highlight putative effector

6 genes, tissues and mechanisms underpinning this link.

7

## 1 **Data Access Statement**

2 This research has been conducted using the UK Biobank resource. Data on glycemic traits were contributed  
3 by the MAGIC consortium investigators. Associations with type 2 diabetes were obtained from the DIAGRAM  
4 (DIABetes Genetics Replication And Meta-analysis) consortium investigators. Data on coronary heart disease /  
5 myocardial infarction have been contributed by the CARDIoGRAMplusC4D consortium investigators. Data on  
6 body mass index, waist, hip, waist-to-hip ratio were contributed by the GIANT consortium investigators. Data  
7 about triglycerides and high-density lipoprotein cholesterol were contributed by the Global Lipids Genetics  
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9 results for clamp- or insulin suppression test-based insulin resistance. The authors would like to thank the Exome  
10 Aggregation Consortium and the groups that provided exome variant data for comparison. A full list of  
11 contributing groups can be found at <http://exac.broadinstitute.org/about>. Raw exome sequence data from FPLD1  
12 individuals and family members is available from the European Genome-Phenome Archive  
13 (<https://www.ebi.ac.uk/ega/home>, see full accession codes in Supplementary Table 7). Understanding Society:  
14 The UK Household Longitudinal Study is led by the Institute for Social and Economic Research at the University  
15 of Essex and funded by the Economic and Social Research Council. The survey was conducted by NatCen and  
16 the genome-wide scan data were analysed and deposited by the Wellcome Trust Sanger Institute. Information on  
17 how to access the data can be found at <https://www.understandingsociety.ac.uk/>. Genome-wide genotyping data  
18 of 5,296 unrelated women from UKHLS is publically available through the European Genome-phenome Archive  
19 (Dataset Accession: EGAD00010000891).

## 20 **Data download:**

21 MAGIC consortium (<http://www.magicinvestigators.org/>)  
22 GLGC consortium (<http://csg.sph.umich.edu/abecasis/public/lipids2013/>)  
23 GIANT (<https://www.broadinstitute.org/collaboration/giant/>)  
24 DIAGRAM consortium (<http://diagram-consortium.org/>)  
25 CARDIoGRAMplusC4D (<http://www.cardiogramplusc4d.org/>)  
26 Exome Aggregation Consortium (<http://exac.broadinstitute.org/about>)  
27 European Genome-Phenome Archive (<https://www.ebi.ac.uk/ega/home>)

## 28 **Study websites:**

29 Fenland (<http://www.mrc-epid.cam.ac.uk/research/studies/fenland/>)  
30 EPIC-Norfolk (<http://www.srl.cam.ac.uk/epic/>)  
31 EPIC-InterAct (<http://www.inter-act.eu/>)  
32 UK Biobank (<http://www.ukbiobank.ac.uk/>)  
33 Understanding Society: The UK Household Longitudinal Study (<https://www.understandingsociety.ac.uk/>)  
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26  
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## 1 Figure Legends

2  
3 **Figure 1. Combined associations with detailed anthropometry and metabolic disease risk at the 53 genomic loci.** *Panel A:* association of the 53-SNP genetic score with anthropometric and glycaemic traits in meta-analyses of genetic association studies. Body mass index (BMI), waist-to-hip ratio (WHR), waist and hip circumference data are from the GIANT consortium and the UK Biobank study. Body fat percentage data are from the UK Biobank, EPIC-Norfolk and Fenland studies. Fasting plasma glucose (FPG), 2 hour glucose and HbA1c data are from the MAGIC consortium. Squares with error bars represent the per-allele beta coefficients in standard deviation units and their 95% confidence intervals. *Panel B:* association of genetic scores with compartmental body masses. Data are from 12,848 participants of the Fenland and EPIC-Norfolk studies who underwent a DEXA scan. Squares with error bars represent the per-allele beta coefficients in standard deviation units and their 95% confidence intervals. *Panel C:* association with lower levels of leg fat mass and higher hazard of incident type 2 diabetes by quintiles of the 53-SNP genetic risk scores. Associations are reported for individuals in the exposed category compared with the bottom quintile (reference category). Associations with leg fat mass are from 9,747 participants of the Fenland study and are reported on the left. Associations with incident type 2 diabetes are from 7,420 incident cases and 9,267 controls of the InterAct study and are reported on the right. Squares represent the beta coefficients in grams of leg fat mass (left plot) or the hazard ratio (HR) for incident type 2 diabetes (right plot) in each category compared with the lowest quintile. Error bars represent the 95% confidence intervals of these estimates. *Panel D:* associations of individual lead SNPs at eight loci with waist, hip circumference (left) and type 2 diabetes (right). Loci were selected on the basis of their genome-wide significant association with hip circumference or body fat percentage (i.e. *PIK3R1*). Waist and hip circumference analyses are from a meta-analysis of the GIANT and UK Biobank studies. Type 2 diabetes analyses are from a meta-analysis of the DIAGRAM, InterAct and UK Biobank studies. Squares with error bars represent the per-allele beta coefficients in standard deviation units of waist and hip circumference (left plot) or the per-allele odds ratio (OR) of type 2 diabetes (right plot). Error bars represent the 95% confidence intervals of these estimates. \*Detailed associations at the *PIK3R1* locus, which was primarily associated with lower body fat percentage, are presented in *Supplementary Figure 9*.

28  
29 **Figure 2. Associations at the 53 genomic loci with familial partial lipodystrophy type 1 (FPLD1).** *Panel A:* distribution of leg fat mass as a function of the fat mass of the rest of the body (from DEXA) in women of the Fenland study at the extreme quintiles (Q) of the 53-SNP genetic score and in 14 FPLD1 subjects. Q1 represents a low genetic burden, whereas Q5 a high genetic burden. Lines of fit are plotted for each group. *Panel B:* histograms of the distribution of risk alleles in the FPLD1 subjects and in control women from the UKHLS study. *Panel C:* bi-dimensional box plots of the distribution of leg fat mass as a function of the distribution of the number of risk alleles in women of the Fenland study at the extreme quintiles (Q) of the 53-SNP genetic score and in FPLD1 subjects. Q1 represents a low genetic burden, whereas Q5 a high genetic burden. Each rectangle represents a group of individuals. For each dimension, the two sides of the rectangle represent the interquartile range and the central line the median. Data for obese women from Fenland were plotted to show the relationship between genetic risk and levels of leg fat in a group of women with a similar body mass index to that of FPLD1 patients.

40  
41 **Figure 3. Putative effector genes, tissues and cell types.** *Panel A:* schematic representation of some established components of the insulin signalling pathway with stars reporting the location in the pathway of putative effector genes, with their respective lead single nucleotide polymorphism listed. *Panel B:* associations of gain- and loss-of-function genetic variants in the *LPL* gene with type 2 diabetes. The reference number in parenthesis refers to the study reporting the association with triglycerides and coronary heart disease (see reference number 38 of this manuscript).<sup>38</sup> *Panel C:* summary of evidence about links between genetic variants, lipodystrophy, insulin resistance, and type 2 diabetes at different levels of the population phenotypic distribution. \*Rare syndromes caused by autosomal dominant *INSR* mutations are not usually associated with lipodystrophy and the *INSR* rs8101064 polymorphism is not associated with body fat percentage. *Panel D:* overlap of the 53 loci (lead SNPs plus proxy variants in  $r^2 > 0.8$ ) with chromatin state annotations from the NIH Roadmap. *Panel E:* DEPICT's annotation of cell types and tissues on the basis of expression patterns in 37,427 human microarray samples. The y-axis represents the  $-\log_{10}(p\text{-value})$  for enrichment of signal in a cell or tissue type attributed by DEPICT. The horizontal broken line represents the multiple-test corrected threshold of statistical significance (Bonferroni  $p=0.00072$ ).

55  
56 **Figure 4. Experimental knockdown of putative effector genes in cellular adipogenesis models and comparisons with phenotypic associations.** *Panel A:* results of experimental knockdown in OP9-K cells. Full circles represent the difference of the means from knockout experiments of a given gene compared with control experiments ( $n=4-7$ ). Error bars represent the 95% confidence intervals of the difference of the means. Top graph: effect on mRNA levels of knockdown experiments of target genes using short interfering RNA (siRNA) in OP9-

1 K cells. The two-tailed t-test p-values for differences in means were: *IRS1*,  $p=4.6 \times 10^{-06}$ ; *CCDC92*,  $p=2.7 \times 10^{-09}$ , *DNAH10*,  $p=2.4 \times 10^{-06}$ ; *L3MBTL3*,  $p=4.6 \times 10^{-06}$ ; *FAM13A*,  $p=2.4 \times 10^{-05}$ . Bottom graph: effect on lipid  
2 accumulation in siRNA knockdown experiments. The two-tailed t-test p-values for differences in means were:  
3 *IRS1*,  $p=0.0047$ ; *CCDC92*,  $p=1.2 \times 10^{-05}$ , *DNAH10*,  $p=0.0027$ ; *L3MBTL3*,  $p=0.00013$ ; *FAM13A*,  $p=0.92$ . *Panel*  
4 *B*: illustrative images showing florescence microscopy from lipid accumulation experiments. Red indicates  
5 adipored staining of neutral lipid, blue is hoechst staining of nuclei. *Panel C*: Association of the risk (insulin-  
6 raising) allele of the lead single nucleotide polymorphism in or near each of the putative effector genes with (a)  
7 the expression of the corresponding gene in subcutaneous adipocytes in the EUROBATS project (top graph in the  
8 panel); (b) hip circumference in a meta-analysis of GIANT and UK Biobank (mid graph); and (c) type 2 diabetes  
9 in a meta-analysis of InterAct, DIAGRAM and UK Biobank (bottom graph). Full circles represent the  $-\log_{10}(p$ -  
10 value) for the association of the insulin-raising allele multiplied by the direction of the beta coefficient (i.e. a  
11 “directional”  $-\log_{10}(p)$ ). For graphic display purposes, the  $-\log_{10}(p$ -value) for the association with type 2  
12 diabetes of the rs2943645-T allele near *IRS1* is represented as 10 instead of 16.9.  
13

1 **Tables**

2

3 **Table 1. Association with “gold-standard” insulin resistance measures, type 2 diabetes**  
 4 **and coronary heart disease of genetic scores comprising lead polymorphisms at identified**  
 5 **loci.** Results are displayed for genetic scores comprising either (a) the lead SNP at each of the  
 6 53 associated loci or (b) the lead SNP at each of the 43 additional loci identified in this study  
 7 after removing 10 previously implicated in insulin resistance or (c) the lead SNP at each of the  
 8 28 loci not previously associated with levels of HDL cholesterol or triglycerides.

9

Exposure	Outcome	Sample size, N or N cases and N controls	Beta or odds ratio	SE or 95% CI	p-value
<i>Association with “gold-standard” measures of insulin sensitivity</i>					
53-SNP score	Insulin sensitivity <sup>a</sup>	2,764	-0.09	0.019	4.3 x 10 <sup>-06</sup>
43-SNP score			-0.08	0.022	4.6 x 10 <sup>-04</sup>
28-SNP score			-0.09	0.022	2.6 x 10 <sup>-05</sup>
53-SNP score	Insulin sensitivity index <sup>b</sup>	4,769	-0.10	0.016	7.3 x 10 <sup>-10</sup>
43-SNP score			-0.08	0.018	4.6 x 10 <sup>-05</sup>
28-SNP score			-0.09	0.027	0.0010
<i>Association with disease endpoints</i>					
53-SNP score	Type 2 diabetes	45,836 cases and 230,358 controls	1.12	1.11, 1.14	9.2 x 10 <sup>-61</sup>
43-SNP score			1.09	1.08, 1.11	7.6 x 10 <sup>-29</sup>
28-SNP score			1.11	1.09, 1.13	1.9 x 10 <sup>-25</sup>
53-SNP score	Coronary heart disease	63,746 cases and 130,681 controls	1.05	1.04, 1.06	1.8 x 10 <sup>-13</sup>
43-SNP score			1.04	1.03, 1.06	5.7 x 10 <sup>-08</sup>
28-SNP score			1.04	1.02, 1.06	1.2 x 10 <sup>-05</sup>

10 Abbreviations: N, number of participants; SE, standard error; CI, confidence interval; SNP, single nucleotide polymorphism.  
 11 Beta coefficients are in standardised units per standard deviation of the 53-SNP genetic score (i.e. 4.5 alleles); odds ratios are  
 12 per standard deviation of the 53-SNP genetic score (i.e. 4.5 alleles). The association with insulin sensitivity is from 2,764  
 13 participants of the GENESIS consortium<sup>27</sup> and the association with the insulin sensitivity index is from 4,769 participants of  
 14 the MAGIC consortium who underwent a frequently sampled oral glucose tolerance test (OGTT)<sup>33</sup>; the association with type  
 15 2 diabetes is from the InterAct, DIAGRAM and UK Biobank studies; the association with coronary heart disease is from the  
 16 CARDIoGRAM and the C4D consortia.

17 a In MAGIC, insulin sensitivity index (ISI) = 10,000/√ (fasting plasma glucose (mg/dl) × fasting insulin × mean glucose  
 18 during OGTT (mg/dl) × mean insulin during OGTT).<sup>33</sup>

19 b In GENESIS, insulin sensitivity was measured by clamp or insulin suppression test using study-specific parameters (e.g.  
 20 glucose disposal or M-value) which were then standardised before meta-analysis.<sup>27</sup>

## 1 **Online Methods**

### 2 *Study design*

3 We integrated the results of genome-wide analyses on insulin and lipid phenotypes with  
4 the aim of identifying genetic variants associated with an insulin resistance phenotypic pattern  
5 (**Supplementary Figures 1-4**). We then investigated the mechanistic links of genetic variation  
6 at 53 identified genomic regions with cardiometabolic diseases by integrating analyses of: (a)  
7 cardiometabolic traits and outcomes from up to 451,193 individuals; (b) detailed continuous  
8 metabolic traits from 12,848 deeply-phenotyped individuals; (c) genetic and clinical features  
9 from 37 individuals diagnosed with familial partial lipodystrophy type 1; (d) gene expression  
10 from over 100 separate eQTL datasets and (e) siRNA mediated knockdown of putative effector  
11 genes in experimental adipogenesis models (**Supplementary Table 1 and Supplementary**  
12 **Figures 1-2**).

13

### 14 *Participating studies*

15 Lists of phenotypes, participating studies and sample sizes for each analysis are in  
16 **Supplementary Table 1 and Supplementary Figures 1-2**. Details about participants and  
17 cohorts with individual-level genotype data are in **Supplementary Table 14**. Ethical approvals  
18 were obtained at each study site and informed consent was obtained from all participants.

19 The Fenland study is a population-based cohort study of 12,435 participants without  
20 diabetes born between 1950 and 1975. Participants were recruited from general practice  
21 surgeries in Cambridge, Ely and Wisbech (United Kingdom) and underwent detailed metabolic  
22 phenotyping and genome-wide genotyping.

23 EPIC-Norfolk is a prospective cohort study of 25,639 individuals aged between 40 and 79  
24 and living in the Norfolk county in the United Kingdom<sup>78</sup> at recruitment. EPIC-Norfolk is a  
25 constituent cohort of the European Prospective Investigation of Cancer (EPIC).<sup>79</sup> A total of

1 3,101 participants with available dual energy X-ray absorptiometry (DEXA) were included in  
2 analyses of detailed anthropometry, while 9,150 participants were included in analyses of  
3 change in hip or waist circumference in individuals who gained weight during follow-up.

4 EPIC-InterAct is a case-cohort study nested within the EPIC study, a cohort study of  
5 519,978 European participants.<sup>80</sup> During an average of 8 years of follow-up, 12,403 individuals  
6 who were free of diabetes at baseline were identified incident type 2 diabetes cases.<sup>80</sup> InterAct  
7 has also defined a randomly-selected subcohort of 16,154 individuals free of diabetes at  
8 baseline.<sup>80</sup> Data on 15,357 individuals with available genotyping and not overlapping with  
9 DIAGRAM<sup>34</sup> were included.

