Whispering in Ol Chiki: Cross-Lingual Transfer Learning for Santali Speech Recognition

Anonymous ACL submission

Abstract

India, a country with a large population, possesses two official and twenty-two scheduled languages, making it the most linguistically diverse nation. Despite being one of the scheduled languages, Santali remains a low-resource language. Although Ol Chiki is recognized as the official script for Santali, many continue to use Bengali, Devanagari, Odia, and Roman scripts. In tribute to the upcoming centennial anniversary of the Ol Chiki script, we present an Automatic Speech Recognition for Santali in the Ol Chiki script. Our approach involves cross-lingual transfer learning by utilizing the Whisper framework pre-trained in Bengali and Hindi on the Santali language, using Ol Chiki script transcriptions. With the adoption of the Bengali pre-trained framework, we achieved a Word Error Rate (WER) score of 28.47 %, whereas the adaptation of the Hindi pre-trained framework resulted in a score of 34.50 % WER. These outcomes were obtained using the Whisper Small framework.

1 Introduction

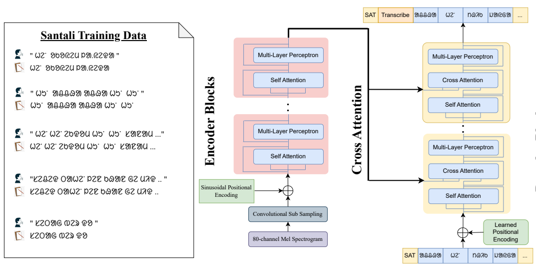

Figure 1: Overview of the Whisper-based ASR system fine-tuned for Santali speech recognition. The input audio is converted into an 80-channel Mel spectrogram and processed by convolutional sub-sampling and sinusoidal positional encoding. The encoder, composed of Transformer blocks with self-attention and multi-layer perceptrons, extracts audio features. The decoder, with self-attention, cross-attention, and learned positional encoding, generates character-level transcriptions in the Ol Chiki script, guided by cross-attention between encoder and decoder representations.

Speech recognition has emerged as an important technology in the field of human-computer interaction, bridging the gap between spoken language and digital systems. With the advent of advanced deep learning, Automatic Speech Recognition (ASR) systems have been significantly improved, achieving human-level performance for widely spoken languages such as English, Mandarin, and Spanish (Graves et al., 2013; Amodei et al., 2016; Baevski et al., 2020). However, developing robust ASR systems for low-resource languages remains a challenging task due to the scarcity of annotated datasets, linguistic resources, and pre-trained language models (Besacier et al., 2014; Arivazhagan et al., 2019). One such low-resourced language is Santali, which is predominantly spoken by approximately 7.6 million people in India, Bangladesh, Nepal, and Bhutan. Despite its recognition as one of India's important languages, technological advancements in speech processing for Santali are still in an early stage.

Existing research in speech recognition for low-resource languages have explored various modeling techniques, including Hidden Markov Models (HMM) (Rabiner, 1989), Gaussian Mixture Models (GMM) (Reynolds et al., 2009), and deep learning based frameworks such as Transformers and Convolutional Neural Networks (CNN) (Graves et al., 2006; Gulati et al., 2020). For instance, Singh et al. (2023) demonstrated the efficacy of model adaptation for Bengali and Bhojpuri, while Priya et al. (2022) improved ASR performance using sequence modelling and transformer-based spell correctors. Additionally, Shetty and Sagaya Mary N.J. (2020) highlighted the advantages of multilingual frameworks for low-resource Indian languages. Existing studies on Santali have focused on language processing tools, such as a finite-state morphological analyzer by Akhtar et al. (2017) and a dialect classifier using deep autoencoders by Sahoo et al. (2021). In ASR, Kumar et al.

(2020) showed that triphone models outperform monophone models for Santali digits in Roman script. However, despite these advancements, the development of ASR systems specifically developed for Santali remains largely unexplored. Existing approaches have either relied on Roman or regional scripts such as Bengali, Hindi, and Odia, neglecting the Ol Chiki script of Santali.

