**Abstract**

Haplotype-based scans to detect natural selection are useful to identify recent or ongoing positive selection in genomes. As both real and simulated genomic datasets grow larger, spanning thousands of samples and millions of markers, there is a need for a fast and efficient implementation of these scans for general use. Here we present selscan, an efficient multi-threaded application that implements Extended Haplotype Homozygosity (EHH), Integrated Haplotype Score (iHS), and Cross-population Extended Haplotype Homozygosity (XPEHH). selscan performs extremely well on both simulated and real data and over an order of magnitude faster than existing available implementations. It calculates iHS on chromosome 22 (22, 147 loci) across 204 CEU haplotypes in 502s on one thread (77s on 16 threads) and calculates XPEHH for the same data relative to 210 YRI haplotypes in 907s on one thread (107s on 16 threads). Source code and binaries (Windows, OSX and Linux) are available at https://github.com/szpiech/selscan.

1 Introduction

Extended Haplotype Homozygosity (EHH) [Sabeti et al. 2002], Integrated Haplotype Score (iHS) [Voight et al. 2006], and Cross-population Extended Haplotype Homozygosity (XPEHH) [Sabeti et al. 2007] are statistics designed to identify putative regions of recent or ongoing positive selection in genomes. They are all based on the model of a hard selective sweep, where a de novo adaptive mutation arises on a haplotype that quickly sweeps toward fixation, reducing diversity around the locus. If selection is strong enough, this occurs faster than recombination or mutation can act to break up the haplotype, and thus a signal of high haplotype homozygosity can be observed extending from an adaptive locus.

As genetics data sets grow larger both in number of individuals and number of loci, there is a need for a fast and efficient publicly available implementation of these statistics. Below we introduce these statistics and provide concise definitions for their calculations. We then evaluate the performance of our implementation, selscan.

1.1 Extended Haplotype Homozygosity

In a sample of \( n \) chromosomes, let \( C \) denote the set of all possible distinct haplotypes at a locus of interest (named \( x_0 \)), and let \( C(x_i) \) denote the set of all possible distinct haplotypes extending from the locus \( x_0 \) to the \( i \)th marker either upstream or downstream from \( x_0 \). For example, if the locus of interest \( x_0 \) is a biallelic SNP where 0 represents the ancestral allele and 1 represents the derived allele, then \( C := \{0, 1\} \). If \( x_1 \) is an immediately adjacent marker, then the set of all possible haplotypes is \( C(x_1) := \{11, 10, 00, 01\} \).

EHH of the entire sample, extending from the locus \( x_0 \) out to marker \( x_1 \), is calculated as

\[
EHH(x_1) = \sum_{h \in C(x_1)} \frac{n_h}{n^2},
\]

where \( n_h \) is the number of observed haplotypes of type \( h \in C(x_1) \).

In some cases, we may want to calculate the haplotype homozygosity of a sub-sample of chromosomes all carrying a ‘core’ haplotype at locus \( x_0 \). Let \( \mathcal{H}_c(x_i) \) be a partition of \( C(x_i) \) containing all distinct haplotypes carrying the core haplotype, \( c \in C \), at \( x_0 \) and extending to marker \( x_i \). Note that

\[
C(x_i) = \bigcup_{c \in C} \mathcal{H}_c(x_i).
\]

Following the example above, if the derived allele (1) is chosen as the core haplotype, then \( \mathcal{H}_1(x_1) := \{11, 10\} \). Similarly, if the ancestral allele is the core haplotype, then \( \mathcal{H}_0(x_1) := \{00, 01\} \).

We calculate the EHH of the chromosomes carrying the core haplotype \( c \) to marker \( x_i \) as

\[
EHH_c(x_i) = \sum_{h \in \mathcal{H}_c(x_i)} \frac{n_h}{n^2},
\]

where \( n_h \) is the number of observed haplotypes of type \( h \in \mathcal{H}_c(x_i) \) and \( n_c \) is the number of observed haplotypes carrying the core haplotype \( (c \in C) \).

1.2 Integrated Haplotype Score

iHS is calculated by using Equation 3 to track the decay of haplotype homozygosity for both the ancestral and derived...
haplotypes extending from a query site. To calculate iHS at a site, we first calculate the integrated haplotype homozygosity (iHH) for the ancestral (0) and derived (1) haplotypes (C := \{0, 1\}) via trapezoidal quadrature.

\[
iHH = \sum_{i=1}^{\lvert D \rvert} \frac{1}{2} (EHH_c(x_{i-1}) + EHH_c(x_i)) g(x_{i-1}, x_i) + \sum_{i=1}^{\lvert U \rvert} \frac{1}{2} (EHH_c(x_{i-1}) + EHH_c(x_i)) g(x_{i-1}, x_i),
\]

(4)

where D is the set of markers downstream from the current locus such that \( x_i \in D \) denotes the \( i^{th} \) closest downstream marker from the locus of interest (\( x_0 \)). U and \( x_i \in U \) are defined similarly for upstream markers. \( g(x_{i-1}, x_i) \) gives the genetic distance between two markers. The (unstandardized) iHS is then calculated as

\[
\ln \left( \frac{iHH_1}{iHH_0} \right).
\]

(5)

Note that this definition differs slightly from that in \cite{voight2006}, where unstandardized iHS is defined with \( iHH_1 \) and \( iHH_0 \) swapped.