10 UK Biobank is a population-based cohort study of ~500,000 people aged between 40-69  
11 years who were recruited in 2006-2010 from several centres across the United Kingdom.<sup>81</sup>  
12 Associations with prevalent type 2 diabetes were estimated in 111,016 individuals (4,586 cases  
13 and 106,430 controls) of the initial UK Biobank dataset. We also used the UK Biobank data  
14 for anthropometry analyses and for a sensitivity analysis of prevalent coronary heart disease  
15 (i.e. self-reported myocardial infarction or angina) in 5,369 cases and 106,969 controls.

16 The United Kingdom Household Longitudinal Study (UKHLS; also known as  
17 Understanding Society) is a longitudinal panel survey of 40,000 households representative of  
18 the population of the United Kingdom. Participants were surveyed annually since 2009 and  
19 contributed information relating to their socioeconomic circumstances, attitudes, and  
20 behaviours via a computer assisted interview. For a subset of individuals who took part in a  
21 nurse health assessment, blood samples were taken and genomic DNA analysed.

22 In addition to individual-level genotyping data, we used genome-wide meta-analyses  
23 results on a variety of cardiometabolic traits and disease endpoints (**Supplementary Table 1**  
24 **and Supplementary Figures 1-2**).

25

1 *Detailed anthropometric analyses*

2 In the Fenland and EPIC-Norfolk studies, body composition was determined by dual-  
3 energy X-ray absorptiometry (DEXA) using a Lunar Prodigy advanced fan beam scanner (GE  
4 Healthcare, Bedford, UK) using the encore software version 14.10.022 (GE Healthcare,  
5 Bedford UK). Participants were scanned by trained operators using standard imaging and  
6 positioning protocols. The coefficient of variation for scanning precision, calculated from 30  
7 consecutive scans, was 2% for total fat mass. The enCORE software was used to demarcate  
8 regional boundaries. All the images were manually processed by one trained researcher, who  
9 corrected demarcations according to a standardized procedure. Boundaries of body regions are  
10 described in details in the **Supplementary Note**. In the UK Biobank study, body fat percentage  
11 was estimated by bio-impedance using the Tanita BC418MA body composition analyser.

12

13 *Association of genetic variants with insulin resistance phenotypes*

14 A dyslipidaemic pattern with higher triglyceride levels and lower HDL cholesterol is  
15 considered characteristic of the clinical presentation of insulin resistance<sup>13</sup> and has been used  
16 to specifically identify individuals with insulin resistance.<sup>30</sup> In a previous large-scale genome-  
17 wide discovery of genetic determinants of fasting insulin levels, among 19 fasting insulin-  
18 associated loci we identified ten that were strongly associated with higher triglycerides and  
19 lower HDL cholesterol.<sup>28</sup> This pattern of association was used to refine loci which were then  
20 validated as being associated with “gold-standard” measures of insulin resistance.<sup>31</sup> Loci  
21 associated with insulinaemia but not with lipid traits included *TCF7L2*,<sup>28</sup> which is primarily  
22 implicated in insulin secretion, rather than resistance.<sup>82</sup> These findings suggested that the  
23 combined association with this triad of phenotypes could help identify specific genetic  
24 determinants of insulin resistance.

1 With this background, we systematically triangulated the results of the association of  
2 ~2.4M single nucleotide polymorphisms (SNPs) with fasting insulin adjusted for body mass  
3 index (FIadjBMI; from up to 108,557 participants of the MAGIC consortium),<sup>28,29</sup> HDL-  
4 cholesterol, and triglycerides (from up to 188,577 participants of the Global Lipids Genetics  
5 Consortium)<sup>32</sup> using publicly available genome-wide results (**Supplementary Figures 1-4**).  
6 For FIadjBMI analyses, we used metabochip association results<sup>28</sup> when available. We aligned  
7 alleles across the three phenotypes such that the effect allele was the insulin-raising allele. We  
8 took forward for further analysis all SNPs associated with higher FIadjBMI, higher  
9 triglycerides and lower HDL cholesterol at  $p < 0.005$  for each of the three traits. The prior  
10 probability for association of a given SNP with the three traits and in the pre-specified  
11 directional concordance under the null hypothesis corresponds to  $0.005 * 0.0025 * 0.0025 = 3.1$   
12  $\times 10^{-08}$ . In each 1 Mb locus, we retained the lead SNP for association with fasting insulin for  
13 further analysis (**Supplementary Figure 4**).

14 Fasting insulin analyses adjusted for BMI were chosen because we were interested in  
15 identifying genetic determinants of insulin resistance for a given level of adiposity. It has been  
16 proposed that adjusting genetic association analyses for covariates such as BMI might result in  
17 a bias known as “collider bias”.<sup>83,84</sup> Therefore, we assessed the association of the 53 lead SNPs  
18 for a bias in the identification of variants primarily associated with BMI and artificially  
19 associated with fasting insulin, but found no evidence on such bias (**Supplementary Figure**  
20 **12**).

21

## 22 *Statistical methods*

23 We studied the association of individual SNPs and of genetic scores with continuous  
24 metabolic traits and endpoints. Where individual level genotype data was available, the  
25 associations of genetic variants or scores (i.e. the sum of effect alleles) with outcomes were

1 estimated using multivariable linear, logistic or Cox regression models. For result-level  
2 association data, we used the inverse-variance weighted method developed by Burgess et al.,  
3 assigning a weight of 1 to each SNP, to approximate the association of an unweighted genetic  
4 risk score.<sup>85</sup> Statistical analyses were conducted using STATA v14.1 (StataCorp, College  
5 Station, Texas 77845 USA), R v3.2.2 (The R Foundation for Statistical Computing), and  
6 METAL.<sup>29</sup> All p-values presented in the study are two-tailed p-values.

7

#### 8 *Analyses in a severe form of partial lipodystrophy and insulin resistance*

9 We studied the clinical and genetic characteristics of 37 women with familial partial  
10 lipodystrophy type 1 (FPLD1; also called Köbberling-type familial partial lipodystrophy).

11 All cases were referred to the insulin resistance/lipodystrophy specialist centre led by Drs  
12 Semple, Savage and O’Rahilly in Cambridge. FPLD1 is currently a clinical diagnosis used to  
13 describe predominantly women with selective paucity of limb adipose tissue, central obesity,  
14 severe insulin resistance, and a higher risk of type 2 diabetes.<sup>86,87</sup> As some women with  
15 lipodystrophy due to loss-of-function mutations in *PPARG* manifest a similar phenotype (i.e.  
16 FPLD3), mutations in this gene were excluded in all FPLD1 cases included in this study. The  
17 biochemical and anthropometric phenotype of the 37 FPLD1 patients was compared with that  
18 of female participants of the Fenland study. In these analyses we compared the phenotypes of  
19 the 37 FPLD1 patients with those of all Fenland study women (**Figure 2**) and with those of  
20 obese Fenland study women (**Figure 2 and Supplementary Table 8**), who have a similar BMI  
21 to that of FPLD1 women.

22 To understand the genetic basis of FPLD1, we carried out exome sequencing analyses in  
23 18 individuals from 9 pedigrees with FPLD1 without identifying any clear candidate mutations  
24 or genes. Sequencing, variant calling and annotation were performed as described previously  
25 (Family 2;<sup>88</sup> Families 1 and 3–9 as part of the UK10K project).<sup>89</sup> Calls were annotated with

1 1000 Genomes allele frequencies and the NCBI dbSNP database build 132  
2 ([ftp://ftp.ncbi.nih.gov/snp/organisms/human\\_9606/](ftp://ftp.ncbi.nih.gov/snp/organisms/human_9606/)). Variants were defined as potentially  
3 functional if they were non-synonymous, resulted in loss or gain of a stop codon or a frameshift,  
4 or occurred within essential splice sites. Those unlikely to have a functional impact were  
5 removed, as were all variants found with a MAF >1% in individuals of European descent from  
6 the 1000 Genomes Phase 1v3 (<ftp://ftp.1000genomes.ebi.ac.uk/vol1/ftp/release/20110521/>) or  
7 the NHLBI ESP Exomes (URL: <http://evs.gs.washington.edu/EVS/>; January 2012). Further  
8 filtering was then implemented to retain only variants in genes seen in multiple patients.

9         We compared the burden of the 53-SNP genetic score in the 37 FPLD1 patients with  
10 that of 5,296 unrelated control women from UKHLS. Genome-wide genotyping of UKHLS  
11 women was performed using the Illumina Infinium HumanCoreExome-12 v1.0 BeadChip.  
12 Genotype calling was performed using the Illumina GenCall software. Genome-wide  
13 genotyping of FPLD1 patients was performed using the Illumina® Infinium CoreExome-  
14 24v1.0 chip. Prior to imputation, the following quality control criteria were applied for  
15 exclusion of SNPs in PLINK<sup>90</sup> (version 1.07): (1) minor allele frequency <0.01; (2) Hardy-  
16 Weinberg equilibrium  $p < 1 \times 10^{-6}$ ; (3) call rate <99%; (4) differential missingness between  
17 cases and controls  $p < 1 \times 10^{-6}$ ; (5) SNPs showing differential genotyping between the  
18 CoreExome-24v1.0 and CoreExome-12v1.0 chips. Samples were excluded prior to imputation  
19 in PLINK based on the following criteria: (1) call rate <95%; (2) autosomal heterozygosity >3  
20 standard deviations from the mean; (3) pairwise identity by descent was calculated and one  
21 individual was removed for every pair of individuals with a  $\pi$ -hat >0.05, with preference given  
22 to retaining female samples; (4) identity assessed by the concordance between the genome-  
23 wide and Fluidigm® genotypes at 24 sites (excluding individuals with concordance <90%); (5)  
24 ethnic outliers based on a principal components analysis. Imputation was performed using the  
25 1000 Genomes Phase 3 reference panel using SHAPEIT2<sup>91</sup> (version 2.r644) and IMPUTE2<sup>92</sup>

1 (version 2.3.1). FPLD1 cases and UKHLS controls were imputed together. In an analysis of  
2 the genetic principal components derived from genome-wide genotyping (defined based on the  
3 combined sample), the 37 FPLD1 patients clustered with UKHLS control women  
4 (**Supplementary Figure 13**). Association analyses were performed in R by logistic regression  
5 adjusting for age and the first 10 genetic principal components. We also derived a permutation-  
6 based null comparator by performing 100,000 permutations of randomly selecting 53 SNPs  
7 (>1Mb apart) from genome-wide analyses of FPLD1 status adjusted for age and principal  
8 components and performing summary statistic Mendelian randomisation.<sup>85</sup> Of 100,000  
9 iterations, 201 had a p-value less than our observed association ( $p_{\text{permutation}} = 2.01 \times 10^{-03}$ ).

10

#### 11 *Prioritisation of putative effector genes*

12

13 We sought to determine the putative effector genes at the 53 loci. We combined  
14 information on (a) physical proximity, (b) eQTL data from over 100 repositories, (c) functional  
15 and regulatory annotations and (d) previous knowledge about causal genes for monogenic  
16 forms of insulin resistance.

17 For physical proximity analysis, we reviewed genes within a 1 Mb-window of each lead  
18 SNP and generated regional association plots using LocusZoom.<sup>93</sup> For eQTL analysis, we  
19 analysed both publicly available and unpublished datasets (see below). For functional  
20 annotation, we used the gene and the tissue/cell type prioritisation functions of the integrative  
21 software DEPICT,<sup>44</sup> in order to gain insights about putative effector genes, tissues and cell  
22 types. We also looked for nonsynonymous variants in linkage disequilibrium with the lead SNP  
23 ( $r^2 > 0.8$ ) in European ancestry populations using Haploreg v3.<sup>94</sup>

24 We assessed the overlap of identified loci with chromatin state definitions of active  
25 enhancers and active promoters for 98 cell types from the NIH Epigenome Roadmap project,  
26 including a total of 196 genomic annotations. For each of the 53 lead SNPs, we identified the

1 set of proxy variants in high linkage disequilibrium (CEU  $r^2 > 0.8$ ) using SNAP<sup>95</sup> and defined a  
2 ‘locus’ as a lead SNP plus its proxies. We then calculated the number of loci where at least one  
3 variant at the locus overlapped a given annotation. We determined enrichment in the overlap  
4 at the 53 loci compared to an expected distribution built from randomly selected matched loci.  
5 First, we identified all variants with genome-wide significant association ( $p < 5 \times 10^{-08}$ ) to any  
6 trait in Europeans from the GWAS catalog.<sup>96</sup> We then pruned this set of variants (using a CEU  
7  $r^2$  threshold of 0.1), resulting in a list of independent trait-associated variants. For each of these  
8 variants, we constructed a background ‘locus’ as the set of proxy variants in high linkage  
9 disequilibrium (CEU  $r^2 < 0.8$ ). For each of the 53 loci, we then selected a locus from the  
10 background set matched on total number of proxy variants, total genomic distance covered,  
11 and distance of the midpoint to the closest gene transcription start site. We then re-calculated  
12 the overlap of each annotation in the set of matched background loci. We obtained the expected  
13 overlap for each annotation by averaging over 1 million permuted background locus sets. We  
14 then tested for enrichment of each annotation with a binomial test using the observed number  
15 of overlapping loci, total number of loci and expected percentage of overlapping loci.

16 We compiled a list of 13 genes (*PPARG*, *INSR*, *PIK3R1*, *TBC1D4*, *LMNA*, *PLIN1*, *AKT2*,  
17 *CIDEA*, *AGPAT2*, *BSCL2*, *CAVI*, *PTRF*, *PCYT1A*) known to cause monogenic forms of  
18 insulin resistance from the literature<sup>13</sup> and used that to look for overlap with genes in identified  
19 regions. Two experts in the clinical care of patients with monogenic insulin resistance (Drs  
20 Semple and Savage) reviewed the curated list.

21

## 22 *Analysis of eQTLs in multiple tissues*

23 Using a curated collection of over 100 separate eQTL datasets, we queried whether the 53  
24 lead SNPs or their proxies ( $r^2 > 0.8$ ) were associated with transcript expression in a wide range  
25 of tissues. Proxy SNPs in linkage disequilibrium in European ancestry populations were

1 identified using SNAP.<sup>95</sup> For this study, we considered all associations below a p-value cut-off  
2 of  $1 \times 10^{-6}$ . A general overview of a subgroup of >50 eQTL datasets has been published,<sup>97</sup>  
3 with specific citations for the >100 datasets included in the current query provided in the  
4 **Supplementary Note.**

5

#### 6 *Specific analysis of eQTLs in subcutaneous adipose tissue*

7 We analysed in depth the association of lead SNPs with gene expression in subcutaneous  
8 adipose tissue using two subcutaneous adipose tissue cis-eQTL datasets. The first dataset was  
9 generated by the EUROBATs consortium and consists of samples from well-phenotyped  
10 healthy female twins (n=766) with eQTLs derived as described previously.<sup>98</sup> We also used the  
11 subcutaneous adipose tissue data (n=298) generated by the GTEx consortium (version 6),<sup>99</sup>  
12 which were obtained from [www.gtexportal.org](http://www.gtexportal.org) on 20/11/15. GTEx results were limited to  
13 GENCODE “protein\_coding” and “lincRNA” biotype transcripts, and only variants with a  
14 minor allele frequency >0.01 were used. Linkage disequilibrium statistics between the index  
15 SNP (lead SNP for fasting insulin at the locus) and the most significant expression SNP for the  
16 gene were calculated in PLINK 1.9 using 1000 Genomes phase 1 version 3 European ancestry  
17 samples.<sup>90</sup> We also assessed the regulatory trait concordance (RTC) value for SNPs associated  
18 with gene expression in adipose tissue, in order to assess the likelihood of co-localisation of  
19 signal with the lead eQTL signal at that region.<sup>100</sup> In brief, if the index variant and the eQTL  
20 do tag the same causal variant, it is expected that removing the genetic effect of the index  
21 variant will have a significant consequence on the eQTL association. To this end, the RTC  
22 method assesses the likelihood of a shared functional effect between a GWAS variant and an  
23 eQTL by quantifying the change in the statistical significance of the eQTL after correcting for  
24 the genetic effect of the index variant and comparing its correction impact to that of all other  
25 SNPs in the interval. We considered an RTC of  $\geq 0.8$  or high linkage disequilibrium between

1 the lead eQTL SNP and trait-associated SNP ( $r^2>0.8$ ) to be supporting evidence of co-  
2 localisation.

