# Cross-Linguistic Phonological Similarity Analysis in Sign Languages Using HamNoSys

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## Abstract

This paper presents a cross-linguistic analysis of phonological similarity in sign languages using symbolic representations from the Hamburg Notation System (HamNoSys). We construct a dataset of 1000 signs each from British Sign Language (BSL), German Sign Language (DGS), French Sign Language (LSF), and Greek Sign Language (GSL), and compute pairwise phonological similarity using normalized edit distance over HamNoSys strings. Our analysis reveals both universal and language-specific patterns in handshape usage, movement dynamics, non-manual features, and spatial articulation. We explore intra and inter-language similarity distributions, phonological clustering, and co-occurrence structures across feature types. The findings offer insights into the structural organization of sign language phonology and highlight typological variation shaped by linguistic and cultural factors.

## 1 Introduction

Sign languages (SLs) are complex visual-gestural languages that convey meaning through a combination of hand configurations, movements, orientations, and spatial locations (Sinha, 2009). Unlike spoken languages, sign languages lack a standardized written form (Langer et al., 2014), making computational analysis and cross-linguistic comparison particularly challenging. One of the foundational aspects of sign language linguistics is phonology-the study of minimal visual units that distinguish signs. Phonological modeling in sign languages has been a growing area of interest in computational linguistics and sign language processing. Early work focused on rule-based systems and handcrafted features to capture phonological components such as handshape, location, and movement (Stokoe, 1960; Brentari, 1998). These approaches laid the foundation for formal linguistic analysis but lacked scalability and cross-linguistic generalization.

This paper addresses the problem of identifying signs that are phonologically similar within and across multiple sign languages. Specifically, we focus on four major sign languages: British Sign Language (BSL), German Sign Language (DGS), French Sign Language (LSF), and Greek Sign Language (GSL). For each language, we construct a dataset of 1000 signs, each annotated with its phonological structure using the Hamburg Notation System (HamNoSys) (Prillwitz and für Deutsche Gebärdensprache und Kommunikation Gehörloser, 1989). We compute pairwise phonological similarity between all sign pairs using a normalized edit distance over their HamNoSys representations, resulting in a $1000 \times 1000$ similarity matrix per language.

Unlike prior work that focuses on building computational models for sign recognition or translation (Cihan Camgoz et al., 2017; Camgoz et al., 2018; Stoll et al., 2020; Saunders et al., 2020; Chen et al., 2022), our objective is to perform a detailed analytical study of phonological similarity patterns. We explore intra-language and inter-language similarity distributions, identify phonological clusters, and investigate the structural properties of the resulting similarity matrices. Our findings offer insights into the phonological organization of signs and provide a foundation for future work in multilingual sign language processing.

### 1.1 Overview of HamNoSys

The Hamburg Notation System (HamNoSys) (Prillwitz and für Deutsche Gebärdensprache und Kommunikation Gehörloser,



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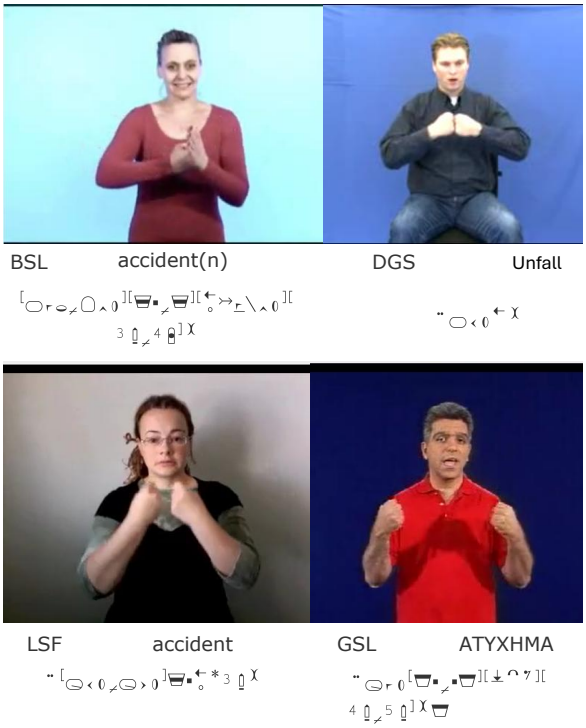


Figure 1: Phonological representation (using HamNoSys) of the word "ACCEIDENT" across different languages.

