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Kernel score statistic for dependent data

Dörthe Malzahn*, Stefanie Friedrichs, Albert Rosenberger, Heike Bickeböller

From Genetic Analysis Workshop 18
Stevenson, WA, USA. 13-17 October 2012

Abstract

The kernel score statistic is a global covariance component test over a set of genetic markers. It provides a flexible modeling framework and does not collapse marker information. We generalize the kernel score statistic to allow for familial dependencies and to adjust for random confounder effects. With this extension, we adjust our analysis of real and simulated baseline systolic blood pressure for polygenic familial background. We find that the kernel score test gains appreciably in power through the use of sequencing compared to tag-single-nucleotide polymorphisms for very rare single nucleotide polymorphisms with <1% minor allele frequency.

Background

Lately, much interest has been focused on global multilocus procedures that test for overall association of sets of markers. This is appealing if the loci carry rare variants or are thought to belong to a specific gene set, such as a pathway or genes with similar functions. The kernel score statistic is a specific type of such a global covariate-adjusted multilocus association test. Depending on context, it has received different names, such as SKAT (sequence kernel association test) [1]. Kernel methods provide flexible semiparametric regression models of multimarker genetic influence on expected trait outcome and can conveniently be implemented within the linear mixed-model formalism [2,3]. The kernel expresses genetic correlation between subjects. It allows us to test a whole model class by defining a prior probability in function space in a bayesian manner [4]. In contrast, standard regression models are limited to just 1 *a priori* stated submodel of such a class.

Until very recently, kernel methods were only applied to independent data (see Ref. [5] for a review). An extension to include familial dependence was made for trait prediction [6], but not for testing genetic influence. This changed with independent Genetic Analysis Workshop 18 (GAW18) contributions by ourselves and others (Huang et al [7], Chen et al [8], Dufresne et al [9], and Schifano et al [10]). Huang et al [7] applied the kernel

method to trios. The other 4 contributions (including ours) use a similar kernel extension to families with different study aims. We generalize the kernel score statistic to adjust for dependency in metric trait data. We apply it to real and simulated GAW18 baseline systolic blood pressure (SBP) and contrast its performance on the sequenced panel in comparison to tag-single-nucleotide polymorphisms (SNPs) of a genome-wide association study (GWAS).

Methods

Data

GAW18 provided blood pressure trait data from Mexican Americans participating in the San Antonio Family Heart Study or the San Antonio Family Diabetes/Gallbladder Study, and in the Type 2 Diabetes Genetic Exploration by Next-generation sequencing in Ethnic Samples (T2D-GENES) Project 2 study [11]. The sample is enriched for type 2 diabetes and for rare variants. Complete dense SNP allele dosage data were provided for 959 subjects from 20 large pedigrees with 22 to 86 members. Data are based on genome-wide tag-SNP genotyping of all subjects, whole-genome sequencing of 464 selected subjects, and imputation of all missing dosages for the remaining SNPs and subjects, exploiting kinship within pedigrees [11]. We considered only subjects with known baseline SBP, sex, and age, who were not on blood pressure medication: 706 subjects with real SBP, excluding the first listed twin of monozygotic twin pairs and 740 to 781 subjects with simulated SBP (subject numbers vary for 200

* Correspondence: dmalzah@gwdg.de

Department of Genetic Epidemiology, University Medical Center, Georg-August University Göttingen, Humboldtallee 32, 37073 Göttingen, Germany

simulated study replicates as a result of inclusion criteria). We tested candidate genes on chromosome 3 only (real SBP: 5 genes selected based on previous association reports [12], simulated SBP: gene *MAP4*). From group discussions, we knew that *MAP4* associates with simulated SBP and that simulated trait Q1 mimics the segregation of genes within families, but otherwise represents the genetic null hypothesis.

Kernel score statistic with adjustment for random confounders

We analysed baseline SBP, which has a right-skewed distribution toward large extremes. This was amended by a priori rank-normalization (Blom transformation [13]) of SBP to a standard normally distributed target variable $Y_i = F^{-1}((r_i-3/8)/(n_{\text{obs}}+1/4))$. F^{-1} denotes the standard normal distribution quantile; n_{obs} the number of observed SBP values; and r_i their respective rank. Individual traits Y_i for $i = 1, \dots, n$ subjects were modeled to depend on fixed effects \mathbf{b} of covariates \mathbf{X}_i (intercept, age, sex, age \times sex interaction), on random effects \mathbf{c} for shared familial polygenic background, and on a semi-parametric model $h(\mathbf{G})$ of a genetic marker set \mathbf{G} .