Our investigations distinguish themselves by focusing on Santali speech transcribed in the Ol Chiki script, unlike previous studies that used Roman script, bridging a crucial gap in ASR research. Our approach addresses these limitations by fine-tuning OpenAI's Whisper framework (Radford et al., 2022), a state-of-the-art (SOTA) ASR model. We used pre-trained in Bengali and Hindi, two linguistically and geographically proximate languages, to enhance the recognition of Santali phonetic patterns, applying cross-lingual transfer learning to improve ASR performance. Unlike previous works, we leverage Whisper's multilingual capabilities to adapt the model for Santali ASR for Ol Chiki script. This approach marks a significant step toward developing inclusive and accurate speech recognition systems for the Santali-speaking community, addressing both linguistic diversity and technological accessibility. Our work not only advances the field of low-resource ASR but also sets a precedent for future research on indigenous languages, ensuring that linguistic diversity is preserved and celebrated in the digital age.

Our Contributions: The primary contributions of our work are summarized as follows:

- We develop the first ASR system specifically for Santali speech in Ol Chiki script, marking a significant step toward digital inclusion for the Santali-speaking community.
- Our approach employs cross-lingual transfer learning by fine-tuning Whisper models pre-trained in Bengali and Hindi, achieving WERs of 28.47% and 34.50%, respectively, demonstrating the effectiveness of linguistic proximity in low-resource scenarios.
- We provide a comprehensive evaluation of various Whisper model sizes (Tiny, Base, Small, Medium, Large), mentioning the trade-offs between model complexity and recognition performance.
- We studied the impact of LoRA-based parameter efficient fine-tuning on various Whisper model (Tiny, Base, Small, Medium, Large).

2 Language Perspective

The official script for the Santali language is Ol Chiki. Pandit Raghunath Murmu proposed the script in 1925. The shapes of the Ol Chiki characters are believed to be inspired by nature, physical forms, and the daily life of the Santals. The same principle applies to the sounds represented by these symbols. For example, the pronounced sound /at/ (ᱚ) is depicted by a circle, whose shape symbolizes the earth, and the meaning of the sound matches this representation. Likewise, the letter /ut/ (ᱩ) resembles the shape and sound of a mushroom. Ol Chiki is written from left to right and consists of six vowels and twenty-four consonants with five basic diacritics. The letters are arranged in a 6 by 5 matrix, where the first letter of each row, or the first column, represents the vowels, while the remaining letters are consonants. Furthermore, three vowels can be formed using the diacritic /gahla tudag/ (.), which can follow the vowels /la/ (ᱚᱹ), /laa/ (ᱟᱹ), and /le/ (ᱮᱹ). The diacritic /mu tudag/ (ᱸ) nasalized vowels, and the combination of /mu tudag/ (ᱸ) and /gahla tudag/ (.) create a nasalized version of a newly formed vowel. The other three diacritics—/rela/ (ᱻ), /phaarkaa/ (ᱼ), and /ahad/ (ᱽ) —serve as a length marker, glottal protector, and deglottalization, respectively. Ol Chiki also includes two punctuation marks, /mucaad/ (᱾) and double /mucaad/ (᱿), both used in poetry, while only /mucaad/ (᱾) is employed in prose to indicate the end of a sentence. Latin punctuation marks such as commas, question marks, exclamation marks, parentheses, and quotation marks are also utilized. Lastly, Ol Chiki employs the decimal number system and has its own set of numerals (᱐, ᱑, ᱒, ᱓, ᱔, ᱕, ᱖, ᱗, ᱘, ᱙).

Despite belonging to a different language family, the prolonged interaction between Santali speakers and those of Indo-Aryan languages such as Bengali, Odia, and Hindi has led to some similarities in speech. However, Santali retains its uniqueness in fundamental linguistic structure, grammar, and vocabulary. Here are some key areas of similarity in speech:

1. Sentence Structure and Syntax
   - Subject-Object-Verb (SOV) Order
     Like Bengali, Odia, and Hindi, Santali follows the SOV word order. The sentences in all four languages typically place the subject first, followed by the object, and the verb at the end.

2. Pronunciation and Accent
   - Consonant Sounds:
     Santali exhibits patterns of aspirated and unaspirated consonants comparable to those found in Bengali, Odia, and Hindi. The aspirated sounds (like /p$^{\mathrm{h}}$/ (ᱯᱦ), /b$^{\mathrm{h}}$/ (ᱵᱦ), /k$^{\mathrm{h}}$/ (ᱠᱦ)) in these languages contribute to a similar pronunciation style, particularly in formal or deliberate speech. Additionally, the retroflex consonants characteristic of Hindi and Odia are also present in Santali.
   - Nasalization:
     Santali displays a significant use of nasalized sounds, a feature also found in Bengali and, to a lesser extent, Odia. This nasalization influences the pronunciation of vowels, imparting a melodic quality comparable to that of the spoken forms of these languages. Although Hindi has fewer nasalized vowels compared to Santali and Bengali, nasalization does occur in specific contexts.