Finally, the unstandardized scores are normalized in frequency bins across the entire genome.

\[
iHS = \frac{\ln \left( \frac{iHH_1}{iHH_0} \right) - E_p \ln \left( \frac{iHH_1}{iHH_0} \right)}{SD_p \left[ \ln \left( \frac{iHH_1}{iHH_0} \right) \right]},
\]

(6)

where \( E_p \left[ \ln \left( \frac{iHH_1}{iHH_0} \right) \right] \) and \( SD_p \left[ \ln \left( \frac{iHH_1}{iHH_0} \right) \right] \) are the expectation and standard deviation in frequency bin \( p \).

In practice, the summations in Equation 4 are truncated once \( EHH_c(x_i) < 0.05 \). Additionally with low density SNP data, if the physical distance \( b \) (in kbp) between two markers is \( > 20 \), then \( g(x_{i-1}, x_i) \) is scaled by a factor of \( 20/b \) in order to reduce possible spurious signals induced by lengthy gaps. During computation if the start/end of a chromosome arm is reached before \( EHH_c(x_i) < 0.05 \) or if a gap of \( b > 200 \) is encountered, the iHS calculation is aborted for that locus. iHS is not reported at core sites with minor allele frequency \( < 0.05 \). In \texttt{selscan}, the EHH truncation value, gap scaling factor, and core site MAF cutoff value are all flexible parameters definable on the command line.

1.3 Cross-population Extended Haplotype Homozygosity

To calculate XPEHH between populations A and B at a marker \( x_0 \), we first calculate iHH for each population separately, integrating the EHH of the entire sample in the population (Equation 1).

\[
iHH = \sum_{i=1}^{\lvert D \rvert} \frac{1}{2} (EHH(x_{i-1}) + EHH(x_i)) g(x_{i-1}, x_i) + \sum_{i=1}^{\lvert U \rvert} \frac{1}{2} (EHH(x_{i-1}) + EHH(x_i)) g(x_{i-1}, x_i),
\]

(7)

If \( iHH_A \) and \( iHH_B \) are the iHHS for populations A and B, then the (unstandardized) XPEHH is

\[
\ln \left( \frac{iHH_A}{iHH_B} \right),
\]

(8)

and after genome-wide normalization we have

\[
XPEHH = \frac{\ln \left( \frac{iHH_A}{iHH_B} \right) - E \left[ \ln \left( \frac{iHH_A}{iHH_B} \right) \right]}{SD \left[ \ln \left( \frac{iHH_A}{iHH_B} \right) \right]}.
\]

(9)

In practice, the sums in each of \( iHH_A \) and \( iHH_B \) (Equation 7) are truncated at \( x_i \)—the marker at which the EHH of the haplotypes pooled across populations is \( EHH(x_i) < 0.05 \). Scaling of \( g(x_{i-1}, x_i) \) and handling of gaps is done as for iHS, and these parameters are definable on the \texttt{selscan} command line.

2 Performance

Here we evaluate the performance of \texttt{selscan} (https://github.com/szpiech/selscan) for computing the iHS and XPEHH statistics. In addition, we compare performance on these statistics with the programs \texttt{ihs} \cite{voight2006} and \texttt{xpehh} \cite{pickrell2009} (both available for download at http://hgdp.uchicago.edu/Software/). All computations were run on a MacPro running OSX 10.8.5 with two 2.4 GHz 6-core Intel Xeon processors with hyperthreading enabled.

2.1 iHS

For runtime evaluation of iHS calculations, we simulated a 4 Mbp region of DNA with the program \texttt{ms} \cite{hudson2002} and generated four independent data sets with varying numbers of sampled haplotypes (\( \theta = 1600 \) and \( \rho = 1600 \)). We sampled 250 haplotypes (9, 625 SNP loci), 500 haplotypes (10, 646 SNP loci), 1,000 haplotypes (11, 655 SNP loci), and 2,000 haplotypes (12, 724 SNP loci). We name these data sets IHS250, IHS500, IHS1000, IHS2000, respectively. These data sets represent a densely typed region similar to next-generation sequencing data. Although these data sets are generated via strictly neutral processes, they serve the purpose of runtime evaluation perfectly well. We also use data from The 1000 Genomes Project \cite{1000genomes2012} Omni genotypes, calculating iHS scores at 22, 147 SNP loci on chromosome 22 across 102 CEU individuals (204 haplotypes). We name this data set CEU22.
2.2 XPEHH