$$Y_i \sim \mathbf{X}_i \mathbf{b}^T + \mathbf{Z}_i \mathbf{c}^T + h(\mathbf{G}) \quad (1)$$

Vectors \mathbf{X}_i and \mathbf{Z}_i represent the subject rows of respective design matrices \mathbf{X} , \mathbf{Z} for fixed covariate effects and random family effects. The semiparametric model $h(\mathbf{G})$ can be written as $\mathbf{h} = \mathbf{K} \mathbf{a}^T$ with $n \times n$ dimensional kernel matrix \mathbf{K} and multivariate normally distributed random effects estimates $\mathbf{a} \sim \mathcal{N}(0, \tau \mathbf{K})$ [2]. The kernel score statistic tests for a genetic covariance component τ with null hypothesis $H_0: \tau = 0$. Most conveniently, it can be computed based on restricted maximum likelihood parameter estimates of the genetic null model

$$\mathbf{Y} = \mathbf{X} \mathbf{b}_0^T + \mathbf{Z} \mathbf{c}_0^T + \mathbf{e}, \quad (2)$$

which estimates only fixed covariate effects \mathbf{b}_0 , random pedigree effects \mathbf{c}_0 , polygenic component variance s_{fam}^2 and residual variance s^2 , $\mathbf{e} \sim \mathcal{N}(0, s^2 \mathbf{I})$. Extending the kernel score statistic to adjust for familial dependencies, we obtain test statistic

$$Q = (\mathbf{Y} - \mathbf{X} \mathbf{b}_0^T)^T \mathbf{V}_0^{-1} \mathbf{K} \mathbf{V}_0^{-1} (\mathbf{Y} - \mathbf{X} \mathbf{b}_0^T) / 2 \quad (3)$$

with matrix $\mathbf{V}_0 = s^2 \mathbf{I} + s_{\text{fam}}^2 \mathbf{Z} \mathbf{Z}^T$. With fixed effects estimate $\mathbf{b}_0 = (\mathbf{X}^T \mathbf{V}_0^{-1} \mathbf{X})^{-1} \mathbf{X}^T \mathbf{V}_0^{-1} \mathbf{Y}$, we rewrite test statistic (3) as quadratic form $Q = \mathbf{R}^T \mathbf{M} \mathbf{R}$ of standard normally distributed residuals $\mathbf{R} = \mathbf{P}_0^{1/2} \mathbf{Y}$ with matrix $\mathbf{M} = (\mathbf{P}_0^{1/2} \mathbf{K} \mathbf{P}_0^{1/2}) / 2$ and null projection matrix $\mathbf{P}_0 = \mathbf{V}_0^{-1} - \mathbf{V}_0^{-1} \mathbf{X} (\mathbf{X}^T \mathbf{V}_0^{-1} \mathbf{X})^{-1} \mathbf{X}^T \mathbf{V}_0^{-1}$. The p values for test statistic (3) can be calculated by the Davies exact method [14] with the R package CompQuadForm from sample estimates

Q and all eigenvalues of matrix \mathbf{M} . We adjusted for polygenic familial background based on the kinship coefficient matrix $\Phi_{\text{kin}} = \mathbf{Z} \mathbf{Z}^T$ using R-packages kinship2 and coxme with R-function lmeKin for genetic null model (2). We employed a linear kernel on allele dosages. This allows for additive genetic models on tested markers. The kernel matrix entry $\mathbf{K}_{ij} = \mathbf{g}_i^T \mathbf{g}_j$ for 2 subjects i, j is the scalar product of their subject-specific vectors $\mathbf{g}_i, \mathbf{g}_j$ of allele dosages for N_{SNP} SNP marker. SNPs were included for testing if their Hardy-Weinberg equilibrium test p values $\geq 10^{-5}$ (rounding imputed dosages for this purpose only). We contrasted test performance for the same subjects on 2 SNP panels, sequence (allele dosage data) versus GWAS (allele dosage data reduced to intersection with GWAS SNPs).

Results

Permutation testing demonstrated overall test validity: 50,000 permutations of subject-genotype assignment (permuting across families) yielded type I error 0.049 ± 0.0019 , 0.00046 ± 0.00019 at significance level 0.05, 0.0005 for simulated SBP on all sequenced rare *MAP4* SNPs. Simulated trait Q1 was used to test the quality of polygenic adjustment. We analyzed Q1 analogously to SBP on gene *MAP4* and obtained p values ≤ 0.05 with rate 0.02 (all SNPs, and SNPs with minor allele frequency (MAF) $> 5\%$), rate 0.05 (for MAF 1% to 5%), and 0.06 (for MAF $< 1\%$). This is within 95% tolerance limits (0.02, 0.08) for true value 0.05 on 200 replicates.