3. Intonation and Rhythm
   - Melodic Patterns:
     Santali and Bengali, in particular, possess a melodious and flowing intonation that gives the spoken languages a softer and more rhythmic quality. Odia exhibits a similar trait in informal conversation, whereas Hindi tends to be more monotonic and straightforward. Although the tonal quality of Santali speech is not as pronounced as in tonal languages, it has been shaped by the influence of neighboring languages, especially Bengali.
   - Stress and Lengthening of Syllables:
     The inclination to elongate specific syllables in both Santali and Bengali contributes to a rhythmic quality in their speech. For example, vowel lengthening is a prevalent feature in spoken Bengali and Santali, where vowels are extended in certain contexts for emphasis or to adhere to the phonological rules of the language. Although Odia exhibits some of this trait, Hindi generally features less vowel elongation.

4. Code-Switching and Borrowed Vocabulary
   - Shared Loanwords
     As a result of significant interaction between the Santali-speaking community and speakers of Bengali, Odia, and Hindi, Santali has adopted numerous words from these languages, particularly for contemporary concepts, administration, and technology. In urban or bilingual settings, speakers frequently code-switch between Santali and the neighboring Indo-Aryan languages.

3 Methodology

Task Description: The objective of this study is to develop an ASR system tailored specifically for the Santali language in the Ol Chiki script. Given an audio input sequence $X = \{x_1, x_2, \ldots, x_T\}$, $x_t \in \mathbb{R}^d$, where T is the number of time steps and d is the feature dimension, the system aims to predict the corresponding text transcription. The goal is to generate a sequence of characters $Y = \{y_1, y_2, \ldots, y_L\}$, $y_l \in \mathcal{V}$, where L is the number of characters and $\mathcal{V}$ denotes the vocabulary of Ol Chiki characters. The ASR model aims to maximize the conditional probability $P(Y \mid X; \theta) = \prod_{l=1}^{L} P(y_l \mid X, y_1, \ldots, y_{l-1}; \theta)$, where θ denotes the model parameters.

3.1 Encoder-Decoder Framework

Our proposed ASR system is built upon Whisper (Radford et al., 2022) framework, which is an encoder-decoder model. Overview of our framework is shown in Figure 1. The model is fine-tuned on Santali speech data using cross-lingual transfer learning from pre-trained Bengali and Hindi models due to proximity and phonetic similarities.

Feature Extraction: The audio waveform is first preprocessed to standardize the input features. Each audio sample is resampled to a sampling rate of 16 kHz and converted to a 16-bit mono channel. Then, an 80-channel log-Mel spectrogram, $X \in \mathbb{R}^{T \times 80}$ is computed, for the input to the encoder.

Encoder: The encoder processes the input spectrogram using N Transformer blocks. Each block consists of a multi-head self-attention layer and a feedforward neural network with residual connections:

$$H_0 = X,$$

$$H_n = \text{LayerNorm}\big(H_{n-1} + \text{SelfAttention}(H_{n-1})\big)$$

$$H_n = \text{LayerNorm}\big(H_n + \text{FFN}(H_n)\big), n = 1, \ldots, N$$

where $\text{SelfAttention}(H)$ is computed as:

$$\text{SelfAttention}(Q, K, V) = \text{softmax}\left(\frac{QK^T}{\sqrt{d_k}}\right)V$$

with query Q, key K, and value V matrices obtained from the input H.

