bioinformatics, 2025, 1–9
doi: XXX
Advance Access Publication Date: Day Month Year
Paper

MutBERT: Probabilistic Genome Representation Improves Genomics Foundation Models

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Abstract

Motivation: Understanding the genomic foundation of human diversity and disease requires models that effectively capture sequence variation, such as single nucleotide polymorphisms (SNPs). While recent genomic foundation models have scaled to larger datasets and multi-species inputs, they often fail to account for the sparsity and redundancy inherent in human population data, such as those in the 1000 Genomes Project. SNPs are rare in humans, and current masked language models (MLMs) trained directly on whole-genome sequences may struggle to efficiently learn these variations. Additionally, training on the entire dataset without prioritizing regions of genetic variation results in inefficiencies and negligible gains in performance.

Results: We present MutBERT, a probabilistic genome-based masked language model that efficiently utilizes SNP information from population-scale genomic data. By representing the entire genome as a probabilistic distribution over observed allele frequencies, MutBERT focuses on informative genomic variations while maintaining computational efficiency. We evaluated MutBERT against DNABERT-2, various versions of Nucleotide Transformer, and modified versions of MutBERT across multiple downstream prediction tasks. MutBERT consistently ranked as one of the top-performing models, demonstrating that this novel representation strategy enables better utilization of biobank-scale genomic data in building pretrained genomic foundation models.

Availability: https://github.com/ai4nucleome/mutBERT

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Introduction

Recent advancements in natural language processing (NLP) have driven transformative progress in genomics, particularly through the development of genomic foundation models Benegas et al. (2025), Consens et al. (2023). These models leverage deep learning techniques to analyze DNA sequences, enabling the prediction of functional elements, regulatory mechanisms, and variant effects. Building on the success of models like BERT Devlin (2018) and GPT Radford (2018) in NLP, the genomics community has adapted these concepts to address challenges such as modeling long-range dependencies in DNA sequences Nguyen et al. (2024), Cheng et al. (2025) and improving predictions based on genomic data Benegas et al. (2023).

The development of DNA foundation models began in 2021 with DNABERT Ji et al. (2021), which utilized overlapping k-mers Celikkanat et al. (2024) as tokens and the original BERT architecture to analyze DNA sequences. Trained exclusively on the human reference genome, DNABERT could handle sequences up to 500 base pairs and established an early standard for genomic representation learning. However, its tokenization methods, constrained sequence lengths, and an outdated architecture restricted its ability to generalize to broader and more complex genomic contexts.

Building on these foundations, the rapid progress in NLP during subsequent years, including the rise of ChatGPT Achiam et al. (2023), introduced advanced methodologies and architectures that were adapted to genomic modeling Sanabria et al. (2024). For instance, DNABERT-2 Zhou et al. (2023) incorporated byte pair encoding (BPE) tokenization Sennrich (2015) to improve data representation efficiency. It also adopted ALiBi Press et al. (2021) for managing longer sequences and flash attention Dao et al. (2022) for computational optimization, enabling the model to process multi-species datasets. These innovations, although derived from NLP, demonstrated the potential to extend the capabilities of genomic modeling by enhancing sequence length scalability and data diversity.

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Nucleotide Transformer Dalla-Torre et al. (2024) further explored the benefits of scaling model size and input diversity by training various models on the human reference genome, individual genomes from the 1000 Genomes Project Byrska-Bishop et al. (2022), and multi-species data. It highlighted the advantages of leveraging both larger models and richer datasets. Meanwhile, models such as HyenaDNA Nguyen et al. (2024) and MambaDNA Schiff et al. (2024) addressed the limitations of handling long-range genomic dependencies by extending input lengths to hundreds of kilobases using attention-free architectures. These models successfully overcame the quadratic scaling bottlenecks of traditional transformers, demonstrating their efficacy for tasks requiring large genomic contexts.

Other approaches explored integrating additional data, such as evolutionary information through multispecies sequence alignments. For instance, GPN-MSA Benegas et al. (2024) introduced a framework that combined target sequences with their corresponding multiple sequence alignments from diverse species to improve variant effect predictions, particularly in functional genomic regions.

These developments reflect three key trends in genomic foundation modeling: increasing model size often enhances performance, innovations like flash attention and ALiBi enable longer sequence contexts, and incorporating diverse datasets—particularly multi-species data—yields more robust models. Despite these advancements, efficiently leveraging data from the same species, such as the 1000 Genomes Project, remains a significant challenge. The 1000 Genomes dataset, though invaluable for understanding human genetic diversity, includes substantial redundancy in DNA segments across individuals, which poses challenges for its effective utilization by conventional methods. Extending these approaches to larger, more complex biobank-scale datasets poses an even greater challenge.