For simulated SBP, associated gene *MAP4* was detected with 100%, 62.5%, and 21.5% power at significance levels 0.05, 10^{-4} , and 10^{-8} on 200 study replicates when subjecting the *MAP4* sequence to the global test. Power diminished by only 0% to 2.5% when using the GWAS panel instead, or only MAF $> 5\%$ SNPs. Figure 1 displays power to detect *MAP4* association based on MAF $\leq 5\%$ SNPs. We varied the significance level to compare test performance on the sequence (filled circles) with the considerably sparser GWAS panel (open circles). Sequenced data are powerful and outperform GWAS data particularly for very rare SNPs (MAF $< 1\%$) where GWAS had no power (Figure 1, right). GWAS outperformed sequence data on SNPs with MAF 1% to 5% (Figure 1, left) with just 11 tag-SNPs compared to 105 sequenced SNPs.

Table 1 displays association of real SBP with the 5 selected candidate genes on chromosome 3. P values do not withstand Bonferroni correction. Note, however, the difference between sequence ($p = 0.150$) and GWAS ($p = 0.031$) for *MECOM* SNPs with MAF 1% to 5%. For *AGTRI*, sequence data tend to reduce p values compared to GWAS, as well as for *SLC4A7* on rare variants. We partitioned the large *MECOM*, *ULK4* sequences based on number of SNPs, as we expect that power improves by

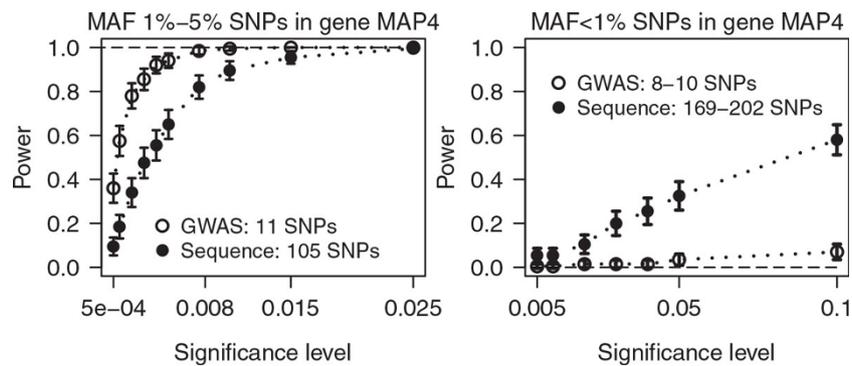


Figure 1 Simulated SBP associates with gene MAP4. Power estimates of the kernel score statistic with 95% confidence limits over 200 simulated study replicates as function of the significance level. The association between rank-normalized simulated systolic blood pressure and MAP4 was tested, adjusting for age, sex, age × sex interaction, and familial polygenic background. Polymorphic SNP numbers vary between study replicates for very rare SNPs with MAF <1% (range in legend, right panel), but not for MAF 1% to 5% (left panel).

Table 1 Real SBP and candidate genes on chromosome 3

Gene	SNP panel	Kernel score statistic (linear kernel on allele dosage data)							
		All SNPs		MAF >5%		MAF 1% to 5%		MAF <1%	
		N _{SNP}	p Value	N _{SNP}	p Value	N _{SNP}	p Value	N _{SNP}	p Value
MECOM	GWAS	212	0.840	176	0.873	33	0.031	3	0.333
	Sequence	2530	0.826	1222	0.864	621	0.150	687	0.289
	Sequence	- 4 consecutive windows							
		633	0.976	364	0.977	93	0.482	176	0.890
		633	0.557	229	0.709	198	0.0071	206	0.197
		632	0.251	340	0.252	161	0.371	131	0.137
ULK4	GWAS	188	0.770	146	0.783	40	0.258	2	0.430
	Sequence	3333	0.510	1569	0.518	1007	0.302	757	0.459
	Sequence	- 5 consecutive windows							
		667	0.661	314	0.648	177	0.499	176	0.301
		667	0.791	373	0.812	125	0.171	169	0.409
		667	0.738	296	0.813	208	0.108	163	0.446
PPARG	GWAS	148	0.693	90	0.664	32	0.880	26	0.998
	Sequence	583	0.841	269	0.803	121	0.989	193	0.990
	Sequence	39	0.277	27	0.296	11	0.097	1	0.482
AGTR1	GWAS	39	0.277	27	0.296	11	0.097	1	0.482
	Sequence	497	0.081	174	0.091	172	0.100	151	0.223
SLC4A7	GWAS	27	0.688	13	0.789	10	0.134	4	0.208
	Sequence	375	0.776	149	0.864	82	0.099	144	0.158