Decoder: The decoder autoregressively generates text output one token at a time by applying masked multi-head attention. Given the encoded representation H_N, the decoder generates output tokens as:

$$Z_0 = \text{Embedding}(y_{\text{<start>}})$$

$$Z_l = \text{LayerNorm}(Z_{l-1} + \text{MaskedAttention}(Z_{l-1}))$$

$$Z_l = \text{LayerNorm}(Z_l + \text{CrossAttention}(Z_l, H_N)),$$
$$l = 1, \ldots, L$$

where $\text{CrossAttention}(Z, H_N)$ is defined as:

$$\text{CrossAttention}(Q, K, V) = \text{softmax}\left(\frac{QK^T}{\sqrt{d_k}}\right)V$$

Finally, a linear layer followed by a softmax function is applied to predict the next character:

$$P(y_l \mid X, y_1, \ldots, y_{l-1}) = \text{softmax}(W_o Z_l + b_o)$$

Training Procedure: The model is fine-tuned using the cross-entropy loss function:

$$\mathcal{L} = -\sum_{l=1}^{L} \log P(y_l \mid X, y_1, \ldots, y_{l-1})$$

The final layer of the pre-trained Whisper Small model is fine-tuned while all other layers are frozen.

Inference: During inference, the decoder generates tokens sequentially using greedy decoding:

$$\hat{y}_l = \arg\max_{y_l \in \mathcal{V}} P(y_l \mid X, \hat{y}_1, \ldots, \hat{y}_{l-1})$$

4 Experiment Set Up

4.1 Dataset Description

For experimental validation, we used the Santali Speech Dataset with the Ol Chiki script transcriptions, compiled from two sources which is publicly accessible: Mozilla Common Voice[1] (Ardila et al., 2020) and AI4Bharat IndicVoices (Javed et al., 2024). On average, Common Voice training segments are 4.8 seconds long (~6 words), while IndicVoices training segments are longer at 6.2 seconds (~12 words). For evaluation, we used the Common Voice test Set which span 5.3 seconds (~6 words) on average. Dataset statistics for training, validation, and test splits are provided in Table 1.

[1]Latest Common Voice dataset was extracted on July 03, 2025, from Link.

Table 1: Summary of the Santali speech corpus used for training and evaluation. The table lists the number of audio samples in the training, validation, and test sets. Note that the test set for IndicVoices is not yet released ([a]).

Sl. No.	Corpus Name	Train	Valid	Test
1	IndicVoices (Javed et al., 2024)	19,779	249	-[a]
2	Common Voice (Ardila et al., 2020)	333	68	127
	Total	20,112,	317	127

4.2 Research Questions

To systematically investigate the effectiveness of cross-lingual transfer learning for ASR in the Santali language using the Ol Chiki script, we formulate the following research questions. These questions aim to analyze the impact of source language proximity, model architecture size, dataset characteristics, and fine-tuning strategies on the overall performance of the adapted Whisper models.

- **RQ1:** Which language, Bengali or Hindi, provides better cross-lingual transfer learning performance for Santali speech recognition, and what factors contribute to this difference?
- **RQ2:** How does the model size (Tiny, Base, Small, Medium, Large) influence the WER when fine-tuned with Bengali and Hindi pre-trained models, and why does the Small variant outperform others?
- **RQ3:** How do different datasets (Common Voice vs. IndicVoices) affect the fine-tuning performance of the Whisper model, and what dataset characteristics contribute to the observed WER differences?
- **RQ4:** How does Parameter Efficient Fine-Tuning (PEFT), specifically LoRA fine-tuning, perform on low-resource dataset scenarios, and what factors contribute to the observed results?

4.3 Implementation Details

Table 2: Architecture parameter(s) of the Whisper framework

Framework	No. of Layers	Width	No. of Heads	Parameters
Tiny	4	384	6	39M
Base	6	512	8	74M
Small	12	768	12	244M
Medium	24	1024	16	769M
Large	32	1280	20	1550M

The training parameters of the Whisper framework are summarized in Table 2. Fine-tuning was performed using a learning rate of 1×10^{-5} with the "AdamW" optimizer. Training was done for 40 epochs with a batch size of 16. Only the final layer was updated during training, while all other layers were frozen. Since Santali is not among the supported languages in Whisper, we used models pre-trained in Bengali and, for comparison, also fine-tuned a Hindi pre-trained model on Santali data. The Bengali and Hindi pretraining refers to the internal representation already available in Whisper for these languages, not separate fine-tuned checkpoints. Our codes are available in following Link[2].

5 Results

In this section, we provides all the findings of the experiments. For evaluation purposes, we used the Common Voice Test set that contains 127 samples.

Table 3: WER (in %) of different Whisper model variants without fine-tuning, using Bengali and Hindi pre-trained checkpoints on the Santali speech dataset. This table provides baseline performance across model sizes before any task-specific adaptation.