To address these issues, we present MutBERT, a probabilistic genome-based masked language model designed to efficiently utilize SNP information from population-scale genomic data. Unlike previous approaches, MutBERT represents genomic sequences as probabilistic distributions over allele frequencies, enabling it to focus on informative regions while mitigating redundancy. Our results show that MutBERT performs well on the 1000 Genomes dataset, effectively capturing population-level variation. Furthermore, we believe that MutBERT's probabilistic representation strategy positions it to better utilize biobank-scale datasets in the future.

By consistently ranking among the top-performing models across multiple downstream tasks, MutBERT demonstrates its potential as a scalable, biologically informed genomic foundation model. This work provides insight into novel strategies for in leveraging population-scale genomic datasets to advance the field of genomics.

Materials and methods

Model Architecture

We proposed MutBERT and its two variants, MutBERT-Ref and MutBERT-Multi, all sharing the same network architecture. MutBERT and MutBERT-Multi utilize probabilistic genome representations as input for masked language modeling (MLM). These probabilistic genomes are derived from the 1000 Genomes Project and 100-way multispecies alignments Benegas et al. (2024),

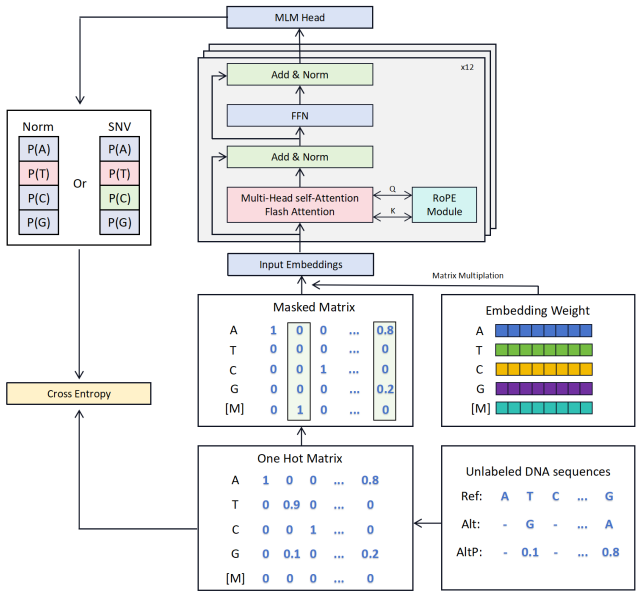

Fig. 1: Overview of MutBERT.

respectively. In contrast, MutBERT-Ref takes one-hot embeddings of the reference genome as input, providing a deterministic genome baseline for comparison.

As shown in figure 1, MutBERT is based on the Transformer Encoder architecture Vaswani (2017), incorporating recent advancements Su et al. (2024), Dao et al. (2022), Liu et al. (2023) in deep learning to enhance efficiency and scalability for genomic data. MutBERT comprises 12 encoder layers, with GELU Dauphin et al. (2017) as the activation function for the feed-forward network. It has 86 million learnable parameters. Unlike other models that take a sequence of tokens as input, MutBERT processes a probabilistic matrix representation. Due to this unique input format, traditional embedding layers implemented in widely used deep learning packages such as PyTorch Paszke et al. (2019) are not directly applicable. Instead, we employ a linear layer to map the probabilistic input matrix into d-dimensional embeddings, ensuring compatibility with the Transformer Encoder architecture. To address the limitations of fixed input lengths in traditional positional embeddings, we integrate Rotary Position Embedding (RoPE) Su et al. (2024), which enables effective handling of variable-length inputs and ensures robust performance across diverse genomic contexts. Additionally, we utilize Flash Attention Dao et al. (2022) to optimize computation and memory efficiency, significantly reducing the quadratic scaling bottleneck associated with standard attention mechanisms, allowing MutBERT to process longer sequences efficiently. MutBERT also includes support for Low-Rank Adaptation (LoRA) Hu et al. (2021) during the fine-tuning stage, enabling parameter-efficient training by adapting only a small subset of parameters. However, as the model presented in this study is relatively small (86 MB), we did not applied LoRA in our experiments.

Probabilistic Genome Representation

In the probabilistic genome representation, each nucleotide position is encoded as a probabilistic distribution over the four nucleotide bases: A, T, C, and G, derived from allele frequencies in

population-scale datasets such as the 1000 Genomes Project. This approach captures genetic diversity across individuals, providing a nuanced representation of both conserved and variable genomic regions.

This method draws inspiration from established genomic practices, such as using position-specific weight matrices (PSWMs) to represent sequence motifs and inferring ancestral states from pairwise alignments. Similar to how PSWMs capture the likelihood of observing specific bases at each position in a motif, the probabilistic genome representation encodes the likelihood of each nucleotide at every position based on observed allele frequencies. Positions without observed variants are represented deterministically, with the reference nucleotide assigned a probability of 1, while variable positions are represented as distributions reflecting the observed allele frequencies.