Kernel score test over N_{SNP} SNP marker for rank-normalized systolic blood pressure, adjusted for age, sex, age × sex interaction, and familial background (p ≤ 0.05 in bold).

changing from a situation where we test over many more SNPs compared to number of subjects (full gene) to a situation with fewer SNPs than subjects (gene parts).

Conclusions

The kernel score statistic is a global covariance component test. P values for genes are dominated by their

common SNPs (see Table 1: all SNPs vs. MAF >5%). Thus, common and rare SNP sets should be tested separately. The kernel method offers a simple and flexible way to perform multimarker analysis and genetic interaction analyses by means of the kernel choice. It improves power compared to single-marker tests by exploiting SNP correlation [10], and if jointly tested SNP sets tag

multiple independent associated loci. The test statistic by Liu et al and Tzeng et al [2,3] had 17% power at the 0.01 level for independent subjects to find *MAP4* association with simulated SBP in 200 replicates. Our extension to families increased this to 98.5% power, used 84% more subjects with twice as many polymorphic SNPs (sequence), without type I error inflation. Ignoring familial dependency would inflate type I error to 16%, 6% at nominal 0.05, 0.01 levels (applying the independent subjects test statistic [2,3] to families for *MAP4* on polygenic trait Q1). We found that sequencing can improve test power appreciably, particularly for MAF <1% variants (Figure 1, right). For more frequent SNPs, the comparison was not decisive and tag-SNPs proved to be strong competitors. With sequencing, even a single, large gene may provide more SNP variants than available study subjects. The kernel score test remains valid because of the Bayesian nature of the underlying nonparametric genetic model [4]. However, one might expect power loss. The kernel score statistic may be susceptible to random confounders. For example, simplistic adjustment of familial and common cultural effects by a familial random intercepts model (instead of the polygenic model) yields valid permutation test results, but shows up as inflated type I errors on simulated polygenic trait Q1 ($p \leq 0.05$ on 10% of 200 study replicates for all *MAP4* SNPs, inflation increases with decreasing MAF). This, in turn, would yield similar but overly optimistic estimates for Figure 1 and Table 1. With such a liberal test, *AGTRI* p values in Table 1 would all drop below 0.05 for all sequence SNP sets. We would like to emphasize that other random confounder effects, such as different trait variability between study subgroups, can be adjusted in exact analogy to the familial polygenic background adjustment.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

DM designed the study concept, developed the statistical method, conducted data extraction, all statistical analyses and data interpretation, and drafted the manuscript. SF and AR provided the SNP mapping to positions (NCBI build 37) and genes. HB contributed throughout with discussions. All authors read and approved the final manuscript.

Acknowledgements

This work was supported by the Deutsche Forschungsgemeinschaft (grant Klinische Forschergruppe [KFO] 241: TP5, BI 576/5-1) and the German Federal Ministry of Education and Research BMBF (German National Genome Research Net NGFN grant 01GS0837). The GAW18 whole genome sequence data were provided by the T2D-GENES Consortium, which is supported by NIH grants U01 DK085524, U01 DK085584, U01 DK085501, U01 DK085526, and U01 DK085545. The other genetic and phenotypic data for GAW18 were provided by the San Antonio Family Heart Study and San Antonio Family Diabetes/Gallbladder Study, which are supported by NIH grants P01 HL045222, R01 DK047482, and R01 DK053889. The Genetic Analysis Workshop is supported by NIH grant R01 GM031575.

This article has been published as part of *BMC Proceedings* Volume 8 Supplement 1, 2014: Genetic Analysis Workshop 18. The full contents of the

supplement are available online at <http://www.biomedcentral.com/bmcproc/supplements/8/S1>. Publication charges for this supplement were funded by the Texas Biomedical Research Institute.

Published: 17 June 2014

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doi:10.1186/1753-6561-8-S1-S41

Cite this article as: Malzahn et al.: Kernel score statistic for dependent data. *BMC Proceedings* 2014 **8**(Suppl 1):S41.

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