Framework	**Bengali pre-Trained without Fine-Tuning**	**Hindi pre-Trained without Fine-Tuning**
Tiny	201.12	201.12
Base	197.05	197.05
Small	111.64	111.64
Medium	115.99	115.99
Large	**108.42**	**108.42**

Table 3 provides the evaluation results of Whisper frameworks done on the Bengali pre-trained and Hindi pre-trained models. The results show that the increase in parameter sizes decreases the WER but yet is unable to recognise the required transcriptions. This is due to the non-presence of the Santali language in Whisper-trained languages.

Language Comparison: Bengali vs. Hindi (RQ1): In response to **RQ1**, Tables 4 and 5 shows that the Bengali pre-trained Whisper Small model achieves a lower WER (28.47%) compared to the Hindi pre-trained model (34.50%) on Common Voice Training Dataset. This performance gap is due to the greater phonetic and syntactic similarity between Bengali and Santali, such as shared vowel nasalization, consonant structures, and SOV word order, which facilitates more effective model adaptation during fine-tuning. Similarly, using IndicVoices Training Dataset, fine-tuned Whisper Base model for both Bengali pre-trained (54.28%) and Hindi pre-trained (53.30%) shows similar results. This is due to the increase in robust Dataset sample, which provides a low-parameter model to optimise.

[2]https://anonymous.4open.science/r/Santali-ASR-6585/

Table 4: Performance comparison (WER in %) of Whisper model variants fine-tuned on the Common Voice Santali corpus, using Bengali and Hindi pre-trained checkpoints. The table highlights model-wise effectiveness after full fine-tuning across both source languages.

Framework	**Bengali pre-Trained with Full Fine-Tuning**	**Hindi pre-Trained with Full Fine-Tuning**
Tiny	118.09	102.81
Base	101.54	98.04
Small	**28.47**	**34.50**
Medium	93.27	129.73
Large	32.96	35.34

Table 5: WER (in %) of trained IndicVoices Santali Corpus on Whisper Frameworks in the Bengali and Hindi pre-trained language.

Framework	**Bengali pre-Trained with Full Fine-Tuning**	**Hindi pre-Trained with Full Fine-Tuning**
Tiny	62.55	111.08
Base	**54.28**	**53.30**
Small	57.36	54.84
Medium	99.86	100.00
Large	117.67	112.06

Impact of Model Size (RQ2): For **RQ2**, Tables 4 and 5 show that the Bengali pre-trained Whisper Small model achieves the lowest WER—28.47% and Bengali pre-trained Whisper Small model 34.50%, outperforming both smaller (Tiny, Base) and larger (Medium, Large) variants. Its balanced architecture (12 layers, 768 hidden dimensions) allows it to capture phonetic patterns without overfitting effectively. In contrast, larger models are harder to optimize with limited data, while smaller ones lack sufficient capacity to model complex linguistic features. It also suggests that smaller models can capture complex linguistic feature if it is provided with robust large datasets.

Dataset Influence: Common Voice vs. IndicVoices (RQ3): For **RQ3**, Tables 4 and 5 show that fine-tuning on the Common Voice dataset yields lower WERs (28.47% for Bengali pretrained Whisper model, 34.50% for Hindi pretrained Whisper model) than IndicVoices (54.28% and 53.30%, respectively). This performance gap is likely due to Common Voice's shorter utterances (4.8 seconds, ~6 words), which allow for more precise alignment

Table 6: Performance comparison (WER in %) of the proposed Whisper-based models against state-of-the-art IndicConformer systems across Common Voice and IndicVoices datasets. The table summarizes results from both full fine-tuning and LoRA-based parameter-efficient tuning across different model sizes and pre-training languages.

Model Name	Pretrained on	cf.	Dataset	WER
IndicConformer-CTC[2]			IndicVoices	53.04
IndicConformer-RNNT[2]			IndicVoices	50.78
Whisper Full Finetune Small	Bengali	Table 4	Common Voice	**28.47**
Whisper Full Finetune Small	Hindi	Table 4	Common Voice	34.50
Whisper Full Finetune Base	Bengali	Table 5	IndicVoices	54.28
Whisper Full Finetune Base	Hindi	Table 5	IndicVoices	53.30
Whisper LoRA Finetune Large	Bengali	Table 7	Common Voice	61.43
Whisper LoRA Finetune Medium	Hindi	Table 7	Common Voice	98.60
Whisper LoRA Finetune Small	Bengali	Table 8	IndicVoices	121.18
Whisper LoRA Finetune Large	Hindi	Table 8	IndicVoices	134.36

between audio and text. In contrast, the longer and more variable utterances in IndicVoices (6.2 seconds, ~12 words) introduce complexity that challenges the model during training.