3

#### 4 *Functional studies in mouse OP9-K cells*

5 We sought to experimentally validate candidate causal genes at loci associated with lower  
6 levels of peripheral adiposity, higher risk of type 2 diabetes and with gene expression in  
7 subcutaneous adipose tissue (**Supplementary Note and Supplementary Figure 11**). We  
8 studied the effects of gene knockdown using siRNA on adipogenic differentiation in murine  
9 OP9-K cell lines. The mouse OP9-K cell line used in this study is a model suitable for mid-  
10 throughput screening of genes influencing adipogenesis. OP9-K cells are clonal cells derived  
11 from mouse stromal OP9 cells obtained from the bone marrow, that accumulate large lipid-  
12 droplets after 72 hours of adipogenic stimulation.<sup>45</sup> OP9-K cells were grown and differentiated  
13 using oleic acid-containing differentiation media as described previously.<sup>45</sup> For siRNA  
14 transfections,  $2.5 \times 10^4$  cells per well were cultured in the 24-well dish. After 24hrs, cells were  
15 transfected with smartpool siRNA (from Dharmacon) against each gene using Optifect reagent  
16 as per the manufacturer protocol. On the following day, differentiation of OP9-K cells into  
17 adipocytes was initiated by replacing the media with 500  $\mu$ L of differentiation media. After  
18 48hrs of differentiation induction, differentiated cells were stained with adipored to assess lipid  
19 accumulation using fluorescent spectroscopy. For quantitative-PCR, total RNA was isolated  
20 from differentiated OP9-K cells and cDNA was synthesized using TaqMan® Fast Cells-to-  
21 CT™ Kit (Applied Biosystems) according to manufacturer's instructions. Quantitative real-  
22 time PCR analysis was performed on a TaqMan ABI Prism 7900 Sequence Detector System  
23 (Applied Biosystems). Expression results were analysed relative to GAPDH mRNA content in  
24 the same sample.

25



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*Online Supplement*

**Integrative genomic analysis implicates limited peripheral adipose storage capacity in the pathogenesis of human insulin resistance**

## Supplementary Note

### *Associations at the 53 loci with changes in hip circumference in weight gainers*

The association with lower levels of peripheral fat mass but higher cardiometabolic risk of the 53-SNP genetic score suggested that individuals with a greater number of alleles are unable to expand their peripheral fat compartment. To corroborate this finding, we used weight gain as a surrogate measure for a positive energy balance and change in hip circumference in weight-gainers as a surrogate measure for the changes in peripheral fat compartments. We tested the associations of the 53-SNP genetic score in longitudinal data from 9,150 participants of the EPIC-Norfolk cohort study who gained weight during a median follow-up of 3.7 years. In these individuals, the 53-SNP genetic score was not associated with the amount of weight gained during follow-up (beta coefficient [standard error] in kg of weight change per SD of genetic score, -0.026 [0.029];  $p=0.37$ ). However, in analyses adjusted for age, sex, hip circumference at baseline and weight at baseline and the amount of weight gained during follow-up, the 53-SNP genetic score was negatively associated with change in hip circumference (beta coefficient [standard error] in cm of hip circumference change per SD of genetic score, -0.069 [0.031];  $p=0.027$ ). In the same participants, in analyses adjusted for age, sex, waist circumference at baseline and weight at baseline and the amount of weight gained during follow-up, the 53-SNP genetic score was not associated with the change in waist circumference during follow-up (beta coefficient [standard error] in cm of waist circumference change per SD of genetic score, 0.055 [0.042];  $p=0.20$ ). These results support the notion that individuals with greater burden of the 53 alleles have a relative incapacity of expanding their peripheral fat compartment when challenged by a positive energy balance.

### ***Selection of putative effector genes for experimental validation***

In light of (a) the enrichment for loci overlapping adipose tissue active enhancer elements and affecting adipocyte gene expression and (b) the association of risk alleles with lower peripheral adiposity, but higher cardiometabolic risk, we hypothesised that some of the risk alleles may act via impaired adipogenesis. We further hypothesised that the effects on adipogenesis could be caused by the altered expression of an effector gene in peripheral adipose tissue (**Supplementary Figure 11A**). Therefore, to test this hypothesis, we selected five genes at four loci associated with (a) expression of a putative effector gene in subcutaneous adipocytes ( $p < 5 \times 10^{-08}$ ), (b) lower levels of peripheral fat ( $p < 5 \times 10^{-05}$  for hip circumference) and (c) higher risk of metabolic disease ( $p < 0.05$  for type 2 diabetes; see **Supplementary Tables 10 and 13 and Supplementary Figure 11** for details). For the *IRSI* ( $RTC=0.86$ ) and *L3MBTL3* genes ( $r^2$  between lead and best expression SNPs=0.83) there was evidence supporting co-localisation of phenotypic and expression signals. For the *CCDC92*, *DNAH10* and *FAM13A* genes, the lead expression SNPs (eSNPs) at the locus (rs825452 for *CCDC92*, rs78985577 for *DNAH10* and rs13149209 for *FAM13A*) were not captured by the HapMap-imputed FIadjBMI association data,<sup>21,22</sup> meaning they could not be captured by our triangulation of fasting insulin and lipid data. However, the best HapMap proxy for each of those eSNPs was also associated with FIadjBMI in MAGIC,<sup>1,2</sup> further supporting our prioritisation of those genes (see below).

For *CCDC92*, the lead eSNP (rs825452,  $p_{\text{expression}}=8.3 \times 10^{-31}$ ) was in very low linkage disequilibrium ( $r^2=0.001$ ) with our lead SNP for association with FIadjBMI (rs7973683). However, rs7973683 was also strongly associated with *CCDC92* expression in adipocytes ( $p_{\text{expression}}=2.1 \times 10^{-29}$ ), indicative of two distinct signals of association with *CCDC92* expression levels. Furthermore, while the lead eSNP was not available in FIadjBMI results, a strong proxy (rs825453;  $r^2=1$ ) for the lead eSNP was also associated with FIadjBMI

( $p=0.0053$ ). In the same locus, we found that our lead SNP for association with FIadjBMI levels (rs7973683) was also associated with expression of *DNAH10* ( $p_{\text{expression}}=1.9 \times 10^{-08}$ ). This was in modest linkage disequilibrium ( $r^2=0.27$ ) with the lead eSNP for *DNAH10* expression (rs78985577,  $p_{\text{expression}}=4.8 \times 10^{-12}$ ). While the lead eSNP was not available in FIadjBMI data, a strong proxy (rs1316952;  $r^2=0.83$ ) was also associated with FIadjBMI levels ( $p=0.000086$ ). At *FAM13A*, our lead SNP for association with FIadjBMI levels (rs3822072) was also associated with expression of *FAM13A* in subcutaneous adipocytes ( $p_{\text{expression}}=7.6 \times 10^{-12}$ ). Our lead SNP was in low linkage disequilibrium ( $r^2=0.038$ ) with the lead eSNP (rs13149209,  $p_{\text{expression}}=4.5 \times 10^{-21}$ ), a modest proxy for which (rs2085600;  $r^2=0.72$ ) was also associated with FIadjBMI levels ( $p=3.5 \times 10^{-06}$ ). These results suggest that multiple independent eQTLs of those genes in adipose tissue are also associated with insulin levels and therefore further support our prioritisation of these genes. Genes at all the loci showing the pre-specified pattern of association were studied experimentally, with the exception of *KLF14*. We did not seek to experimentally validate the *KLF14* gene, because it has been studied previously and previous studies suggest complex aetiologic mechanisms at this locus, including a potential parent-of-origin effect.<sup>3</sup> In dedicated figures and tables, we report association criteria (**Supplementary Figure 11B**), selection flow-chart (**Supplementary Figure 11C**), association estimates at loci with an eQTL signal in subcutaneous adipocytes (**Supplementary Table 10**) and at the prioritised loci (**Supplementary Table 13**). Loci that did not meet the criteria were not prioritised for experimental validation of putative effector genes (**Supplementary Figure 11 and Supplementary Table 10**). Finally, on the basis of our hypothesis, we expected that the siRNA knockdown of the candidate causal gene would have effects on adipogenesis in the direction predicted by the adipose tissue eQTL.

### ***Whole and regional body composition analysis***

Before scanning, the DEXA system was calibrated according to the manufacturer's guidelines using a spine phantom made of calcium hydroxyapatite, embedded in a lucite block. The enCORE software automatically demarcates the regional boundaries. A protocol was established to manually refine these demarcations and all the images were processed by one trained researcher, who corrected the demarcations according to a standardized procedure. The arm region was derived by positioning a line from the crease of the axilla and through the glenohumeral. The trunk region includes the neck, chest, abdominal and pelvic areas. The leg region includes all of the area below the lines that form the lower borders of the trunk. The android region was defined as the area between the ribs and the pelvis, and is enclosed by the trunk region. This region is outlined by iliac crest and with a superior height equivalent to 20% of the distance from the top of the iliac crest to the base of the skull. The gynoid region includes the hips and upper thighs, and overlaps both the leg and trunk regions. The upper demarcation is below the top of the iliac crest at a distance of 1.5 times the android height. The total height of the gynoid region is two times the height of the android region. Estimates of overall and regional body fat, lean and bone masses were derived using the DEXA software. The software also uses an inbuilt algorithm to determine visceral adipose tissue (in grams) within the android region. The subcutaneous abdominal adipose tissue (in grams) was calculated as android fat mass minus visceral abdominal adipose tissue.

### *List of sources for eQTL analyses*

A general overview of a subset of eQTL datasets interrogated in this study has been published.<sup>4</sup> Specific citations for all >100 datasets included in the current query are provided below.

Tissues (PubMed ID): blood cell related eQTL studies included fresh lymphocytes (17873875), fresh leukocytes (19966804), leukocyte samples in individuals with Celiac disease (19128478), whole blood samples (18344981, 21829388, 22692066, 23818875, 23359819, 23880221, 24013639, 23157493, 23715323, 24092820, 24314549, 24956270, 24592274, 24728292, 24740359, 25609184, 22563384, 25474530, 25816334, 25578447), lymphoblastoid cell lines (LCL) derived from asthmatic children (17873877, 23345460), HapMap LCL from 3 populations (17873874), a separate study on HapMap CEU LCL (18193047), additional LCL population samples (19644074, 22286170, 22941192, 23755361, 23995691, 25010687, 25951796), neutrophils (26151758, 26259071), CD19+ B cells (22446964), primary PHA-stimulated T cells (19644074, 23755361), CD4+ T cells (20833654), peripheral blood monocytes (19222302,20502693,22446964, 23300628, 25951796, 26019233), long non-coding RNAs in monocytes (25025429) and CD14+ monocytes before and after stimulation with LPS or interferon-gamma (24604202), CD11+ dendritic cells before and after Mycobacterium tuberculosis infection (22233810) and a separate study of dendritic cells before or after stimulation with LPS, influenza or interferon-beta (24604203). Micro-RNA QTLs (21691150, 26020509), DNase-I QTLs (22307276), histone acetylation QTLs (25799442), and ribosomal occupancy QTLs (25657249) were also queried for LCL. Splicing QTLs (25685889) and micro-RNA QTLs (25791433) were queried in whole blood. Non-blood cell tissue eQTLs searched included omental and subcutaneous adipose (18344981, 21602305, 22941192, 23715323, 25578447), visceral fat (25578447) stomach (21602305), endometrial carcinomas (21226949), ER+ and ER- breast cancer tumor

cells (23374354), liver (18462017,21602305,21637794, 22006096, 24665059, 25578447), osteoblasts (19654370), intestine (23474282) and normal and cancerous colon (25079323, 25766683), skeletal muscle (24306210, 25578447), breast tissue (normal and cancer)(24388359, 22522925), lung (23209423, 23715323, 24307700, 23936167, 26102239), skin (21129726, 22941192, 23715323, 25951796), primary fibroblasts (19644074, 23755361, 24555846), sputum (21949713), pancreatic islet cells (25201977), prostate (25983244), rectal mucosa (25569741), arterial wall (25578447) and heart tissue from left ventricles (23715323, 24846176) and left and right atria (24177373). Micro-RNA QTLs were also queried for gluteal and abdominal adipose (22102887) and liver (23758991). Methylation QTLs were queried in pancreatic islet cells (25375650). Further mRNA and micro-RNA QTLs were queried from ER+ invasive breast cancer samples, colon-, kidney renal clear-, lung- and prostate-adenocarcinoma samples (24907074). Brain eQTL studies included brain cortex (19222302, 19361613, 22685416, 25609184, 25290266), cerebellar cortex (25174004), cerebellum (20485568, 22685416, 22212596, 22832957, 23622250), frontal cortex (20485568, 22832957, 25174004), gliomas (24607568), hippocampus (22832957, 25174004), inferior olivary nucleus (from medulla) (25174004), intralobular white matter (25174004), occipital cortex (25174004), parietal lobe (22212596), pons (20485568), pre-frontal cortex (22031444, 20351726, 22832957, 23622250), putamen (at the level of anterior commissure) (25174004), substantia nigra (25174004), temporal cortex (20485568, 22685416, 22832957, 25174004), thalamus (22832957) and visual cortex (23622250).

Additional eQTL data was integrated from online sources including ScanDB, the Broad Institute's GTEx Portal, and the Pritchard Lab (eqtl.uchicago.edu). Cerebellum, parietal lobe and liver eQTL data was downloaded from ScanDB. Results for GTEx Analysis V4 for 13 tissues were downloaded from the GTEx Portal and then additionally filtered as described below ([www.gtportal.org](http://www.gtportal.org): thyroid, leg skin [sun exposed], tibial nerve, aortic artery, tibial

artery, skeletal muscle, esophagus mucosa, esophagus muscularis, lung, heart (left ventricle), stomach, whole blood, and subcutaneous adipose [23715323]). Splicing QTL (sQTL) results generated with sQTLseeker with false discovery rate  $p \leq 0.05$  were retained.