Under this formulation, a DNA sequence of length L can be represented as a probabilistic matrix of size $4 \times L$, where each column corresponds to the probability distribution of the four nucleotides at a specific genomic position. In the development of MutBERT, we extend it to account for five special tokens, such as [PAD], [CLS], and [MASK], which expand the matrix representation to $9 \times L$. This expanded format ensures compatibility with masked language modeling while preserving the probabilistic representation of the underlying genomic data.

Tokenization and Vocabulary

To ensure high-quality input data, we discard DNA sequences containing ambiguous nucleotides represented by N. The input to our model is processed at the individual nucleotide level, resulting in a vocabulary consisting of A, T, C, and G. Additionally, our vocabulary includes the special tokens [PAD], [CLS], [SEP], [UNK], and [MASK], commonly used in masked language modeling.

Pretraining via Masked Language Modeling

Mask Strategy. We adopt a masked language modeling (MLM) setup similar to that used in BERT, employing a masking ratio of 15%. To prioritize biologically relevant information, we focus on masking single nucleotide variant (SNV) tokens. If the number of SNV tokens exceeds 15% of the sample length, we randomly select 15% of the tokens. Otherwise, we supplement the selection with non-SNV tokens to achieve the required masking ratio. For the selected tokens, we replace them with a [MASK] token 80% of the time and leave them unchanged 20% of the time. Since MutBERT operates on a probabilistic matrix as input, we apply masking by modifying the probability distribution of the selected tokens. Specifically, we assign a probability of 1 to the [MASK] token in the masked position, ensuring compatibility with the probabilistic input format. To further enhance the representation of mutation probabilities, we apply temperature scaling to the input matrix Guo et al. (2017). For each token, we scale the mutation probabilities using a temperature parameter τ, and normalize them using a softmax operation. To evaluate the impact of temperature scaling, we trained models without temperature rescaling and with $\tau = 0.7$ and $\tau = 2$. Among these settings, $\tau = 0.7$ consistently outperformed the others. All results reported in this paper were produced using $\tau = 0.7$.

Loss Function. The dataset includes mutation probabilities as part of the input representation, which we use as target labels during pretraining. We mask the SNV tokens and train the model to predict these probabilities. The loss is computed as the cross-entropy Mao et al. (2023) between the predicted logits and the temperature-scaled nucleotide probabilities as follows:

$$Loss = H(p, q) = -\sum_{i=1}^{n} q(x_i) \log p(x_i) \tag{1}$$

Where $p_(x_i)$ represents the predicted probability for label x_i, and $q_(x_i)$ represents true probability of x_i.

Models and Pre-training Data

We trained three models, each with the same architecture and training procedure. The key difference among these models lies in the source of their training data. The datasets used for training are summarized in Table 1 and include the 1000 Genomes Project data, multispecies data, and the human reference genome. For all models, we performed training on all autosomes and the X chromosome. In each dataset, we removed all N characters locus in the human reference genome and concatenated the remaining DNA segments using the [SEP] token. Among all settings, We used chromosome 22 as the validation set and the remaining chromosomes as the training set.

All models were trained using a batch size of 2048 and a maximum sequence length of 512. The training process consisted of 120,000 steps, employing the AdamW optimizer with parameters $\beta_1 = 0.9, \beta_2 = 0.99, \epsilon = 1e-8$ and weight decay of 0.01. During the initial 10,000 steps, the learning rate was linearly increased from 0 to $4e-4$. For the remaining 110,000 steps, the learning rate decayed gradually following a cosine schedule, reaching 1e-8 at the final step.

MutBERT. It was trained on probabilistic genome data derived from the 1000 Genomes Project. We downloaded Variant Calling Format (VCF) files from the 1000 Genomes Project, which includes data from 3,202 high-coverage genomes spanning 27 geographically structured populations. For each genomic locus, we calculated allele frequencies from the SNP information provided in the VCF files, discarding rare mutations with allele frequencies less than 2%. Using these allele frequencies, we created probabilistic training data, assigning probabilities to each nucleotide at every position based on their observed frequencies. This approach provided a probabilistic representation of human genetic diversity for training MutBERT.

MutBERT-Multi. It was trained on probabilistic genomes derived from the multiz whole-genome alignment dataset Blanchette et al. (2004). This alignment is anchored to the human genome, with mutation probabilities corresponding to positions in the human genome. Following the approach outlined in GPN-MSA Benegas et al. (2024), we included 10 closely related primates to humans, resulting in a dataset containing 100 vertebrate species. Mutation probabilities were calculated by counting the number of nucleotides at each position across the alignment. This dataset enabled us to represent multispecies genomic diversity probabilistically, providing a distinct training context for MutBERT-Multi.