For runtime evaluation of XPEHH calculations, we simulated a 4 Mbp region of DNA with the program ms [Hudson, 2002] with a simple two population divergence model (time to divergence $t = 0.05$, $\theta = 1600$ and $\rho = 1600$) and generated four independent data sets with varying numbers of sampled haplotypes. We sampled 250 haplotypes (125 from each population, 12,920 SNP loci), 500 haplotypes (250 from each population, 14,989 SNP loci), 1,000 haplotypes (500 from each population, 17,142 SNP loci), and 2,000 haplotypes (1,000 from each population, 19,567 SNP loci). We name these data sets XP250, XP500, XP1000, and XP2000, respectively. These data sets represent a densely typed region similar to next-generation sequencing data. Although these data sets are generated via strictly neutral processes, they serve the purpose of runtime evaluation perfectly well. We also use data from The 1000 Genomes Project (The 1000 Genomes Project Consortium, 2012) Omni genotypes, calculating XPEHH scores at 22,147 SNP loci on chromosome 22 across 102 CEU individuals (204 haplotypes) and 105 YRI individuals (210 haplotypes). We name this data set CEU22.

Table 1 summarizes the runtimes of \texttt{ihs} and \texttt{selscan}. Even operating on a single thread, \texttt{selscan} tends to calculate \texttt{iHS} scores at least an order of magnitude faster than \texttt{ihs}. Figure 1A shows the correlation (Pearson’s $r = 0.9946$) of CEU22 unstandardized \texttt{iHS} scores between the two programs. The slight variance in scores between the two programs is due to an undocumented difference in the way \texttt{ihs} calculates its scores (Sabeti \textit{et al.} 2007 Supplemental Information), but the effect is negligible.

Table 2 summarizes the runtimes of \texttt{xpehh} and \texttt{selscan}. Even operating on a single thread, \texttt{selscan} tends to calculate XPEHH scores at least an order of magnitude faster than \texttt{xpehh}. Figure 1B shows the correlation (Pearson’s $r = 0.9999$) of CEUYRI22 unstandardized XPEHH scores between the two programs.

3 Conclusions

\texttt{selscan} achieves a speed up of at least an order or magnitude over both \texttt{ihs} and \texttt{xpehh} through general optimizations of the calculations. Additional empirical testing (data not shown) suggests that \texttt{ihs} is \(O(ND^2)\), \texttt{xpehh} is \(O(N^2D^2)\), and \texttt{selscan} is \(O(ND^2)\) for both calculations, where \(N\) is the number of haploid samples and \(D\) is the SNP locus density. We expect that \texttt{selscan} will be a valuable tool for calculating EHH-based genome-wide scans for positive selection in very large genetic data sets currently being generated for humans and other organisms, as well as testing on large-scale simulations.

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Table 1: Runtime performance (in seconds) of **ihs** and **selscan** for calculating unstandardized iHS for various data sets. Calculations running over 100,000 seconds were aborted.

| Data Set   | ihs   | selscan   |
|------------|-------|-----------|
|            |       | threads = 1 | 2 | 4 | 8 | 16       |
| IHS250     | 19,275| 883       | 464 | 268 | 164 | 117     |
| IHS500     | 40,547| 2,198     | 1,124 | 573 | 360 | 240     |
| IHS1000    | > 100,000 | 5,663 | 2,978 | 1,496 | 948 | 673     |
| IHS2000    | > 100,000 | 10,146 | 5,199 | 2,948 | 1,947 | 1,275   |
| CEU22      | 19,434| 502       | 258 | 172 | 108 | 77      |

Table 2: Runtime performance (in seconds) of **xpehh** and **selscan** for calculating unstandardized XPEHH for various data sets. Calculations running over 100,000 seconds were aborted.

| Data Set   | xpehh   | selscan   |
|------------|---------|-----------|
|            |         | threads = 1 | 2 | 4 | 8 | 16     |
| XP250      | 11,113  | 375       | 189 | 99 | 60 | 41     |
| XP500      | 57,006  | 1,027     | 531 | 285 | 157 | 112   |
| XP1000     | > 100,000 | 2,729 | 1,386 | 722 | 404 | 315   |
| XP2000     | > 100,000 | 7,492 | 3,866 | 2,007 | 1,234 | 871   |
| CEUYRI22   | 37,271  | 907       | 494 | 276 | 148 | 107   |
Figure 1: (A) Unstandardized iHS scores calculated on the CEU22 data set for selscan and ihs (Pearson’s $r = 0.9946$) and (B) Unstandardized XPEHH scores calculated on the CEUYRI22 data set for selscan and xpehh (Pearson’s $r = 0.9999$)