## Supplementary Tables

**Supplementary Table 1. Phenotypes, participating studies and maximum sample size.**

Analysis	Phenotype	Participating studies (N; PMID)	Maximum sample size, N
<b>Identification of 53 loci</b>	FladjBMI	MAGIC (N=108,557; PMID: 22885924, 22581228)	108,557
	HDL cholesterol	GLGC (N=188,577; PMID: 24097068)	188,577
	Triglycerides	GLGC (N=188,577; PMID: 24097068)	188,577
<b>Validation of genetic scores</b>	FladjBMI	Fenland (N=4,694; this study)	4,694
	HDL cholesterol	Fenland (N=6,101; this study)	6,101
	Triglycerides	Fenland (N=6,101; this study)	6,101
	Insulin sensitivity index	MAGIC (N=4,769; PMID: 24699409)	4,769
	Insulin sensitivity	GENESIS (N=2,764; PMID: 25798622)	2,764
<b>Association with intermediate traits</b>	DEXA	Fenland (N=9,747; this study); EPIC-Norfolk (N=3,101; this study)	12,848
	Body fat percentage	UK Biobank (N=110,358; this study); Fenland (N=9,747; this study); EPIC-Norfolk (N=3,101; this study)	123,206
	BMI	GIANT (N=339,198; 25673413); UK Biobank (N=111,995; this study)	451,193
	Waist circumference	GIANT (N=244,419; 25673412); UK Biobank (N=112,180; this study)	356,599
	Hip circumference	GIANT (N=227,412; 25673412); UK Biobank (N=112,172; this study)	339,584
	Waist-to-hip ratio	GIANT (N=226,586; 25673412); UK Biobank (N=112,158; this study)	338,744
	Fasting plasma glucose	MAGIC (N=133,010; PMID: 22885924, 22581228)	133,010
	2 hour glucose	MAGIC (N=42,854; PMID: 22885924, 20081857)	42,854
	HbA1c	MAGIC (N=46,368; PMID: 20858683)	46,368
	Alanine aminotransferase and gamma glutamyl transferase	Fenland (N=10,330; this study)	10,330
<b>Association with disease</b>	Type 2 diabetes	DIAGRAM (cases=34,840; controls=114,981; PMID: 22885922); InterAct (cases=6,410; controls=8,947; this study); UK Biobank (cases=4,586; controls=106,430; this study)	45,836 cases 230,358 controls
	Coronary heart disease	CARDIoGRAMplusC4D (cases=63,746; controls=130,681; PMID: 21378988, 23202125, 21378990);	63,746 cases 130,681 controls
	FPLD1	Cambridge FPLD1 consortium (cases=37; this study); UKHLS (controls=5,296)	37 cases 5,296 controls

**Supplementary Table 2. List of the 53 genomic regions associated with insulin resistance phenotypes.**

SNP	Genomic coordinate	Alleles (effect / other)	Beta FIadjBMI per allele <sup>a</sup>	FIadjBMI p-value	Beta triglycerides per allele <sup>b</sup>	Triglycerides p-value	Beta HDL cholesterol per allele <sup>b</sup>	HDL cholesterol p-value	Locus name	Putative effector genes <sup>c</sup>
<i>Loci previously implicated in insulin resistance</i>										
rs4846565	Chr1:219722104	G / A	0.022	1.76E-09	0.014	0.00019	-0.013	0.00078	<i>RNU5F-1/LYPLAL1</i>	<i>RNU5F-1</i> <sup>[N]</sup>
rs10195252*	Chr2:165513091	T / C	0.029	1.26E-16	0.028	6.99E-15	-0.025	3.49E-11	<i>COBL1/GRB14</i>	<i>COBL1</i> <sup>[N]</sup> , <i>GRB14</i> <sup>[E]</sup>
rs2943645*	Chr2:227099180	T / C	0.032	2.26E-19	0.028	3.76E-15	-0.032	4.16E-17	<i>IRS1</i>	<i>IRS1</i> <sup>[E, EA]</sup>
rs308971	Chr3:12116620	G / A	0.036	2.97E-11	0.021	3.51E-05	-0.016	0.0033	<i>SYN2/PPARG</i>	<i>SYN2</i> <sup>[N, E]</sup> , <i>PPARG</i> <sup>[MF]</sup>
rs3822072*	Chr4:89741269	A / G	0.020	1.80E-08	0.018	5.74E-07	-0.025	4.06E-12	<i>FAM13A</i>	<i>FAM13A</i> <sup>[N, E, EA, D]</sup>
rs6822892	Chr4:157734675	A / G	0.024	2.58E-10	0.012	0.00084	-0.019	1.93E-07	<i>PDGFC</i>	<i>PDGFC</i> <sup>[N, E, EA, D]</sup>
rs4865796*	Chr5:53272664	A / G	0.025	2.16E-12	0.010	0.0030	-0.013	0.00030	<i>ARL15/FST</i>	<i>ARL15</i> <sup>[N]</sup> , <i>FST</i> <sup>[EA]</sup>
rs459193*	Chr5:55806751	G / A	0.025	1.15E-10	0.018	1.31E-05	-0.024	8.10E-09	<i>ANKRD55</i>	<i>ANKRD55</i> <sup>[N]</sup>
rs2745353*	Chr6:127452935	T / C	0.019	4.10E-07	0.017	1.18E-06	-0.020	7.42E-10	<i>RSPO3</i>	<i>RSPO3</i> <sup>[N, E, EA]</sup>
rs731839*	Chr19:33899065	G / A	0.025	5.13E-12	0.022	2.65E-09	-0.022	3.44E-09	<i>PEPD</i>	<i>PEPD</i> <sup>[N, E]</sup>
<i>Additional loci</i>										
rs683135*	Chr1:39895460	A / G	0.014	0.00024	0.017	6.18E-07	-0.027	7.09E-12	<i>MACF1</i>	<i>MACF1</i> <sup>[N, NS, E, EA]</sup>
rs17386142	Chr1:50815783	C / T	0.024	0.00092	0.022	0.0033	-0.022	0.00060	<i>DMRTA2</i>	<i>DMRTA2</i> <sup>[N]</sup> , <i>CDKN2C</i> <sup>[D]</sup>
rs11577194	Chr1:110500175	T / C	0.011	0.0025	0.011	0.0011	-0.019	1.34E-07	<i>CSF1</i>	<i>CSF1</i> <sup>[N]</sup>
rs9425291	Chr1:172312769	A / G	0.015	2.71E-05	0.016	1.9E-05	-0.014	0.00046	<i>DNM3</i>	<i>DNM3</i> <sup>[N, E]</sup> , <i>PIGC</i> <sup>[E, EA]</sup>
rs2249105	Chr2:65287896	A / G	0.016	1.04E-05	0.016	2.35E-06	-0.016	0.00016	<i>CEP68</i>	<i>CEP68</i> <sup>[N, E, EA]</sup>
rs492400	Chr2:219349752	T / C	0.010	0.0038	0.018	2.25E-06	-0.011	0.0049	<i>USP37</i>	<i>USP37</i> <sup>[N, E]</sup> , <i>ZNF142</i> <sup>[NS, E, EA]</sup>
rs3864041	Chr3:15185634	T / C	0.011	0.0038	0.009	0.0038	-0.013	0.00028	<i>COL6A4P1</i>	<i>COL6A4P1</i> <sup>[N]</sup>
rs295449*	Chr3:47375955	A / G	0.011	0.0020	0.014	0.00093	-0.019	0.00011	<i>KLHL18</i>	<i>KLHL18</i> <sup>[N, E]</sup> , <i>SCAP</i> <sup>[NS, E]</sup> , <i>SETD2</i> <sup>[E, D]</sup>
rs11130329*	Chr3:52896855	A / C	0.024	0.00051	0.020	0.0018	-0.024	0.0010	<i>TMEM110-MUSTN1</i>	<i>TMEM110-MUSTN1</i> <sup>[N]</sup>
rs9881942	Chr3:123082416	A / G	0.013	0.00014	0.010	0.0036	-0.015	4.79E-06	<i>ADCY5</i>	<i>ADCY5</i> <sup>[N]</sup>
rs645040*	Chr3:135926622	T / G	0.014	0.0012	0.029	1.83E-12	-0.031	1.53E-12	<i>MSL2</i>	<i>MSL2</i> <sup>[N, D]</sup>
rs2699429*	Chr4:3480136	C / T	0.011	0.0037	0.025	1.15E-11	-0.013	0.0042	<i>DOK7</i>	<i>DOK7</i> <sup>[N, E]</sup>
rs4976033	Chr5:67714246	G / A	0.015	0.00013	0.014	0.00020	-0.022	6.42E-08	<i>PIK3R1</i>	<i>PIK3R1</i> <sup>[N, MF, D]</sup>
rs6887914	Chr5:112711486	C / T	0.013	0.0037	0.014	0.0024	-0.017	0.00039	<i>MCC</i>	<i>MCC</i> <sup>[N]</sup>
rs1045241	Chr5:118729286	C / T	0.012	0.0020	0.015	4.06E-05	-0.014	0.00040	<i>TNFAIP8</i>	<i>TNFAIP8</i> <sup>[N, E, EA]</sup>
rs2434612	Chr5:158022041	G / A	0.016	0.00034	0.015	0.00025	-0.020	0.000015	<i>EBF1</i>	<i>EBF1</i> <sup>[N, D]</sup>
rs966544	Chr5:173350405	G / A	0.012	0.0010	0.016	1.63E-06	-0.013	0.0018	<i>CPEB4</i>	<i>CPEB4</i> <sup>[N, E]</sup>
rs12525532	Chr6:35004819	T / C	0.019	8.95E-08	0.011	0.0026	-0.015	0.000040	<i>ANKS1A</i>	<i>ANKS1A</i> <sup>[N, EA]</sup>
rs6937438*	Chr6:43815364	A / G	0.013	0.0011	0.014	0.00034	-0.019	1.94E-06	<i>LOC100132354</i>	<i>LOC100132354</i> <sup>[N]</sup>
rs9492443	Chr6:130398731	C / T	0.014	0.0004	0.016	7.43E-05	-0.013	0.0042	<i>L3MBTL3</i>	<i>L3MBTL3</i> <sup>[N, E, EA]</sup>
rs3861397*	Chr6:139828916	G / A	0.014	0.00011	0.024	1.08E-10	-0.024	8.40E-11	<i>LOC645434</i>	<i>LOC645434</i> <sup>[N]</sup> , <i>CITED2</i> <sup>[D]</sup>
rs17169104	Chr7:15883727	G / C	0.020	1.52E-06	0.017	7.62E-05	-0.017	0.00028	<i>MEOX2</i>	<i>MEOX2</i> <sup>[N]</sup>

rs972283*	Chr7:130466854	G / A	0.022	4.41E-06	0.017	2.34E-07	-0.029	4.60E-16	<i>KLF14</i>	<i>KLF14</i> <sup>[N, E, EA]</sup>
rs2126259*	Chr8:9185146	T / C	0.041	3.30E-13	0.017	0.0020	-0.075	1.53E-42	<i>PPP1R3B</i>	<i>LOC157273</i> <sup>[N]</sup> , <i>PPP1R3B</i> <sup>[E]</sup>
rs1011685*	Chr8:19830769	C / T	0.019	0.00098	0.168	6.12E-197	-0.156	8.65E-150	<i>LPL</i>	<i>LPL</i> <sup>[N, NS, E, D]</sup>
rs4738141	Chr8:72469742	G / A	0.014	0.0014	0.020	2.45E-05	-0.019	0.00030	<i>EYA1</i>	<i>EYA1</i> <sup>[N, EA]</sup> , <i>LOC105375892</i> <sup>[D]</sup>
rs7005992*	Chr8:126528955	C / G	0.016	0.0014	0.021	5.87E-06	-0.016	0.0011	<i>TRIB1</i>	<i>TRIB1</i> <sup>[N, D]</sup>
rs498313	Chr9:78034169	A / G	0.013	0.00073	0.011	0.0026	-0.014	0.00033	<i>MIR548H3</i>	<i>MIR548H3</i> <sup>[N]</sup>
rs10995441*	Chr10:64869239	G / T	0.014	0.00085	0.017	1.19E-06	-0.018	0.00011	<i>NRBF2</i>	<i>NRBF2</i> <sup>[N, E]</sup>
rs11231693	Chr11:63862612	A / G	0.036	7.19E-07	0.030	0.00012	-0.029	0.000069	<i>MACROD1</i>	<i>MACROD1</i> <sup>[N]</sup>
rs17402950	Chr12:14571671	G / A	0.027	0.0047	0.032	0.0049	-0.034	0.0028	<i>ATF7IP</i>	<i>ATF7IP</i> <sup>[N]</sup>
rs718314	Chr12:26453283	G / A	0.017	3.65E-05	0.012	0.0015	-0.020	5.88E-06	<i>ITPR2</i>	<i>ITPR2</i> <sup>[N, E, D]</sup>
rs7973683*	Chr12:124449223	C / A	0.019	6.99E-07	0.025	4.67E-12	-0.029	5.26E-14	<i>CCDC92/DNAH10</i>	<i>CCDC92</i> <sup>[N, NS, E, EA]</sup> , <i>DNAH10</i> <sup>[E, EA]</sup>
rs7323406	Chr13:111628195	A / G	0.015	0.0027	0.014	0.0044	-0.016	0.0032	<i>ANKRD10</i>	<i>ANKRD10</i> <sup>[N, E, D]</sup>
rs7176058	Chr15:39464167	A / G	0.013	0.0036	0.016	0.00094	-0.015	0.00028	<i>C15orf54</i>	<i>C15orf54</i> <sup>[N]</sup> , <i>THBS1</i> <sup>[EA]</sup>
rs8032586	Chr15:73081067	C / T	0.019	0.0046	0.025	0.0010	-0.021	0.0030	<i>LOC100287559</i>	<i>LOC100287559</i> <sup>[N]</sup>
rs754814	Chr17:4657034	T / C	0.011	0.0042	0.011	0.0022	-0.013	0.0014	<i>ZMYND15</i>	<i>ZMYND15</i> <sup>[N, E]</sup>
rs7227237*	Chr18:47174679	C / T	0.017	0.0013	0.017	0.00088	-0.020	0.00041	<i>LIPG</i>	<i>LIPG</i> <sup>[N, E]</sup>
rs8101064*	Chr19:7293119	T / C	0.042	0.00062	0.069	1.91E-06	-0.066	0.000022	<i>INSR</i>	<i>INSR</i> <sup>[N, MF, D]</sup>
rs4804833*	Chr19:7970635	A / G	0.016	7.11E-06	0.015	9.90E-06	-0.022	9.89E-08	<i>MAP2K7</i>	<i>MAP2K7</i> <sup>[N, E, D]</sup>
rs4804311*	Chr19:8615589	A / G	0.019	0.0026	0.039	1.49E-09	-0.051	3.74E-14	<i>MYO1F</i>	<i>MYO1F</i> <sup>[N, E, EA]</sup>
rs6066149	Chr20:45602638	G / A	0.013	0.0019	0.018	5.22E-06	-0.010	0.0037	<i>EYA2</i>	<i>EYA2</i> <sup>[N]</sup>
rs132985*	Chr22:38563471	C / T	0.016	4.69E-06	0.022	6.65E-11	-0.015	0.000017	<i>PLA2G6</i>	<i>PLA2G6</i> <sup>[N]</sup> , <i>MAFF</i> <sup>[E, EA, D]</sup>

Genomic coordinates refer to human genome build 37 (hg19). Beta coefficients are in standardised units, fasting insulin beta coefficients were standardised using the standard deviation in 8,917 participants of the Fenland study. The gene column reports the nearest gene and/or additional candidate effector genes at the locus.

\*polymorphism within 500 kb of a lead SNP for HDL cholesterol or triglyceride levels reported by the Global Lipids Genetics Consortium (PubMed ID: 24097068).

a From up to 108,557 participants of the MAGIC consortium (PubMed ID: 22885924, 22581228)

b From up to 188,577 participants of the Global Lipids Genetics Consortium (PubMed ID: 24097068)

c Assigned on the basis of the following criteria: N, nearest gene; NS, nonsynonymous variant in linkage disequilibrium with lead SNP ( $r^2 > 0.8$ ); E, evidence of association with gene expression in surveyed eQTL repositories; AE, evidence of association with gene expression in subcutaneous adipose tissue; MF, monogenic insulin resistance forms associated with mutations in this gene; D, gene prioritised by DEPICT software as likely causal (significant p-value after accounting for false discovery rate). Relevant criteria are reported as superscript near each gene. Further details about methodology for the adjudication of these criteria are reported in the Online Methods sections dedicated to prioritisation of putative effector genes.

Abbreviations: SNP, single nucleotide polymorphism; FladjBMI, fasting insulin adjusted for body mass index; HDL, high-density lipoprotein cholesterol.

**Supplementary Table 3. Association with type 2 diabetes of the 53-polymorphism genetic score in analyses stratified by sex or body mass index.** Results are scaled per 4.5 alleles, i.e. a standard deviation of genetic risk score. Results are from the EPIC-InterAct and the UK Biobank studies.