Table 7: Performance comparison (WER in %) of Whisper model variants fine-tuned using LoRA on the Common Voice Santali corpus, with Bengali and Hindi as source pre-trained languages. The table presents the impact of parameter-efficient fine-tuning across different model sizes.

Framework	Bengali pre-Trained with LoRA Fine-Tuning	Hindi pre-Trained with LoRA Fine-Tuning
Tiny	113.04	131.00
Base	185.41	158.35
Small	101.26	121.80
Medium	62.97	**98.60**
Large	**61.43**	99.58

Table 8: Performance comparison (WER in %) of Whisper model variants fine-tuned using LoRA on the IndicVoices Santali corpus, based on Bengali and Hindi pre-trained checkpoints. The table highlights model-wise adaptation under parameter-efficient fine-tuning in a low-resource setting.

Framework	Bengali pre-Trained with LoRA Fine-Tuning	Hindi pre-Trained with LoRA Fine-Tuning
Tiny	268.16	374.47
Base	134.92	108.56
Small	**121.18**	211.92
Medium	188.36	364.38
Large	126.51	**134.36**

LoRA Finetuning (RQ4): To address RQ4, we evaluate the impact of LoRA-based parameter-efficient fine-tuning using Bengali and Hindi pre-trained Whisper models across different model sizes, as shown in Tables 7 and 8. A clear trend emerges where larger models (e.g., Medium and Large) consistently outperform smaller ones (Tiny, Base, Small) under LoRA fine-tuning, particularly on the Common Voice dataset. This can be attributed to the fact that larger models possess greater capacity to retain and adapt relevant linguistic patterns even when only a subset of parameters specifically in the attention layers—is updated. However, despite this relative gain, none of the LoRA tuned models match the performance of their fully fine-tuned counterparts, underscoring LoRA's limited expressiveness when operating under strict parameter constraints. The degradation is more noticeable on the IndicVoices dataset, where longer and acoustically varied utterances challenge the model's ability to generalize, especially when the fine-tuning signal is narrow. These results suggest that while LoRA offers an efficient and stable training paradigm suitable for large models in low-resource scenarios, it struggles to fully adapt to complex linguistic and phonetic variations without broader parameter updates.

For Benchmarking, we evaluated our results with state-of-the-art IndicConformer[3] framework proposed by AI4Bharat. IndicConformer is a multilingual 130M conformer based model following the same architecture as proposed by Tjandra et al. (2023). Table 6 shows the benchmarking results.

6 Error Analysis

While metrics like Word Error Rate (WER) offer a broad view of model accuracy, they often miss the specific types of errors that impact usability. To address this, we analyzed individual outputs from the Bengali Common Voice evaluation set to bet-

[3]Model is available at https://huggingface.co/ai4bharat/indicconformer_stt_sat_hybrid_ctc_rnnt_large.

Table 9: Example of prediction errors and their types.