MutBERT-Ref. It was trained exclusively on data derived from the human reference genome (hg38). The training dataset was generated by retaining all autosomal and X chromosomes. All N characters were removed, and the remaining DNA segments were concatenated using the [SEP] token. Tokenization was performed at the individual nucleotide level, as described previously. This model is similar to other genomic models, such as DNABERT and

Pretraining dataset	Human-Ref		1000G		Multi	
split	Train (M)	Test (M)	Train (M)	Test (M)	Train (M)	Test (M)
Total bp	2872	39	2872	39	2872	39
Num. SNVs	0	0	9(0.34%)	0.1(0.37%)	2008(69.92%)	25(64.60%)
Num. Samples	30	0.15	30	0.15	30	0.15
Num. Samples w/ SNVs	0	0	21(71.49%)	0.11(72.06%)	29(96.90%)	0.13(92.68%)

Table 1. Pretraining dataset statistics for Human-Ref, 1000G, and Multispecies

Nucleotide Transformer trained on the human reference genome, but it employs single nucleotide-level tokenization instead of k-mer-based or BPE approaches. To enable MutBERT to train effectively on this deterministic data, we represented the input as a probabilistic matrix, assigning a probability of 1 to the reference allele at all positions.

Alternative Models

We compared MutBERT against DNABERT-2 Zhou et al. (2023) and Nucleotide Transformer (NT) Dalla-Torre et al. (2024). DNABERT-2 is pre-trained on the human genome and 134 other species, incorporating advanced techniques such as BPE, ALiBi, and Flash Attention. These techniques enable DNABERT-2 to handle sequences longer than those encountered during pretraining, making it highly versatile for various genomic tasks. Nucleotide Transformer represents a family of transformer-based models for DNA sequence analysis. We evaluated three variants of NT-v1: NT-500M-humanRef, NT-500M-1000G, and NT-2500M-multi, pre-trained on the human reference genome, the 1000 Genomes Project, and genomes from 850 species, respectively. NT-v1 models can process sequences up to 1,000 tokens, equivalent to 6,000 base pairs. Additionally, we evaluated NT-v2, which is pre-trained exclusively on the multi-species dataset. NT-v2 includes four variants: NTv2-50M-multi, NTv2-100M-multi, NTv2-250M-multi, and NTv2-500M-multi, with the capability to process sequences up to 2,048 tokens, equivalent to 12,000 base pairs. We utilized pre-trained weights for these models, obtained from Hugging Face, for all evaluations. It is important to note that some NT models are significantly larger than MutBERT. Due to limited computational resources, we applied standard fine-tuning techniques only to models with fewer than 300 million parameters. For larger models, we utilized LoRA for parameter-efficient fine-tuning.

Downstream Tasks

We developed MutBERT to better utilize large-scale genomic data from individuals of the same species, with a primary focus on training a model for humans. Consequently, we evaluated MutBERT's performance on tasks specifically designed for human genomic analysis.

Transcription factor binding site prediction. We evaluated MutBERT and other foundation models on the task of transcription factor binding site (TFBS) prediction in humans, using datasets from the GUE benchmark Zhou et al. (2023). This task includes five datasets, each designed as a binary classification task, with input sequences fixed at a length of 100 bp.

Nucleotide Transformer downstream tasks. We assessed MutBERT and other foundation models on 18 datasets from the Nucleotide Transformer benchmark Dalla-Torre et al. (2024). These datasets include a mix of binary and multi-class classification tasks designed to provide a consistent evaluation framework for genomic models. The benchmark encompasses four primary tasks: Epigenetic Marks Prediction (EMP), Promoter Sequence Prediction (PSP), Enhancer Sequence Prediction (ESP), and Splice Site Prediction (SSP). Chromosomes 21 and 22 were reserved for testing, while the remaining chromosomes were used for fine-tuning. Most datasets involve binary classification tasks, with the exception of splice_sites_all and enhancers_types, which are multi-class classification tasks.

eQTL Variant Effect Prediction. The expression quantitative trait loci (eQTL) dataset used in this task is derived from Enformer Avsec et al. (2021) and Nucleotide Transformer Dalla-Torre et al. (2024). Each sample in the dataset consists of a reference sequence and an alternative sequence, with the mutation site located at the center. The output is a binary value referring to whether the variant has a causal effect on gene expression.

Context Length and Speed Optimization

Rotary Position Embedding (RoPE). Attention mechanisms are inherently permutation-invariant, requiring explicit positional information to capture the order of input sequences. RoPE offers an efficient and scalable alternative by encoding positional information directly into the attention mechanism through a rotation-based transformation. It introduces a rotation matrix to modulate the query and key vectors based on their positions. The transformation can be expressed in two-dimensional form as:

$$f(q,m) = qe^{im\theta} = \begin{pmatrix} \cos(m\theta) & -\sin(m\theta) \\ \sin(m\theta) & \cos(m\theta) \end{pmatrix} \begin{pmatrix} q_0 \\ q_1 \end{pmatrix} \tag{2}$$

where q represents the input vector, m is the position, and θ is a frequency parameter that varies with the dimension of the input. This mechanism ensures that the relative positional relationships between tokens are preserved during attention computation, as the rotation operation is inherently sensitive to distances between positions.