Stratum	Participants, type 2 diabetes cases / non- cases	OR (95% CI)	p-value	p-interaction
<i>Sex-stratified analysis</i>				
Men	6,588 / 52,887	1.12 (1.09 – 1.16)	4.13E-14	0.90
Women	5,418 / 62,811	1.12 (1.08 – 1.16)	1.48E-11	
<i>BMI-stratified analysis*</i>				
BMI < 25	1,298 / 39,930	1.16 (1.09 – 1.23)	3.71E-06	0.16
BMI ≥ 25 and BMI < 30	4,663 / 49,317	1.17 (1.13 – 1.22)	1.73E-16	
BMI ≥ 30	5,945 / 26,090	1.12 (1.08 – 1.16)	7.86E-10	

Abbreviations: OR, odds ratio; CI, confidence interval; BMI, body mass index.

\*Pairwise category heterogeneity tests: lean vs overweight: p=0.73; lean vs obese: p=0.31; overweight vs obese, p=0.061.

**Supplementary Table 4. Associations of lead single nucleotide polymorphisms at the 53 loci with glycaemic, anthropometric traits and disease endpoints.**  
(see *Supplementary Table Excel file*)

**Supplementary Table 5. Single nucleotide polymorphisms associated with higher risk of type 2 diabetes (45,836 cases 230,358 controls) and of coronary heart disease (63,746 cases 130,681 controls).**

<b>SNP</b>	<b>Locus name</b>	<b>Per allele OR type 2 diabetes (95% CI)</b>	<b>p-value</b>	<b>Per allele OR coronary heart disease (95% CI)</b>	<b>p-value</b>
rs2943645	<i>IRS1</i>	1.09 (1.07-1.11)	1.1E-17	1.03 (1.01-1.05)	0.0010
rs6822892	<i>PDGFC</i>	1.04 (1.02-1.07)	2.1E-05	1.02 (1.00-1.04)	0.035
rs459193	<i>ANKRD55</i>	1.08 (1.06-1.11)	8.0E-13	1.02 (1.00-1.04)	0.025
rs4976033	<i>PIK3R1</i>	1.03 (1.01-1.05)	0.0022	1.07 (1.02-1.12)	0.0080
rs9492443	<i>L3MBTL3</i>	1.05 (1.03-1.07)	3.1E-05	1.02 (1.00-1.04)	0.028
rs3861397	<i>LOC645434</i>	1.03 (1.01-1.05)	0.0026	1.02 (1.00-1.04)	0.037
rs972283	<i>KLF14</i>	1.04 (1.02-1.06)	1.2E-05	1.03 (1.01-1.04)	0.0037
rs1011685	<i>LPL</i>	1.07 (1.04-1.10)	3.4E-05	1.09 (1.05-1.13)	8.7E-06
rs7973683	<i>CCDC92 / DNAH10</i>	1.03 (1.01-1.05)	0.0037	1.02 (1.00-1.04)	0.019
rs8101064	<i>INSR</i>	1.08 (1.01-1.16)	0.020	1.13 (1.02-1.25)	0.016
rs731839	<i>PEPD</i>	1.04 (1.02-1.06)	0.00021	1.03 (1.01-1.04)	0.0090

Abbreviations: SNP, single nucleotide polymorphism; OR, odds ratio; CI, confidence interval.

**Supplementary Table 6. Association of the genetic scores with alanine aminotransferase and gamma glutamyl transferase in 10,330 participants of the Fenland study.**

<b>Exposure</b>	<b>Outcome</b>	<b>Beta per SD of genetic score in SDs of biomarker</b>	<b>SE</b>	<b>P-Value</b>
53-SNP score	Alanine aminotransferase	0.054	0.009	1.37E-09
43-SNP score		0.049	0.010	1.83E-06
53-SNP score	Gamma glutamyl transferase	0.054	0.009	1.04E-09
43-SNP score		0.045	0.010	6.39E-06

Abbreviations: SNP, single nucleotide polymorphism; SD, standard deviation; SE, standard error. Beta coefficients are in standardised units per SD of genetic score (4.5 alleles).

**Supplementary Table 7.** European Genome-Phenome Archive Study, Dataset and Sample IDs for the raw, whole exome sequence data for 9 FPLD1 individuals and their family members.

<b>Family ID</b>	<b>Sample</b>	<b>EGA Study ID</b>	<b>EGA Dataset ID</b>	<b>EGA Sample ID</b>
<b>1</b>	Proband	EGAS00001000130	EGAD00001000419	EGAN00001015630
<b>2</b>	Proband	EGAS00001000025	EGAD00001000380	EGAN00001001252
<b>2</b>	Mother	EGAS00001000025	EGAD00001000380	EGAN00001001832
<b>2</b>	Father	EGAS00001000025	EGAD00001000380	EGAN00001001825
<b>3</b>	Proband	EGAS00001000130	EGAD00001000419	EGAN00001015627
<b>4</b>	Proband	EGAS00001000130	EGAD00001000419	EGAN00001015629
<b>5</b>	Proband	EGAS00001000130	EGAD00001000419	EGAN00001015628
<b>6</b>	Proband	EGAS00001000130	EGAD00001000419	EGAN00001015631
<b>7</b>	Proband	EGAS00001000130	EGAD00001000419	EGAN00001015624
<b>7</b>	Father	EGAS00001000130	EGAD00001000419	EGAN00001015625
<b>8</b>	Proband	EGAS00001000130	EGAD00001000419	EGAN00001015633
<b>8</b>	Father	EGAS00001000130	EGAD00001000419	EGAN00001015651
<b>8</b>	Sister 1	EGAS00001000130	EGAD00001000419	EGAN00001015652
<b>8</b>	Sister 2	EGAS00001000130	EGAD00001000419	EGAN00001015653
<b>8</b>	Sister 3	EGAS00001000130	EGAD00001000419	EGAN00001015654
<b>8</b>	Sister 4	EGAS00001000130	EGAD00001000419	EGAN00001015656
<b>8</b>	Brother	EGAS00001000130	EGAD00001000419	EGAN00001015655
<b>9</b>	Proband	EGAS00001000130	EGAD00001000419	EGAN00001015632

**Supplementary Table 8. Characteristics of women with FPLD1 compared with obese women of the Fenland study.** The *phenotype comparison* column summarises the results of comparisons between FPLD1 women and obese (BMI  $\geq 30$ ) Fenland study women for a given clinical variable (Student's t-test), whereas the *genetic score association pattern* column summarises the association of the 53-SNP genetic score with a given phenotype in our genetic association analyses (see Figure 1A and Supplementary Table 6).

Variable, units	FPLD1 women			Fenland - obese women			Phenotype comparison, FPLD1 vs Fenland obese women, direction of association (p-value) <sup>a</sup>	Pattern of association of genetic score, direction of association (p-value) <sup>a</sup>
	N	Mean (SD)	Median (range)	N	Mean (SD)	Median (range)		
Age, years	37	49 (12)	48 (22 - 75)	1171	49 (7)	50 (29 - 64)	N/A	N/A
Body mass index, kg/m <sup>2</sup>	35	33 (4)	33 (26 - 47)	1171	35 (5)	33 (30 - 60)	N/A*	↓ (p=4.5E-08)
Waist circumference, cm	27	111 (12)	112 (78 - 143)	1170	103 (10)	102 (79 - 154)	↑ (p=4.6E-05)	↑ (p=0.0028)
Hip circumference, cm	27	108 (12)	108 (84 - 147)	1163	118 (10)	116 (96 - 178)	↓ (p=3.7E-07)	↓ (p=2.3E-34)
Waist-to-hip ratio	27	1.04 (0.09)	1.02 (0.91 - 1.22)	1163	0.87 (0.07)	0.87 (0.63 - 1.17)	↑ (p=3.1E-33)	↑ (p=3.3E-88)
Fasting plasma glucose, mmol/L	33	11 (5)	10.7 (4.9 - 21.9)	1163	5.0 (0.7)	4.9 (3.4 - 12.3)	↑ (p=8.5E-161)	↑ (p=2.9E-10)
HbA1c, %	35	9 (2)	8.4 (4.9 - 13.2)	789	5.6 (0.5)	5.6 (3.9 - 9.7)	↑ (p=6.9E-140)	↑ (p=2.3E-06)
Fasting insulin, pmol/L	29	208 (230)	151 (7.3 - 1210)	987	71.0 (49.4)	60.4 (2.6 - 702.0)	↑ (p=6.0E-30)	↑**
Triglycerides, mmol/L	34	2.8 (2.1)	2.6 (0.6 - 12.6)	1168	1.3 (0.7)	1.2 (0.2 - 7.4)	↑ (p=1.5E-27)	↑**
HDL cholesterol, mmol/L	34	1 (0.3)	1 (0.5 - 2)	1168	1.5 (0.3)	1.4 (0.6 - 3.4)	↓ (p=5.4E-21)	↓**
Alanine aminotransferase, U/L	34	39 (25)	31 (13 - 126)	1168	29 (17)	25 (6 - 236)	↑ (p=0.00090)	↑ (p=1.4E-09)
Gamma glutamyl transferase, U/L	34	67 (51)	50 (12 - 212)	1168	35 (32)	27 (7 - 530)	↑ (p=2.2E-08)	↑ (p=1.0E-09)

a ↑ indicates associations (p<0.05) with higher levels of a given phenotype in FPLD1 (compared with obese women from the Fenland study) or for a greater number of risk alleles of the genetic score; ↓ indicates an association (p<0.05) with lower levels.

Abbreviations: N, number of participants; SD, standard deviation; FPLD1, familial partial lipodystrophy type 1; N/A not assessed. \*matching variable \*\*not reported, genetic score selection variable

**Supplementary Table 9. Associations at the 53 loci with gene expression from eQTL repositories of multiple tissues.**

*(see Supplementary Table Excel file)*

**Supplementary Table 10. Associations of lead polymorphisms at the 53 loci in subcutaneous adipose tissue eQTL datasets.**

*(see Supplementary Table Excel file)*

**Supplementary Table 11. DEPICT annotation of putative effector genes.**

*(see Supplementary Table Excel file)*

**Supplementary Table 12. Associations at the *PIK3R1* locus.** Comparison between phenotypic association patterns of the common single nucleotide polymorphism rs4976033 (effect allele: G; minor allele: G; minor allele frequency: 49.6%) at the *PIK3R1* locus (this study) and of rare loss-of-function mutations in *PIK3R1* (literature).

Phenotype	N of individuals or N of cases / N of controls	Beta in SDs or ln(OR) per G allele of rs4976033	P-Value	Association of rare loss of function mutations	Pubmed ID for rare loss-of-function mutation association
Height	358,297	-0.003 (0.0027)	0.32	Reduced	26497935; 23810378; 23810379; 23810382
Body mass index	447,441	-0.006 (0.0026)	0.02	Reduced*	26497935; 23810378; 23810379; 23810382
Body fat percentage	123,206	-0.020 (0.0033)	3.04E-09	Lipoatrophy or lipodistrophy*	26497935; 23810378; 23810379; 23810382
Waist-to-hip circumference	337,859	-0.003 (0.0027)	0.27	N/A	
LDL cholesterol	172,987	-0.001 (0.0040)	0.87	Normal*	23810379
HDL cholesterol	187,060	-0.021 (0.0037)	6.42E-08	Normal <sup>o</sup>	23810379
Triglycerides	177,755	0.0141 (0.0036)	0.00020	Normal <sup>o</sup>	26497935
Fasting glucose	133,010	0.002 (0.0023)	0.39	Raised <sup>o</sup>	23810379
2 hour glucose	42,854	0.008 (0.0120)	0.52	N/A	
Fasting insulin adjusted BMI	108,557	0.009 (0.0023)	0.00013	Insulin resistance*	26497935; 23810378
Type 2 diabetes	45,836 cases 230,358 controls	1.03 (1.01-1.05)	0.0022	High prevalence of early onset type 2 diabetes*	26497935; 23810378; 23810379
Coronary heart disease	8,660 cases 47,121 controls	1.07 (1.02-1.12)	0.0080	N/A	

Height data were from a meta-analysis of UK Biobank and GIANT data.

\*Alignment between phenotypes associated with common and rare variants

<sup>o</sup>Lack of alignment between phenotypes associated with common and rare variants

**Supplementary Table 13. Association estimates at loci selected for experimental validation of putative effector genes in cellular adipogenesis models.**

SNP genomic coordinates	Insulin-raising / other allele	Putative effector gene	Direction of association with expression of the putative effector gene in subcutaneous adipocytes	p-value for expression of putative effector gene in subcutaneous adipocytes	Beta for hip circumference in standardised units (p-value)	OR of type 2 diabetes (p-value)
rs2943645 Chr2:227099180	T / C	<i>IRS1</i>	Lower expression	5.2E-09	-0.014 (9.4E-07)	1.09 (1.1E-17)
rs7973683 Chr12:124449223	C / A	<i>CCDC92</i>	Lower expression	2.1E-29	-0.014 (1.3E-06)	1.03 (3.7E-03)
rs7973683 Chr12:124449223	C / A	<i>DNAH10</i>	Lower expression	1.9E-08	-0.014 (1.3E-06)	1.03 (3.7E-03)
rs9492443 Chr6:130398731	C / T	<i>L3MBTL3</i>	Lower expression	9.1E-17	-0.021 (1.2E-11)	1.05 (3.1E-05)
rs3822072 Chr4:89741269	A / G	<i>FAM13A</i>	Higher expression	7.6E-12	-0.017 (5.5E-10)	1.04 (1.6E-05)

Genomic coordinates refer to build 37 (hg19). All association results are aligned to the insulin-raising (risk) allele. The co-localisation between association signals for gene expression in subcutaneous adipocytes and associations with fasting insulin are discussed in the Supplementary Note. Hip circumference association results are from a meta-analysis of the UK Biobank study and of the GIANT consortium. Type 2 diabetes association results are from a meta-analysis of DIAGRAM, InterAct and UK Biobank.

**Supplementary Table 14. Characteristics of the participants with individual-level genotype data included in this study.**

<b>Study</b>	<b>Fenland</b>	<b>EPIC-Norfolk</b>	<b>InterAct</b>	<b>UK Biobank</b>	<b>UKHLS</b>
<b>Country</b>	United Kingdom	United Kingdom	Multiple European countries	United Kingdom	United Kingdom
<b>Participants</b>	10,351	9150	15357	111016	5296
<b>Cases / Controls</b>	N/A	N/A	6410 / 8947	4586 / 106430	N/A
<b>Age</b>	48 (7)	58 (9)	53 (9)	57 (8)	53 (16)
<b>Female sex, N (%)</b>	5506 (53)	5015 (55)	9162 (60)	58390 (53)	5296 (100)
<b>Genotyping chip</b>	Affymetrix genome-Wide Human SNP Array 5.0 and Affymetrix UK Biobank Axiom Array	Affymetrix UK Biobank Axiom Array	Illumina 660w quad and Illumina CoreExome chip	Affymetrix UK Biobank Axiom Array	Illumina CoreExome Chip
<b>Imputation panel</b>	1000 Genomes Phase 1v3 and Phase 3	1000 Genomes Phase 3	1000 Genomes Phase 1v3	1000 Genomes Phase 3 plus UK10K	1000 Genomes Phase 3

## References

- 1 Manning, A. K. *et al.* A genome-wide approach accounting for body mass index identifies genetic variants influencing fasting glycaemic traits and insulin resistance. *Nature genetics* **44**, 659-669, doi:10.1038/ng.2274 (2012).
- 2 Scott, R. A. *et al.* Large-scale association analyses identify new loci influencing glycaemic traits and provide insight into the underlying biological pathways. *Nature genetics* **44**, 991-1005, doi:10.1038/ng.2385 (2012).
- 3 Small, K. S. *et al.* Identification of an imprinted master trans regulator at the KLF14 locus related to multiple metabolic phenotypes. *Nature genetics* **43**, 561-564, doi:10.1038/ng.833 (2011).
- 4 Zhang, X. *et al.* Synthesis of 53 tissue and cell line expression QTL datasets reveals master eQTLs. *BMC genomics* **15**, 532, doi:10.1186/1471-2164-15-532 (2014).
- 5 Myocardial Infarction Genetics and CARDIoGRAM Exome Consortia Investigators. Coding Variation in ANGPTL4, LPL, and SVEP1 and the Risk of Coronary Disease. *The New England journal of medicine*, doi:10.1056/NEJMoa1507652 (2016).