Sl. No.	Reference Sentence	Predicted Sentence	Error Type	WER (%)
1	ᱥᱮᱨᱢᱟᱜ ᱵᱥᱚᱥᱩ ᱫᱳ ᱠᱟᱮᱥᱱᱦ ᱠᱟᱮᱟ।	ᱥᱮᱨᱢᱟᱜ ᱵᱥᱚᱥᱩ ᱫᱳ ᱠᱥᱮᱱᱟᱮ ᱠᱟᱮᱟ।	Consonant substitution ("ᱠᱟᱮᱥᱱᱦ" → "ᱠᱥᱮᱱᱟᱮ")	20.0
2	ᱥᱮᱨᱢᱟᱜ ᱵᱥᱚᱥᱩ ᱫᱳ ᱠᱦᱟᱢᱞᱨᱢᱟᱣ ᱠᱟᱮᱟ।	ᱥᱮᱨᱢᱟᱜ ᱵᱥᱚᱥᱩ ᱫᱳ ᱠᱟᱢᱞᱨᱢᱟ ᱠᱟᱮᱟ।	Suffix omission (missing "ᱣ")	20.0
3	ᱥᱮᱨᱢᱟᱜ ᱵᱥᱚᱥᱩ ᱫᱳ ᱠᱤᱜᱟᱮ ᱠᱟᱮᱟ।	ᱥᱮᱨᱢᱟᱜ ᱵᱥᱚᱥᱩ ᱫᱳ ᱠᱤᱝᱟᱮ ᱠᱟᱮᱟ।	Phonetic confusion ("ᱜ" → "ᱝ")	20.0
4	ᱟᱝ ᱛᱟᱛᱟ ᱴᱥᱮᱜᱤᱯ ᱚᱥᱞᱥᱢ ᱱᱟᱠᱟ ᱤᱩᱟ ᱫᱤᱢᱟᱢ।	ᱟᱝ ᱛᱟᱛᱟ ᱴᱥᱮᱜᱤᱯ ᱚᱥᱞᱥᱢ ᱱᱟᱠᱟ ᱤᱩᱟ ᱫᱤᱢᱟᱢ।	No error	0.0
5	ᱥᱮᱨᱢᱟᱜ ᱵᱥᱚᱥᱩ ᱫᱳ ᱠᱯᱨᱮᱤ ᱠᱟᱮᱟ।	ᱥᱮᱨᱢᱟᱜ ᱵᱥᱚᱥᱩ ᱫᱳ ᱠᱯᱨᱮᱤ ᱠᱟᱮᱟ।	No error	0.0

ter understand where the model performs well and where it breaks down. This sections shows the Error Analysis of our best model i.e. Whisper Small pre-trained in Bengali. Table 9 shows examples of Common Errors the model made.

This qualitative analysis revealed a number of patterns that highlight both strengths and weaknesses of the system.

- Confusion Between Similar Sounding Characters
  In many cases, the model confused characters that sound alike, especially in fast or informal speech. For instance:
  Predictions : ᱥᱮᱨᱢᱟᱜ ᱵᱥᱚᱥᱩ ᱫᱳ ᱠᱤᱡᱣᱟᱮᱛᱟ ᱠᱟᱮᱟ।
  Reference : ᱥᱮᱨᱢᱟᱜ ᱵᱥᱚᱥᱩ ᱫᱳ ᱠᱤᱢᱡᱣᱟᱮᱛᱟ ᱠᱟᱮᱟ।
  WER: 20.0%
  Here, the model missed "ᱢ" before "ᱡ", likely due to phonetic similarity. Although the sentence is still mostly correct, this minor change subtly alters pronunciation and fluency.

- Errors in Suffixes and Grammatical Particles
  Bengali and Santali heavily rely on suffixes and particles to convey tense, mood, and case. The model often mishandled these either by dropping, altering, or misplacing them.
  Predictions : ᱥᱮᱨᱢᱟᱜ ᱵᱥᱚᱥᱩ ᱫᱳ ᱠᱯᱟᱢᱤᱮᱟ ᱠᱟᱮᱟ।
  Reference : ᱥᱮᱨᱢᱟᱜ ᱵᱥᱚᱥᱩ ᱫᱳ ᱠᱯᱟᱨᱮᱤ ᱠᱟᱮᱟ।
  WER: 20.0%
  The substitution of "ᱨᱮᱤ" with "ᱢᱤᱮᱟ" suggests that the model has trouble preserving proper suffix morphology, especially in contexts where nasalization or tense is involved.

- Insertions and Omissions in Longer Sentences
  With longer sentences, the model occasionally skipped words or inserted unnecessary ones. These kinds of structural issues were more pronounced in complex phrases.
  Predictions : ᱛᱤᱜ ᱱᱦᱤᱜ ᱩᱨᱫᱡᱟᱢ ᱟᱞᱤ ᱜᱤᱯ ᱴᱤ ᱱᱟᱠᱟ ᱜᱤ ᱡᱟᱞᱤᱝ ᱠᱟᱮᱟ।
  Reference : ᱛᱤᱠ ᱱᱦᱤᱮ ᱩᱨᱫᱡᱟᱢ ᱟᱞᱤ ᱜᱤᱯ ᱴᱤ ᱱᱟᱠᱟ ᱜᱤ ᱡᱟᱞᱤᱝ ᱠᱟᱮᱟ।
  WER: 20.0%
  The replacement of "ᱛᱤᱠ" with "ᱛᱤᱜ" and "ᱱᱦᱤᱮ" with "ᱱᱦᱤᱜ" changed the meaning of the sentence and introduced fluency issues. Such mistakes indicate that the model may have difficulty aligning longer sequences during decoding.