By incorporating RoPE, MutBERT efficiently handles longer sequences during fine-tuning and inference, despite its single-nucleotide tokenization. Unlike k-mer or BPE-based models, where each token represents multiple base pairs, MutBERT processes one nucleotide per token, resulting in higher token counts for the same sequence length. RoPE enables MutBERT to maintain fine-grained resolution while processing sequences comparable in length to those handled by other models, ensuring strong performance on both short and long sequences.

Dynamic Neural Tangent Kernel (NTK) Extrapolation. To extend RoPE for handling longer sequences, a dynamic scaling method was introduced Liu et al. (2023), where the scaling parameter α is adjusted dynamically based on the sequence length. For sequences shorter than or equal to the pretraining context length, the original positional encoding is used. For longer

sequences, the scale parameter α is modified according to the ratio of the current sequence length to the original pretraining context length, resulting in a progressively increasing scale as the sequence length grows. The scaling of α is computed as:

$$\alpha = \alpha_0 \times \frac{L_{\text{test}}}{L_{\text{train}}} - (\alpha_0 - 1) \tag{3}$$

Where α_0 is the initial scaling parameter, L_{test} is the sequence length during testing, and L_{train} is the sequence length used during training. The updated positional encoding θ is then computed as:

$$\theta = \theta_0 \times \alpha^{\text{dim}/(\text{dim}-2)} \tag{4}$$

Where θ_0 is the initial rotary parameter, and dim represents the dimensionality of the positional encoding.

Flash Attention. Flash Attention is an efficient algorithm designed to perform exact standard attention computations with reduced memory and time overhead. By minimizing IO operations between the GPU's fast on-chip memory and high-bandwidth memory, Flash Attention enables faster and more memory-efficient attention calculations. This is achieved by splitting Key, Query, and Value matrices into smaller blocks and incrementally computing the softmax operation. We utilized the publicly available Flash Attention implementation in PyTorch Paszke et al. (2019) to enhance the computational efficiency of MutBERT, allowing it to handle longer input sequences without compromising performance.

Low-Rank Adaptation (LoRA). Let $W_o, W \in \mathbb{R}^{m\times n}$ represent the original weight matrix before fine-tuning and the task-specific fine-tuned weight matrix, respectively. The relationship between them can be expressed as:

$$W = W_o + \Delta W \tag{5}$$

where $\Delta W \in \mathbb{R}^{m\times n}$ captures the task-specific updates to the weights. In conventional fine-tuning, every element in ΔW is updated independently, resulting in high computational and memory demands. LoRA addresses this by modeling ΔW using a low-rank decomposition, and only updates A and B:

$$\Delta W = BA \tag{6}$$

where $B \in \mathbb{R}^{m\times r}$, $A \in \mathbb{R}^{r\times n}$, and $r \ll \min(m, n)$. This decomposition reduces the number of trainable parameters from $m \times n$ to $r \times (m + n)$, substantially lowering the computational and memory requirements.

Finetune and Sequence Embedding

We used AdamW Loshchilov (2017) as the optimizer in all deep learning based finetuning tasks. Fine-tuning was performed for 1,000 steps, including 50 warm-up steps, with a batch size of 32. For MutBERT, DNABERT-2, NTv2-50M-Multi, NTv2-100M-Multi and NTv2-250M-Multi, we performed standard fine-tuning with a learning rate of 3e-5, while for larger Nucleotide Transformer variants, we applied LoRA with a learning rate of 1e-4, LoRA alpha of 16, LoRA dropout of 0.05, and LoRA r of 8. All models were trained using the Transformers library Wolf et al. (2020). Following established practice Zhou et al. (2023), we used Matthews correlation coefficient (MCC) Jurman et al. (2012) to evaluate model performance on TFBS and Nucleotide Transformer downstream datasets. During the training process, the model was validated every 200 steps. We implemented an early stopping strategy based on the Matthews correlation coefficient (MCC) metric, with a patience of 5 validation checks. Each model was trained using 3 different random seeds, and the average results across these runs are reported.

For the eQTL variant effect prediction task, we used area under the receiver operating characteristic curve (AUROC) as the evaluation metric. Following previous research Schiff et al. (2024); Kao et al. (2024), we extracted embeddings by averaging a 1,536 base pair window around the SNV positions in the reference and alternative sequences, then concatenating them along the channel dimension. Since the maximum supported sequence length varies by model, we used 12,000 base pairs for Nucleotide Transformer and 2,048 base pairs for DNABERT-2 to obtain embeddings. We also used 2048 base pairs for MutBERT. To achieve this, we extended MutBERT's sequence length from 512 to 2048. The embeddings were used to train an SVM with an RBF kernel, stratified by distance to the nearest transcription start site (TSS). For each TSS distance bucket, 5,000 training samples were randomly selected, and the AUROC was recorded on the test set. This process was repeated five times, and the average score was reported.