**Table**

Supplementary Table 4  
Supplementary Table 9  
Supplementary Table 10  
Supplementary Table 11

**Caption**

Associations of lead single nucleotide polymorphisms at the 53 loci  
Associations at the 53 loci with gene expression from eQTL repository  
Associations of lead polymorphisms at the 53 loci in subcutaneous  
DEPICT annotation of putative effector genes.

with glycaemic, anthropometric traits and disease endpoints.  
ories of multiple tissues.  
adipose tissue eQTL datasets.

## Aims

## Description

**Identification and validation of loci associated with insulin resistance phenotypes**

*1. Associations ( $p < 0.005$  in pre-specified direction) with insulin levels, HDL-cholesterol and triglyceride levels in up to 188,577 individuals from genome-wide results*

*2. Independent validation in non-overlapping samples from the Fenland study, as well as studies with "gold-standard" measures of insulin sensitivity*

**Phenotypic characterisation of identified loci**

*Associations with continuous anthropometric and cardiometabolic traits and disease endpoints in up to 451,193 individuals*

**Relevance to rare forms of insulin resistance**

*1. Clinical phenotype and genetic analyses of 37 women with FPLD1 and ~5,000 population based controls*

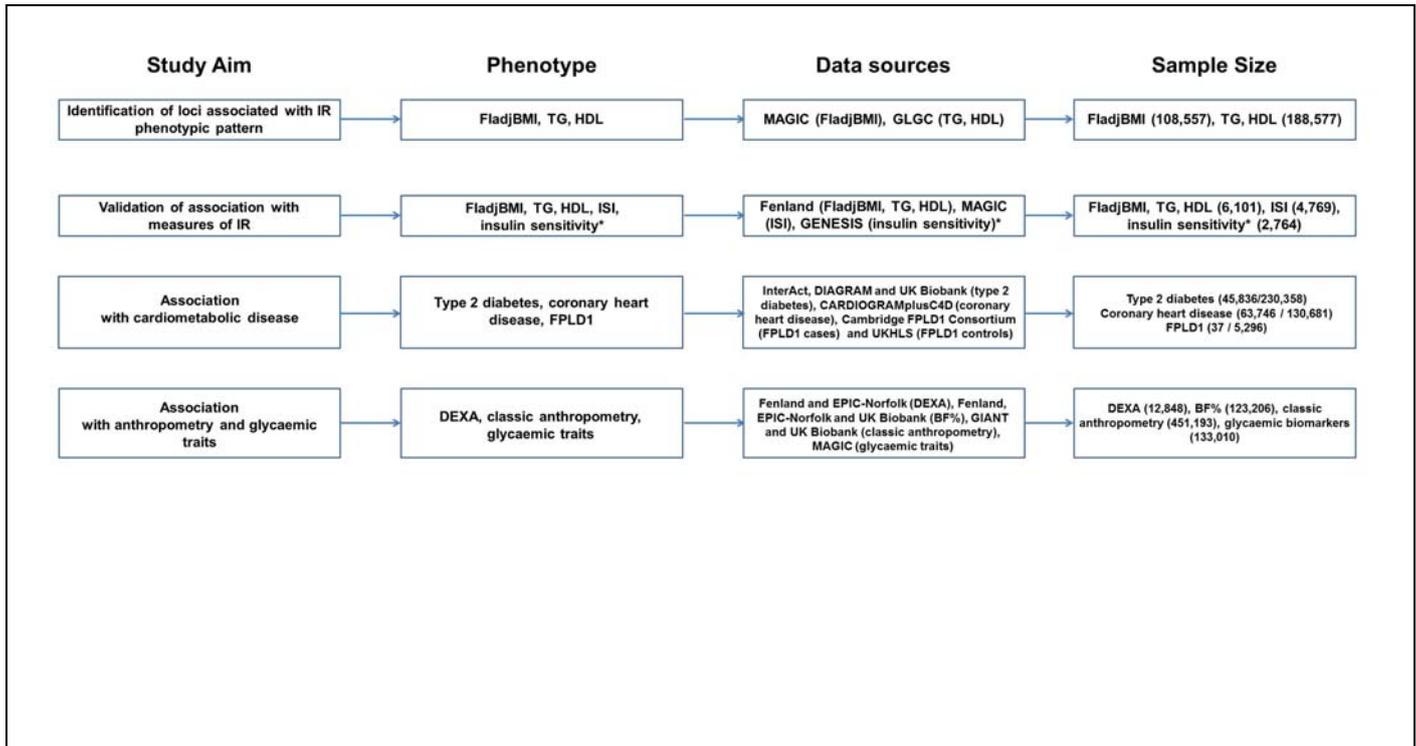
*2. Comparison of associations at extremes of allele frequency spectrum for variants at loci overlapping with rare insulin resistance forms*

**Identification of putative effector genes, cell types and tissues**

*Integration of population-scale association data with gene expression, regulatory annotation and experimental adipogenesis models*

### Supplementary Figure 1

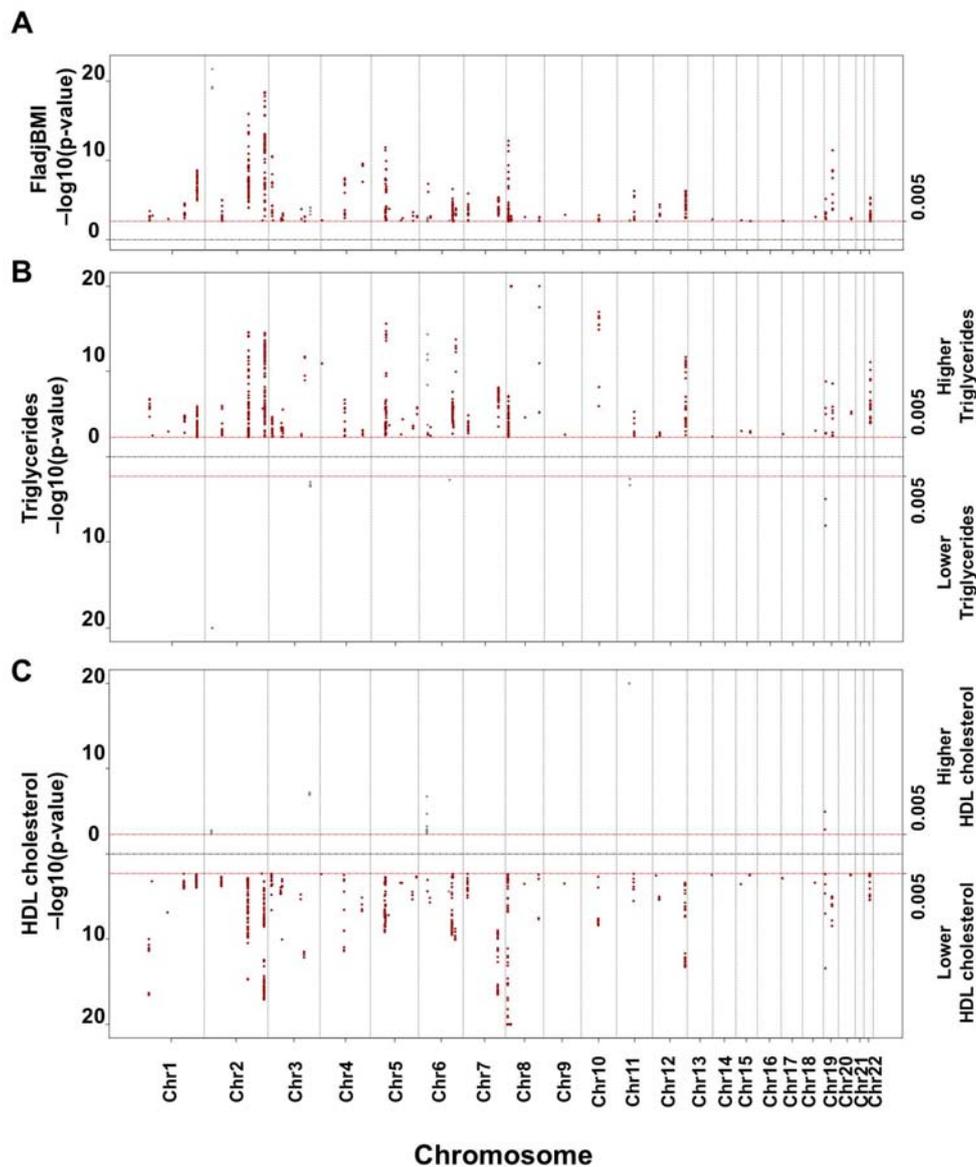
Design and scope of the study.



## Supplementary Figure 2

Design of the study, investigated phenotypes, sources of data and sample size.

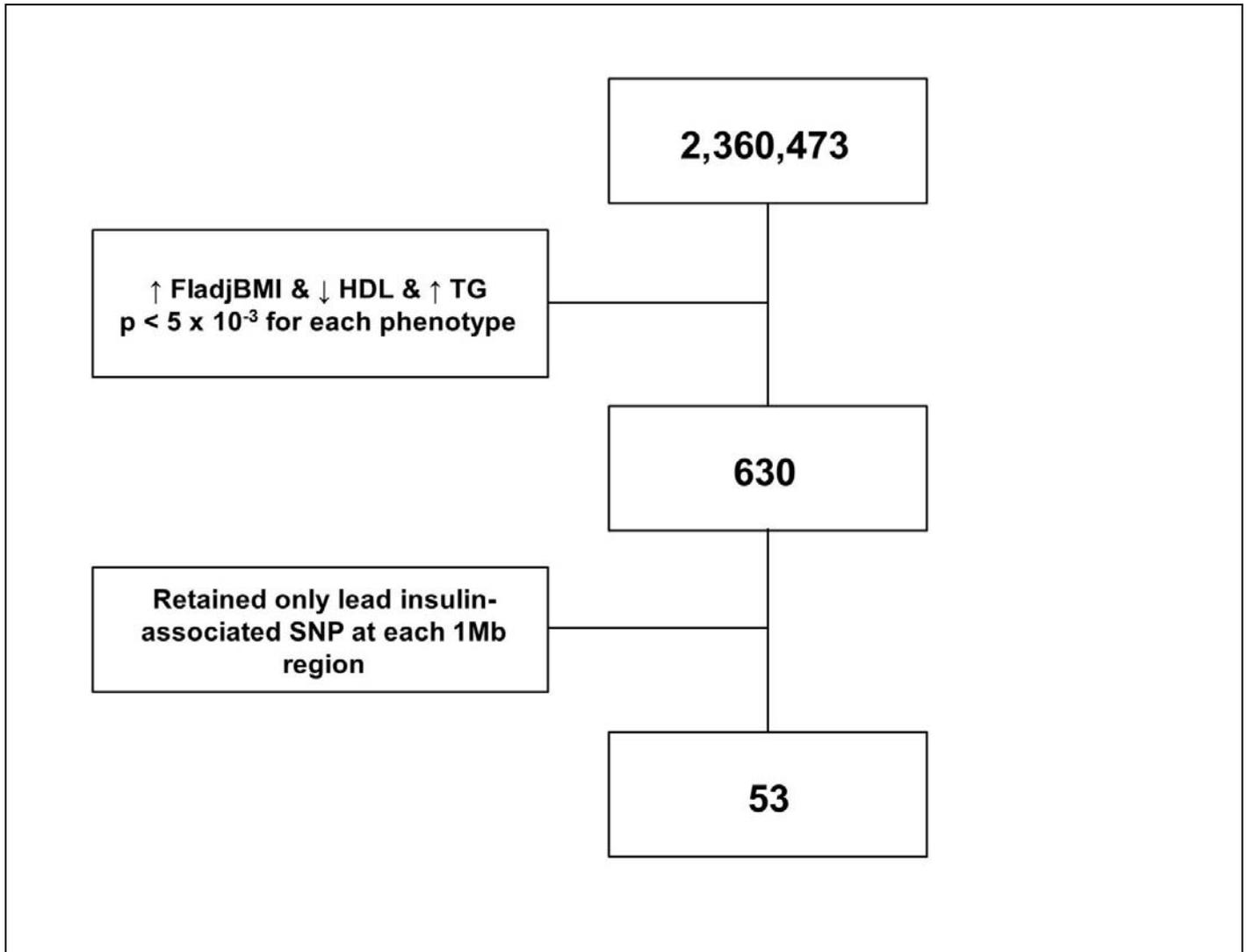
The reported sample size is the maximum available for a given trait or set of traits in this study. \*In the study by Knowles and colleagues (Pubmed ID: 25798622), insulin sensitivity was measured by euglycaemic clamp or insulin suppression test in 2,764 European individuals from four cohorts. Abbreviations: IR, insulin resistance; SNP, single nucleotide polymorphism; FladjBMI, fasting insulin levels adjusted for body mass index; TG, triglyceride levels; HDL, high-density lipoprotein cholesterol levels; ISI, insulin sensitivity index; DEXA, dual-energy X-ray absorptiometry; BF%, body fat percentage; FPLD1, familial partial lipodystrophy type 1; MAGIC, Meta-Analyses of Glucose and Insulin-related traits Consortium; GLGC, Global Lipids Genetics Consortium; GIANT, Genetic Investigation of ANthropometric Traits; DIAGRAM, DIAbetes Genetics Replication And Meta-analysis; CARDIOGRAM, Coronary ARtery Disease Genome wide Replication and Meta-analysis; C4D, Coronary Artery Disease Genetics consortium.



**Supplementary Figure 3**

Combined directional Manhattan plots of the association with insulin resistance related phenotypes.

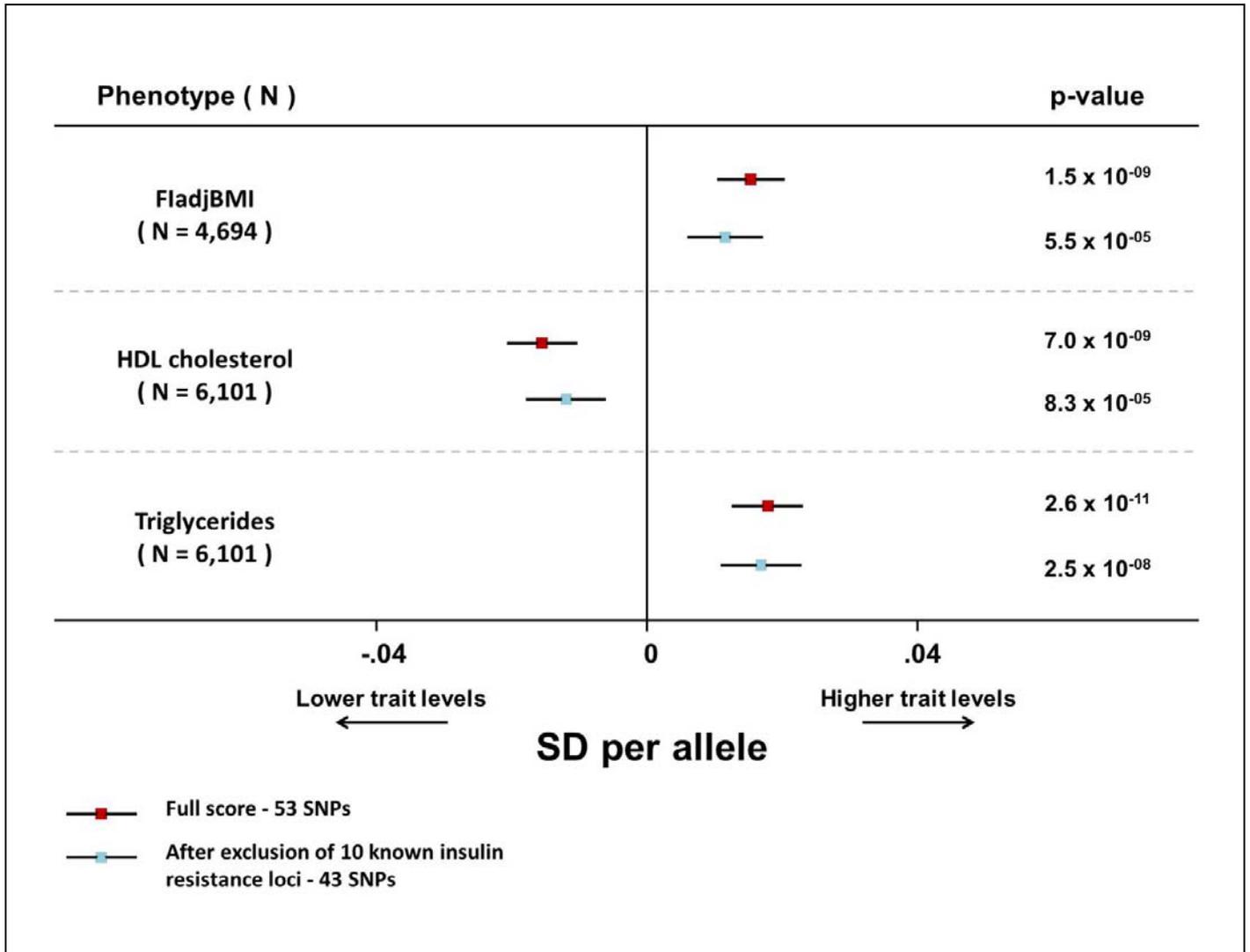
The figure represents Manhattan plots of the association of single nucleotide polymorphisms with fasting insulin adjusted for body mass index (FladjBMI; Panel A), triglycerides (Panel B) and HDL cholesterol (Panel C). We plotted only variants with FladjBMI, triglycerides and HDL cholesterol ( $p < 0.005$  for each phenotype). All associations are represented for the FladjBMI-raising allele. The 630 alleles associated with higher FladjBMI, higher triglycerides and lower HDL cholesterol are plotted in dark red. The graph also plots 21 variants that meet the p-value threshold for the three phenotypes but were not associated in the required direction (grey). For graphic display purposes, p-values below  $10^{-20}$  were represented as  $10^{-20}$ .