- Difficulty with Morphologically Complex Words
  In morphologically rich contexts, particularly those involving compounding or inflections, the model's performance dropped. This is a known challenge in low-resource settings and was reflected in errors like this:
  Predictions : ᱥᱮᱨᱢᱟᱜ ᱵᱥᱚᱥᱩ ᱫᱳ ᱠᱤᱛᱞᱨᱮ ᱠᱟᱮᱟ।
  Reference : ᱥᱮᱨᱢᱟᱜ ᱵᱥᱚᱥᱩ ᱫᱳ ᱠᱤᱛᱞᱢᱨᱮ ᱠᱟᱮᱟ।
  WER: 20.0%
  Here, the model omits the "ᱢ" character in "ᱠᱤᱛᱞᱢᱨᱮ", possibly simplifying the form but in doing so, losing grammatical correctness.

From these examples, we can see that the model generally performs well on shorter, simpler sentences, but its accuracy declines when handling:

- Phonetic similarities that lead to substitutions
- Morphological variations, particularly in suffixes and particles
- Longer utterances where insertions and omissions become more common

These issues highlight the challenges of working with morphologically rich and phonologically complex languages, such as Santali, especially under low-resource conditions.

7 Conclusions & Future Work

This paper has presented an initial, but important, effort in developing an ASR system for Santali using the Ol Chiki script. By fine-tuning the Whisper framework with cross-lingual transfer learning on Bengali and Hindi, we have demonstrated the feasibility of creating accurate speech recognition models for under-resourced languages. Our findings indicate that fine-tuning the Whisper Small model on the Common Voice dataset yields the most promising results, achieving WERs of 28.47% and 34.50% with Bengali and Hindi pre-training, respectively. These results demonstrate that transfer learning offers a viable path to address the ASR challenges faced by under-resourced languages, significantly improving access to digital technologies for their speakers by preserving linguistic diversity. Although this study provides a strong foundation for Santali ASR, several areas are unexplored for future research. These include:

- **Expanding Training Data.** The performance of the ASR system could be further improved by increasing the size and diversity of the Santali speech dataset.
- **Exploring Other Pre-trained Models.** While this work focused on Bengali and Hindi pre-trained models, exploring other linguistically related languages could potentially yield better results.
- **Adapting the Model for Different Accents and Dialects.** Santali exhibits regional variations in pronunciation and vocabulary. Future research could focus on adapting the ASR system to better handle these variations through techniques such as transfer learning or domain adaptation.
- **Incorporating a Language Model.** Integrating a language model trained on Santali text data could help improve the accuracy of the ASR system by providing contextual information and reducing word error rates.

By addressing these challenges and pursuing these future research directions, we can further advance the Santali ASR field and contribute to preserving and promoting this valuable language.

Limitations

Our study makes a meaningful contribution to speech technology for the Santali language, but it has certain limitations. These include

- The scope of our experiments is constrained by the limited size and diversity of available Santali speech data, particularly in the "Ol Chiki" script. This limitation may impact the generalisation of the model to broader dialectal and acoustic variations within the Santali-speaking population.
- Although our approach leverages cross-lingual transfer from Bengali and Hindi due to their linguistic proximity to Santali, these source languages are not perfectly aligned regarding phonetic and syntactic characteristics. As a result, some Santali-specific nuances may not be fully captured by the adapted models.
- The evaluation is limited to the Whisper Small variant. Although we briefly explored models of varying sizes, comprehensive tuning and optimization of larger or alternative architectures were outside the scope of this work due to computational constraints.

Acknowledgments

We are deeply grateful to the Santali-speaking community, whose language and culture continue to inspire this work. This research is especially dedicated to the Ol Chiki script, created by Pandit Raghunath Murmu in 1925. As *the centenary of the Ol Chiki script is being celebrated in 2025*, we hope our work contributes meaningfully to the growing movement to bring Santali onto the digital map and celebrate its unique linguistic identity.

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