Model	Params.	Trn. Tokens	Tokenizer
DNABERT-2	117M	262B	BPE
NT-500M-Human	480M	50B	6-mer
NT-500M-1000G	480M	50B	6-mer
NT-2500M-Multi	2537M	300B	6-mer
NTv2-50M-Multi	56M	300B	6-mer
NTv2-100M-Multi	98M	300B	6-mer
NTv2-250M-Multi	235M	300B	6-mer
NTv2-500M-Multi	498M	300B	6-mer
MutBERT-Ref	86M	126B	Char
MutBERT	86M	126B	Char
MutBERT-Multi	86M	126B	Char

Table 2. The statistics of each model. The 3 columns represent the number of model parameters, the number of tokens and the tokenizer used in pre-training.

Results

To evaluate the effectiveness of our probabilistic genome representation and pretraining method, we compared MutBERT against state-of-the-art genomic language models, including DNABERT-2 and Nucleotide Transformer (NT), both of which represent leading MLM-trained foundation models for genomic data. Additionally, we included MutBERT-Ref and MutBERT-Multi to further dissect the impact of our newly proposed probabilistic genome representation. A summary of the models involved in this study is provided in Table 2. Most of these models contains more parameters than MutBERT.

We evaluated MutBERT and alternative models across 24 genomic datasets, with 23 assessed using the Matthews correlation coefficient (MCC) and one using the area under the receiver operating characteristic curve (AUROC). As shown in Fig. 2, MutBERT demonstrates strong performance across tasks assessed by the average MCC acorss 23 tasks, being only slightly

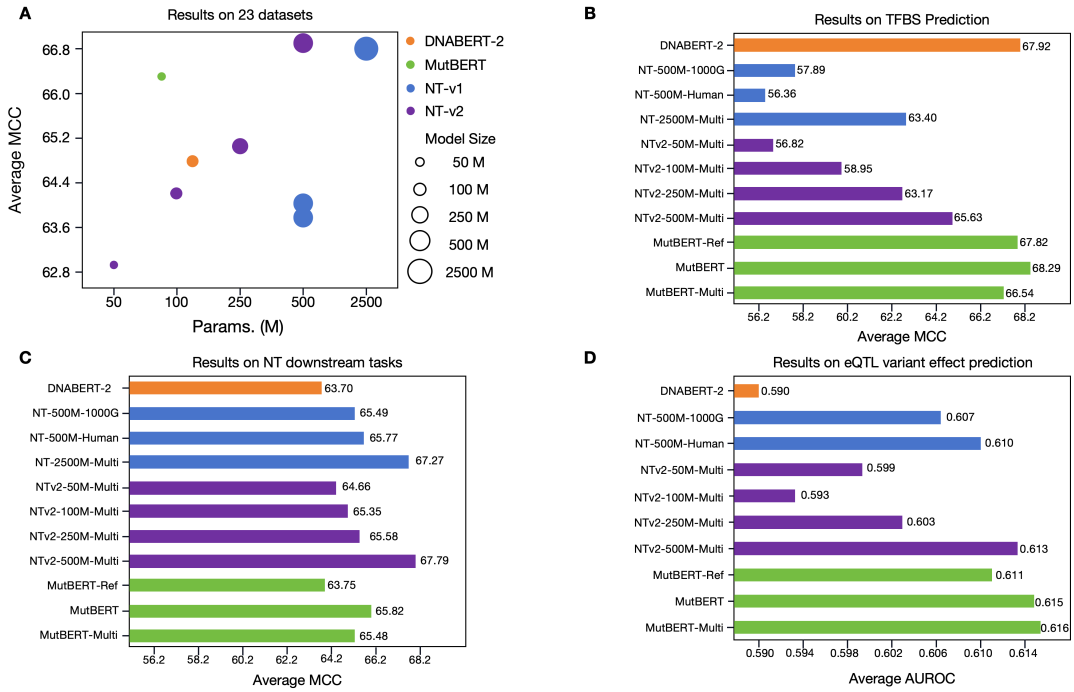

Fig. 2: Results on multiple downstream tasks

outperformed by two models with significantly larger parameter counts (Fig. 1a). Briefly, on the transcription factor binding site (TFBS) prediction task, MutBERT achieves the highest average MCC of 68.29, marginally surpassing DNABERT-2. Across the NT benchmark datasets, MutBERT achieves an average MCC of 65.82, outperforming DNABERT-2 and all Nucleotide Transformers trained exclusively on human data. It is only outperformed by Nucleotide Transformers with substantially more parameters and trained on more diverse datasets (e.g., NTv2-500M-Multi and NT-2500M-Multi). For the eQTL variant effect prediction task, evaluated using average AUROC, MutBERT achieves a score of 0.615, slightly trailing MutBERT-Multi. In addition, all three variants of MutBERT outperform many alternative models, particularly those with a comparable number of parameters. This highlights the effectiveness of our newly proposed model architecture, even when applied to models that take the reference genome sequence as input.