**Supplementary Figure 4**

Flowchart of the identification of insulin resistance loci.

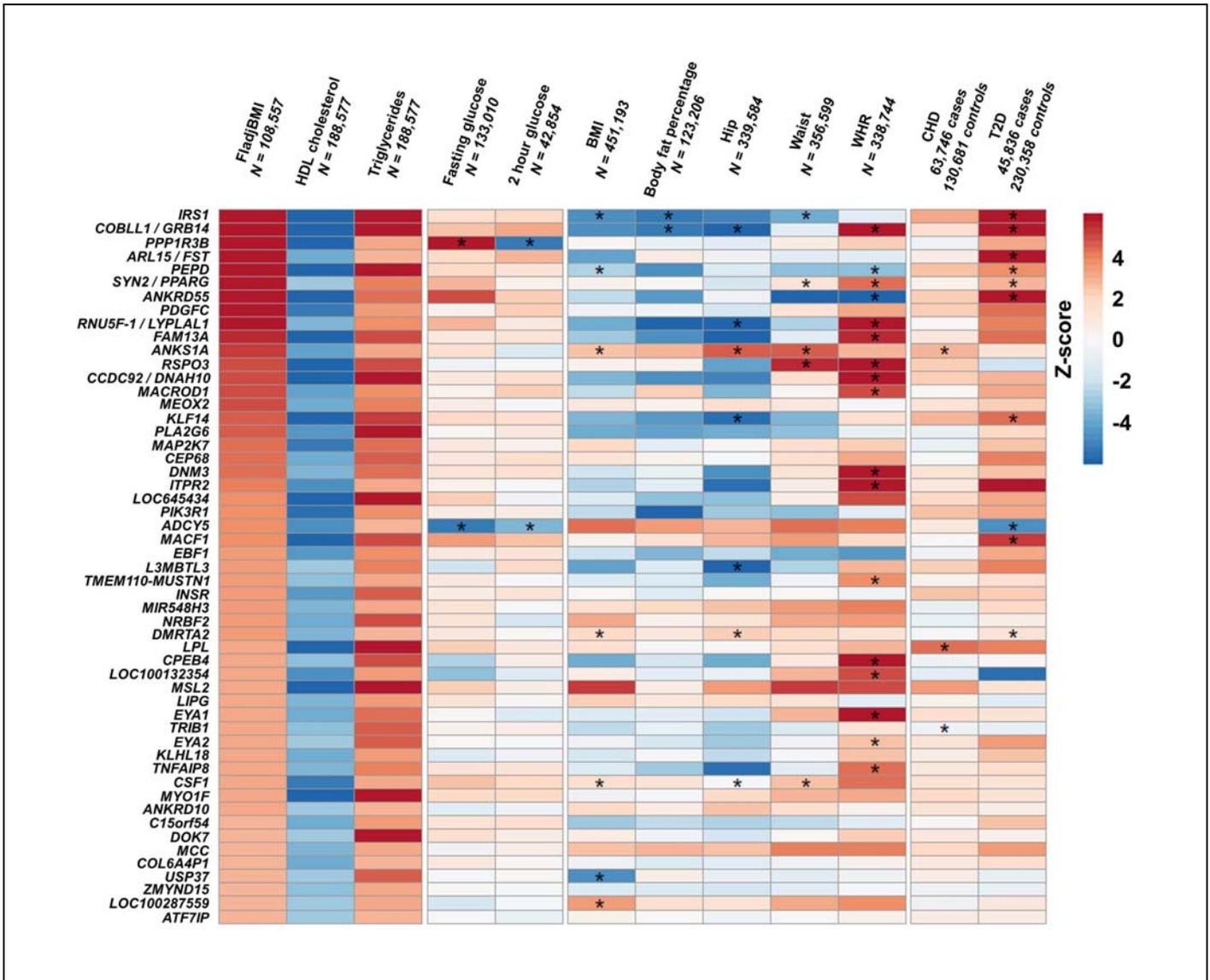
Numbers refer to single nucleotide polymorphisms. Abbreviations: FladjBMI, fasting insulin adjusted for body mass index; HDL, high-density lipoprotein cholesterol; TG, triglycerides; SNP, single nucleotide polymorphism.



**Supplementary Figure 5**

Associations with insulin resistance phenotypes in an independent dataset.

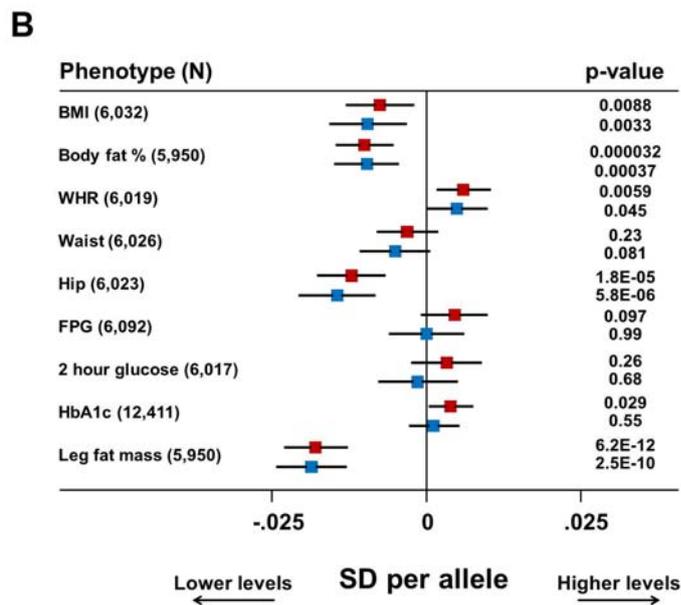
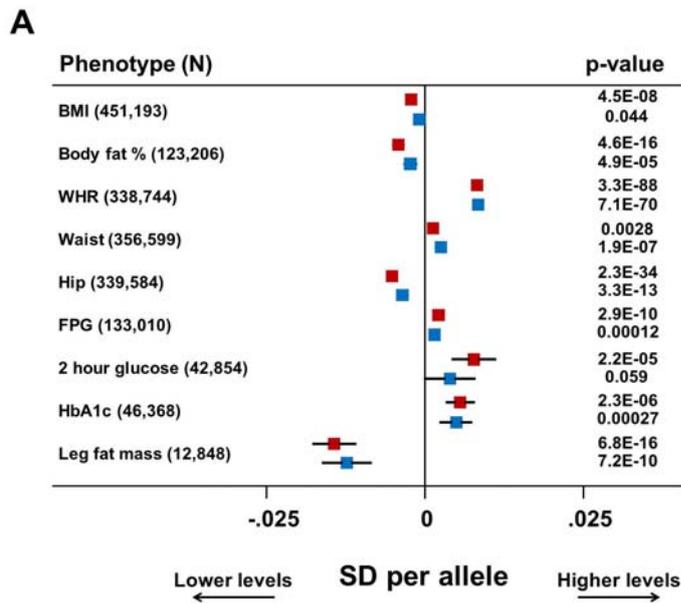
The figure reports associations of the genetic scores comprising the 53 or 43 SNPs with fasting insulin adjusted for body mass index, triglycerides and HDL cholesterol in up to 6,101 participants of the Fenland study who were not included in any of the discovery efforts used for the identification of the 53 loci. Squares indicate the central estimate of the beta coefficient; error bars the 95% confidence interval. Abbreviations: N, number of participants; FladjBMI, fasting insulin adjusted for body mass index; HDL, high-density lipoprotein; SD, standard deviation.



Supplementary Figure 6

Associations with glycaemic, anthropometric traits and disease endpoints at the 53 genomic loci.

The heatmap represents Z-scores for the association of the lead insulin raising allele at each locus. Loci are ranked on the basis of their Z-score for fasting insulin (largest to smallest). With the exception of fasting insulin, none of the association analyses was adjusted for body mass index. Abbreviations: N, maximum sample size; FladjBMI, fasting insulin adjusted for body mass index; HDL, high density lipoprotein cholesterol; BMI, body mass index; WHR, waist-to-hip ratio; CHD, coronary heart disease; T2D, type 2 diabetes. Colour scale: red indicates positive associations for the insulin-raising allele at each locus, while blue indicates negative associations. Asterisks indicate known loci for the traits, i.e. those for which our lead SNP is within 500 kb either side of a lead SNP from the largest GWAS of that trait.

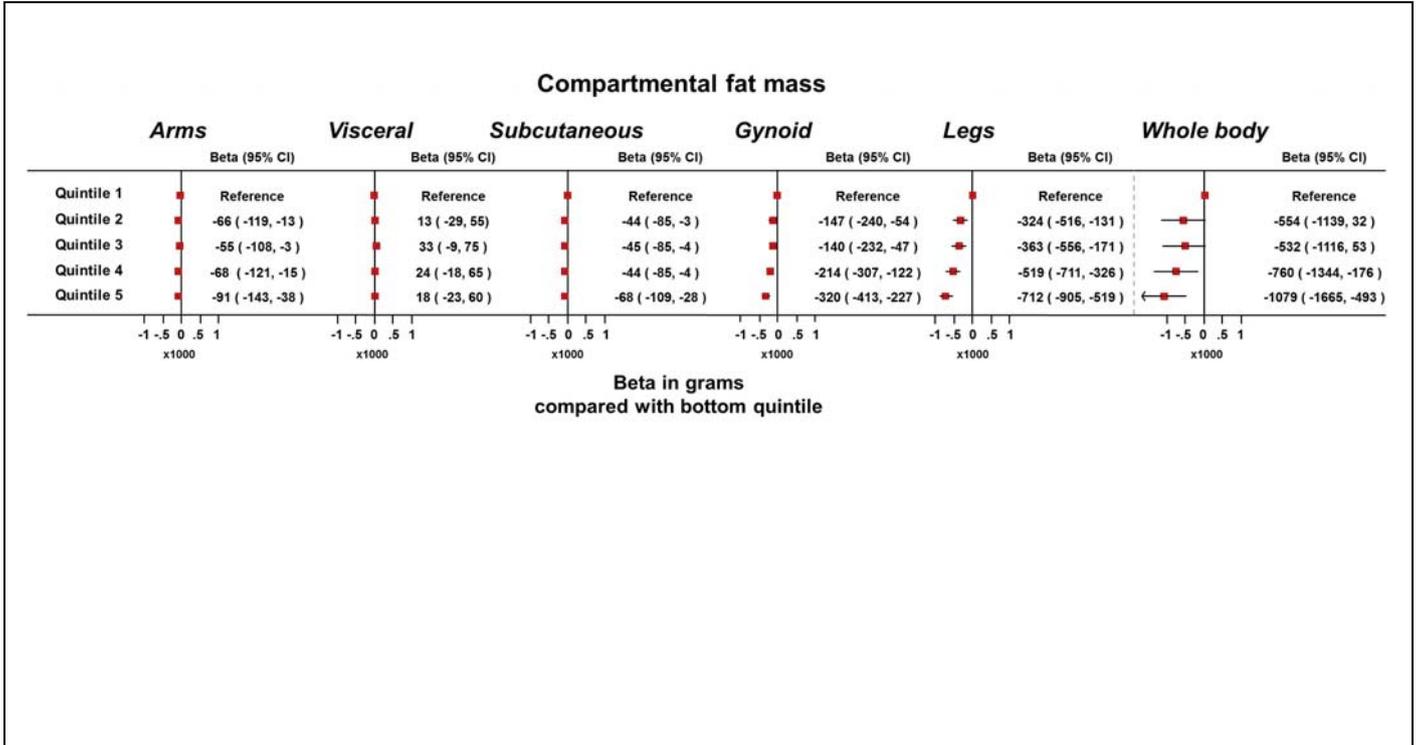


### Supplementary Figure 7

Associations of the genetic scores comprising the 53 or 43 SNPs with glycaemic and anthropometric traits in large-scale meta-analyses and in the Fenland study.

Panel A shows the association of the genetic scores with anthropometric and glycaemic traits in meta-analyses of genetic association studies. Body mass index, waist-to-hip ratio, waist and hip circumference data are from the GIANT consortium and the UK Biobank study. Body fat percentage data are from the UK Biobank, EPIC-Norfolk and Fenland studies. Fasting plasma glucose, 2 hour glucose and HbA1c data are from the MAGIC consortium. Leg fat mass data are from the EPIC-Norfolk and Fenland studies. Squares with error

bars represent the per-allele beta coefficients in standard deviation units and their 95% confidence intervals. Panel B shows the association with the same traits in participants of the Fenland study not included in discovery efforts which contributed to the identification of the 53 loci. Since HbA1c has been measured only in a subset of Fenland, the HbA1c analysis includes also individuals from the InterAct study subcohort who did not take part in discovery efforts which contributed to the identification of the 53 loci. Squares with error bars represent the per-allele beta coefficients in standard deviation units and their 95% confidence intervals. Red and blue squares represent results of the 53-SNP and 43-SNP genetic scores, respectively. None of the results presented in the figure is adjusted for body mass index. Abbreviations: N, number of participants; SD, standard deviation; BMI, body mass index; WHR, waist-to-hip ratio; FPG, fasting plasma glucose.