TFBS Prediction and Nucleotide Transformer Tasks

Table 3 summarizes the performance of MutBERT and other models on the TFBS and Nucleotide Transformer downstream tasks, both evaluated using MCC. Larger models generally perform better, with NT-2500M-Multi consistently ranking among the top two models across most tasks. MutBERT ranked third in average MCC across 23 tasks, showcasing its strong generalization capacity despite its smaller size. However, MutBERT was a top-performing model in only 5 out of 23 individual tasks.

Further analysis revealed that MutBERT performs consistently well across all tasks, achieving results comparable to or slightly below the top-performing models. DNABERT-2 excels in TFBS and histone modification prediction tasks, while Nucleotide Transformers outperform in splice site prediction. Despite its compact size of 86 million parameters, MutBERT shows strong performance across both types of tasks, highlighting its versatility.

Given that DNABERT-2 and Nucleotide Transformers primarily differ in tokenization methods, we hypothesize that BPE tokenization in DNABERT-2 is better suited for TFBS and histone modification predictions, whereas k-mer tokenization in NT is more effective for capturing individual base pair changes, as required for splice site prediction. Results from MutBERT-Ref suggest that single-nucleotide tokenization, as used in MutBERT, provides a balanced capability for both task types. Additionally, comparisons between MutBERT, MutBERT-Multi, and MutBERT-Ref highlight that the probabilistic genome representation used in MutBERT and MutBERT-Multi outperforms the deterministic reference genome sequence used in MutBERT-Ref in training genome language models.

eQTL Variant Effect Prediction

We compared MutBERT with DNABERT-2 and Nucleotide Transformers on the eQTL variant effect prediction task, evaluated using AUROC. Due to GPU limitations, NT-2500M-Multi was excluded from this comparison. As shown in Table 4, MutBERT outperforms alternative models in most of the three distance categories, highlighting its strong mutation detection capabilities. Notably, for long-distance predictions, MutBERT benefits from the robust extrapolation ability of ROPE, which enables it to handle sequences significantly longer than those encountered during pretraining.

Discussion and Conclusion

In this study, we introduced MutBERT, a probabilistic genome-based foundation model specifically designed to train genomic

Task	DNABERT-2	MutBERT-Ref	MutBERT	MutBERT-Multi	NT-500M-1000G*	NT-500M-Human*	NT-50M-Multi	NT-100M-Multi	NT-250M-Multi	NT-500M-Multi*	NT-2500M-Multi*
TF-0	70.43	**71.90**	68.53	70.53	65.02	61.64	61.52	65.61	70.02	66.40	65.20
TF-1	73.73	**76.26**	75.11	73.51	69.57	67.54	65.24	66.19	71.22	72.72	68.13
TF-2	**66.12**	58.27	58.63	60.98	47.31	49.89	53.60	54.69	61.17	62.85	60.21
TF-3	52.32	**60.56**	59.33	54.56	45.93	42.33	37.50	38.02	45.35	51.75	50.83
TF-4	77.00	72.13	**79.84**	73.14	61.63	60.41	66.23	70.26	68.11	74.41	72.62
H2AFZ	**52.79**	50.65	49.61	50.00	49.86	48.78	49.15	50.50	48.91	51.10	52.75
H3K27ac	50.1	51.30	50.25	48.96	46.24	50.11	50.49	46.97	48.84	50.59	**53.72**
H3K27me3	60.61	60.46	**62.07**	61.45	59.69	59.73	58.60	57.97	57.35	61.64	61.36
H3K36me3	63.88	61.7	62.76	62.18	58.80	61.93	59.69	60.77	60.53	65.26	**66.86**
H3K4me1	50.26	47.31	49.38	47.07	49.17	50.53	46.13	48.49	46.74	**51.31**	48.51
H3K4me2	57.45	57.30	57.30	57.17	54.34	52.12	52.63	53.44	53.41	**57.85**	56.83
H3K4me3	53.74	64.73	63.68	63.66	61.60	64.21	62.66	61.11	62.89	**65.50**	61.46
H3K9ac	55.18	51.9	52.06	52.97	50.94	52.22	50.42	45.55	53.64	54.96	**57.89**
H3K9me3	**52.24**	48.78	50.60	48.94	44.95	46.06	41.04	44.76	38.24	48.02	47.14
H4K20me1	64.33	65.42	65.78	66.7	62.01	65.62	64.82	62.65	65.28	**67.74**	67.46
Enhancer	54.31	52.47	51.26	51.9	57.18	59.02	53.01	56.57	55.13	**60.19**	57.85
Enhancer types	49.74	49.62	47.46	49.11	53.95	52.85	52.15	51.48	53.27	**55.65**	52.41
Promoter all	74.40	72.68	75.89	75.64	76.90	75.64	75.89	79.45	76.14	**78.32**	77.40
Promoter non-TATA	78.23	75.54	77.04	75.71	75.54	75.52	73.84	77.35	**79.17**	78.72	78.56
Promoter TATA	88.68	80.22	89.63	87.77	**91.71**	85.15	86.16	90.58	90.58	83.03	80.22
Splice acceptor	75.82	78.98	94.68	93.97	94.54	93.87	95.27	95.60	**96.53**	**96.53**	96.40
Splice site all	84.86	81.57	90.85	93.04	95.61	94.81	95.17	96.05	96.60	96.50	**96.90**
Splice donor	80.01	96.93	94.44	92.47	95.73	95.60	96.67	96.93	97.20	**97.27**	97.14
Avg	64.62	64.64	66.36	65.71	63.84	63.72	62.95	63.96	65.06	**67.32**	66.43