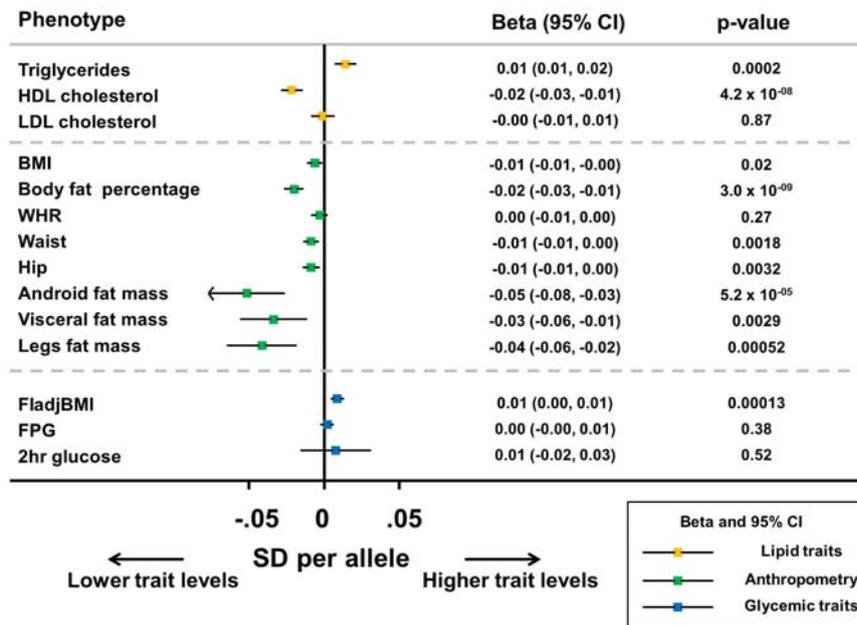


**Supplementary Figure 8**

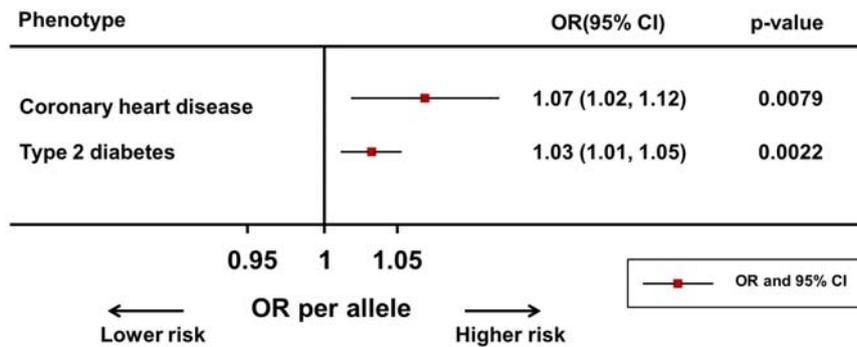
Associations of the 53-SNP genetic score with detailed anthropometric variables from dual energy X-ray absorptiometry.

The figure represents the association of quintiles of the 53-SNP genetic score with the absolute values of compartmental and total fat mass. Data are from 9,747 participants of the Fenland study. The Fenland population was divided into quintiles of the distribution of the genetic score and each quintile was compared with the bottom (reference category). Squares with error bars represent the beta coefficients in grams for individuals in the exposure category compared with the reference category and their 95% confidence intervals.

**A**



**B**

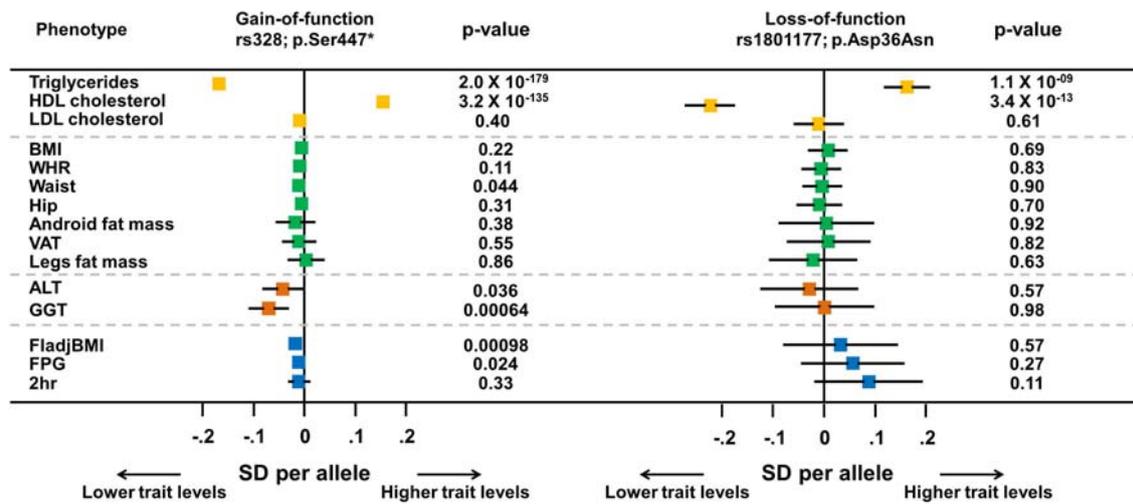


**Supplementary Figure 9**

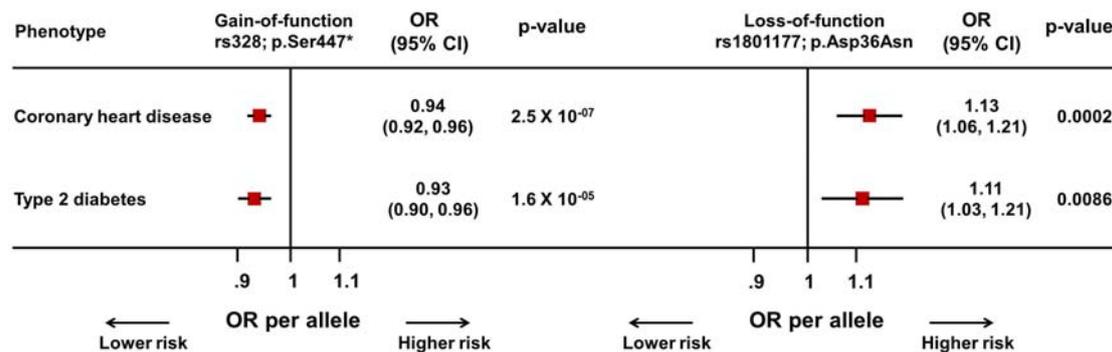
Associations of the rs4976033-G allele near *PIK3R1* with continuous metabolic traits and cardiometabolic disease endpoints.

Panel A represents associations with continuous traits, while Panel B those with disease endpoints. Squares with error bars represent the beta coefficients (Panel A) or odds ratios (Panel B) and their 95% confidence intervals. Abbreviations: HDL, high density lipoprotein; LDL, low density lipoprotein; BMI, body mass index; WHR, waist-to-hip ratio; FladjBMI, fasting insulin adjusted for BMI; FPG, fasting plasma glucose; 2hr glucose, glucose at two hours during an oral glucose challenge; SD, standard deviation; OR, odds ratio.

**A**



**B**



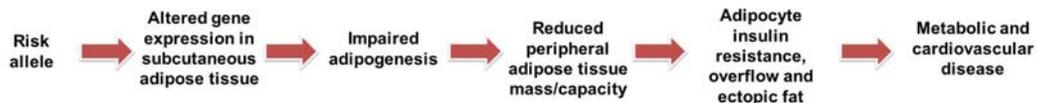
**Supplementary Figure 10**

Associations of functional variants in *LPL* with cardiometabolic traits and disease endpoints.

Panel A represents the association of the gain-of-function p.Ser447\* (rs328; left) and of the loss-of-function p.Asp36Asn (rs1801177; right) in *LPL* with lipid levels, anthropometric traits, liver markers and glycemic traits. Panel B represents the association of the two variants with the risk of coronary heart disease (from the Myocardial Infarction Genetics and CARDIoGRAM Exome Consortia Investigators; PubMed ID: 26934567)<sup>5</sup> and that of type 2 diabetes. Squares with error bars represent the beta coefficients (Panel A) or odds ratios (Panel B) and their 95% confidence intervals. Abbreviations: HDL, high density lipoprotein; LDL, low density lipoprotein; BMI, body mass index; WHR, waist-to-hip ratio; VAT, visceral adipose tissue; ALT, alanine aminotransferase; GGT, gamma-glutamyl transferase; FladjBMI, fasting insulin adjusted for BMI; FPG, fasting plasma glucose; 2hr, glucose at two hours during an oral glucose challenge; SD, standard deviation; OR, odds ratio.

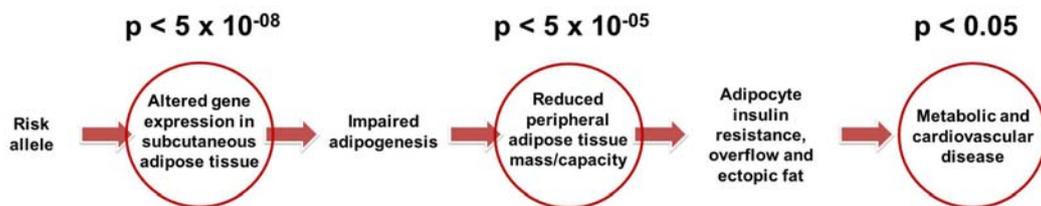
A

### Mechanistic Hypothesis



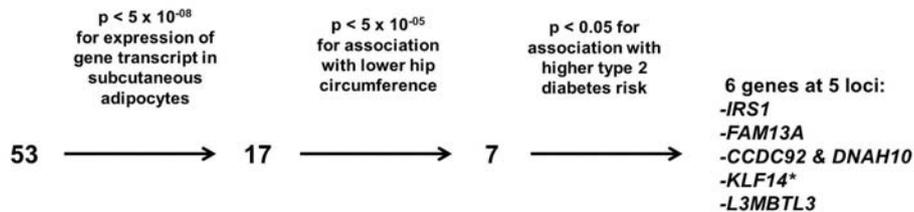
B

### Selection criteria to prioritise genes for experimental validation



C

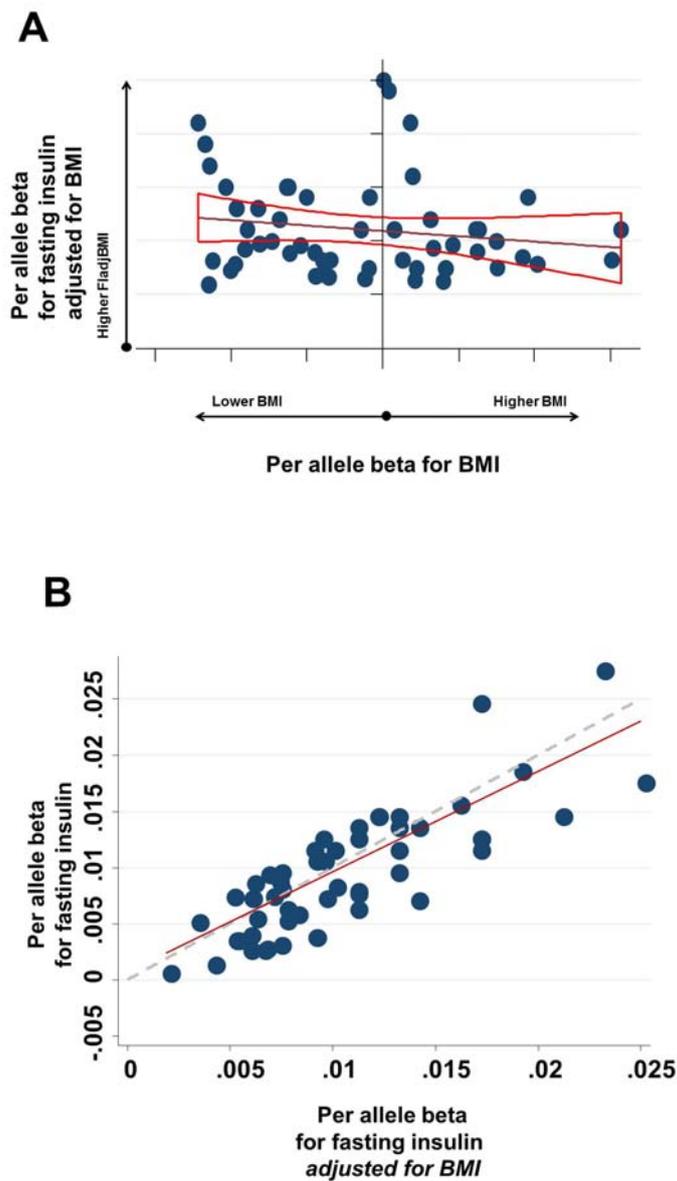
### Selection flowchart



#### Supplementary Figure 11

Mechanistic hypothesis for the implication of putative effector genes in the observed associations and selection of genes for experimental validation in cellular models of adipogenesis.

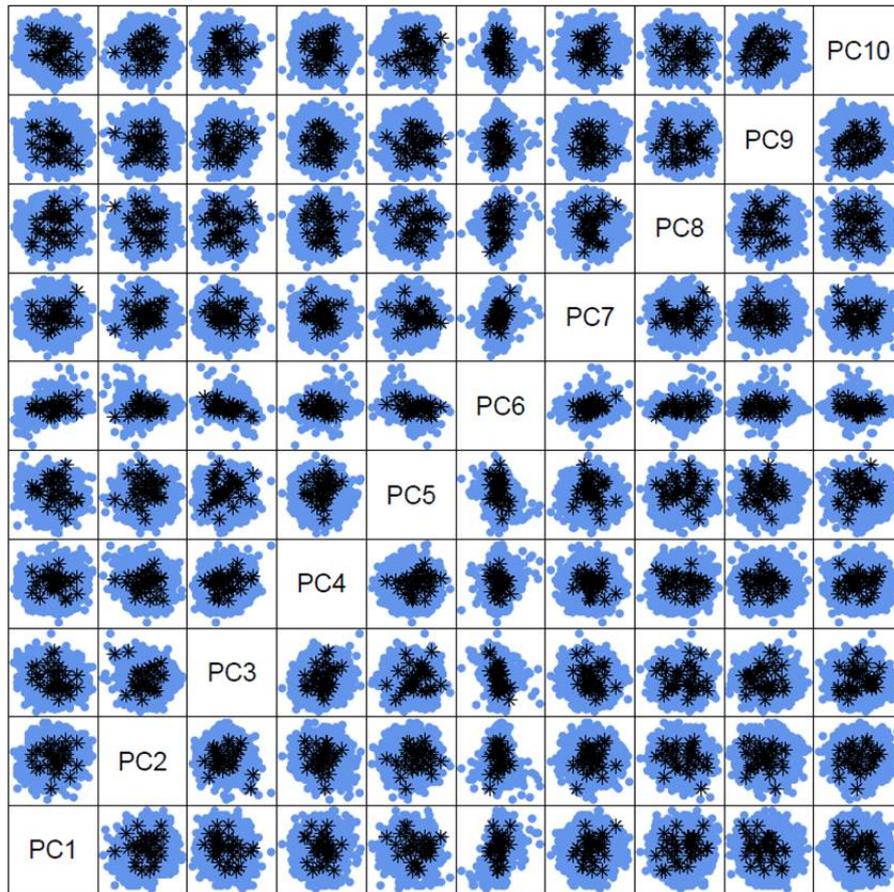
In Panel C, numbers refers to loci meeting certain selection criteria. \*We did not take forward the *KLF14* gene to experimental validation because previous studies about the role of the gene in metabolic disease suggest complex aetiologic mechanisms at this locus including a possible parent-of-origin effect.<sup>3</sup>



**Supplementary Figure 12**

Associations with fasting insulin adjusted for body mass index (FladjBMI), body mass index (BMI), or fasting insulin (FI) of the 53 polymorphisms identified in this study.

Panel A shows the association of the 53 lead polymorphisms from our study with FladjBMI as a function of the association with BMI. There was no clear bias in the association with FladjBMI (linear regression between beta coefficients of 53 polymorphisms,  $p=0.26$ ). Panel B depicts the association with FI (unadjusted for BMI) of the lead 53 polymorphisms as a function of the association with FladjBMI. The line of fit was aligned with the line of equality consistent with no bias. In Panel A, the dark red line and surrounding areas represent the lines of fit with 95% confidence areas. The dashed grey line in Panel B represents the line of equality. Data about fasting insulin associations is from the MAGIC consortium; data about BMI associations is from the GIANT consortium.



\* FPLD1 women  
 ● UKHLS controls

**Supplementary Figure 13**

Scatter plot matrix of the top ten genetic principal components in FPLD1 women and UKHLS control women.