Table 3. Comparison of MCC on TFBS and NT downstream task predictions. Models with * are fine-tuned with LoRA.

model	Dist. to TSS: 0-30k	Dist. to TSS: 30k-100k	Dist. to TSS: 100k+	Avg
DNABERT-2	0.651	0.573	0.546	0.590
NT-500M-Human	0.671	0.605	0.553	0.610
NT-500M-1000G	0.669	0.582	0.570	0.607
NTv2-50M-Multi	0.661	0.591	0.546	0.599
NTv2-100M-Multi	0.663	0.553	0.562	0.593
NTv2-250M-Multi	0.663	0.595	0.552	0.603
NTv2-500M-Multi	0.663	0.608	0.567	0.613
MutBERT-Ref	0.670	0.595	0.569	0.582
MutBERT	**0.672**	0.605	0.568	0.615
MutBERT-Multi	0.667	**0.610**	**0.571**	**0.616**

Table 4. Comparison of AUROC on eQTL variant effect predicted by different models.

models on massive human genome data. Unlike previous approaches that often rely solely on individual genomes, MutBERT harnesses the diversity within population-scale genomic data by representing sequences as probabilistic distributions over allele frequencies. This innovative approach allows MutBERT to focus on informative genomic regions, effectively mitigate redundancy, and capture population-level genetic variation with greater fidelity.

Pre-trained exclusively on the human genome, MutBERT incorporates state-of-the-art techniques such as ROPE for efficient positional encoding, LoRA for parameter-efficient fine-tuning, and flash attention for computational optimization. We evaluated its performance across multiple downstream tasks using existing benchmarks, spanning 6 tasks and 24 datasets. Empirical results demonstrate that MutBERT consistently achieves competitive performance, securing top results in 5 of the 24 datasets and ranking among the leading models in the remaining benchmarks. These findings underscore MutBERT's robustness and its ability to generalize across diverse genomic tasks, all while maintaining computational efficiency. MutBERT's success stems from its ability to integrate population-level diversity into its training paradigm. For instance, consider a scenario where a model is trained on two human genomes. Traditional masked language modeling (MLM) methods would train the model to predict the most probable nucleotide at positions without single-nucleotide variants (SNVs) and assign high probabilities to observed alleles at positions with mutations. While effective, this approach often fails to fully utilize the richness of population-scale data. By contrast, MutBERT introduces a probabilistic framework that emphasizes allele frequencies, allowing the model to efficiently learn from population-level diversity without requiring explicit training on individual genomes.

This representation strategy treats each genomic position independently, which works well in datasets like the 1000 Genomes Project, where SNVs are typically rare and spatially dispersed. In most cases, only one SNV appears within a 512-bp input window, making independent representation sufficient for capturing genomic variation. However, challenges arise when applying this framework to multi species datasets, where regions often contain high densities of mutations. In such cases, MutBERT's independent representation may fail to capture co-variation across loci. Indeed, our results reveal that MutBERT's performance on multi species datasets was lower than its performance on the 1000 Genomes Project data, highlighting the need for future work to address these limitations.

Despite these limitations, MutBERT represents a significant advancement in genomic foundation modeling. Its probabilistic representation method enables efficient training and robust performance on population-scale genomic tasks. For example, our best-performing model, trained on the 1000 Genomes Project data, required only 6 days on 4 L20 GPUs, demonstrating its computational efficiency. However, we recognize that further studies are needed to explore the potential of scaling up MutBERT. We hypothesize that increasing its model size could further enhance its performance, potentially surpassing larger models while retaining its computational efficiency.

In conclusion, MutBERT sets a new standard for genomic representation learning by bridging the gap between computational efficiency and biological insight. Its innovations provide a strong foundation for leveraging biobank-scale genomic data.

Author contributions

W.L. and Y.Z. conceived the study. W.L., H.S., and J.X., performed analysis. Y.Z. supervised the project. W.L. and Y.Z. wrote the article. All authors read and approved the final article.

Acknowledgements

We thanks DNABERT-2's authors for their helps.

Competing interests

The authors declare no competing interests.

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