1989) has emerged as a powerful tool for representing sign language phonology in a language-independent manner. It has been used in various applications, including sign synthesis (Hanke, 2004), avatar animation (Efthimiou et al., 2009), and sign language corpora annotation (Crasborn and Zwitserlood, 2008). It encodes the phonological structure of signs using a linear sequence of symbols that describe the following key features (See figure 2 for sample Hamnosys based phonological features):

**Handshape**: The configuration of the fingers and palm (e.g., `FlatOpen`, `Fist`, `Claw`).

**Location**: The spatial region of the body where the sign is articulated (e.g., `Chest`, `Forehead`, `NeutralSpace`).

**Orientation**: The direction the palm and fingers face during the sign (e.g., `Inward`, `Outward`, `Downward`).

**Movement**: The trajectory, type, and repetition of motion (e.g., `UpDown`, `Circle`, `Sideways`).

Apart from these, there are non-manual features representing facial expressions, head and body posture, and eye gaze. Each sign is represented as a structured string of HamNoSys symbols, allowing for symbolic comparison and computational processing. For example figure 1 depicts the sign representation for the word "Accident". Note that every language has its own phonological patterns of representing the same concept. Also, see Appendix A for explanation of each HamNoSys symbols.

Although these signs differ only in the movement component, such a variation can lead to a different meaning. HamNoSys enables the isolation and comparison of these phonological components, making it a powerful tool for cross-linguistic phonological analysis.

In this study, we leverage HamNoSys to compute phonological similarity between signs using a normalized edit distance metric. This approach allows us to quantify how similar two signs are based on their symbolic phonological structure, independent of signer-specific or visual noise.

## 2 Related Work

Recent studies have explored the use of HamNoSys for computational tasks. For example, Morrissey (2008) used HamNoSys and its SiGML encoding as the intermediate representation in a spoken-to-sign language MT pipeline, while Efthimiou et al. (2010) leveraged it for multilingual sign language resources. Sugandhi et al. (2020) proposed a HamNoSys-based avatar generation approach for text-to-ISL translation. Several other efforts have continued this line of research: Neves et al. (2020) developed a conversion toolkit from HamNoSys to SiGML to support avatar animation; Walsh et al. (2022) introduced transformer baselines for directly translating spoken language text to HamNoSys sequences, demonstrating advantages over gloss-only representations; and Bhagwat et al. (2024) presented a Marathi↔ISL translation pipeline adopting HamNoSys as an intermediate phonetic layer for synthesis. Foundational descriptions such as Hanke (2004) further highlight HamNoSys as a machine-readable phonetic notation beneficial for MT and sign avatar generation.

In the domain of sign similarity, Ormel et al. (2010) proposed methods for measur-

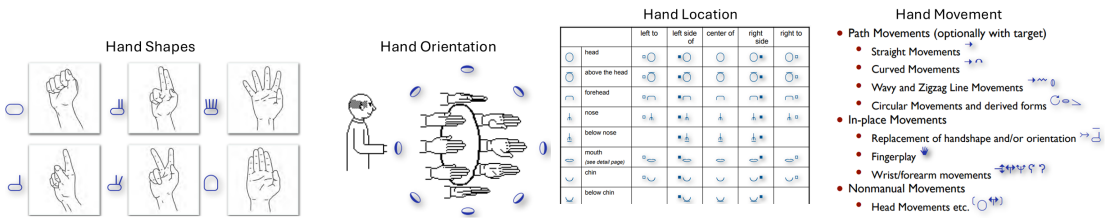


Figure 2: Examples of HamNoSys for hand shape, orientation, location and movement (Hanke, 2010)

ing phonological distance using feature-based representations, but their work was limited to small datasets and single-language settings. More recent work has explored neural models for sign similarity (Camgoz et al., 2020), though these approaches often rely primarily on visual features without explicit phonological grounding. To address this gap, Williams et al. (2017) operationalized phonological similarity by quantifying shared manual parameters, demonstrating psycholinguistic correlates of such similarity measures. Further advances have integrated phonological structure into neural models: Tavella et al. (2022) introduced the WLASL-LEX dataset annotated with phonological properties and showed that graph-based neural networks can recognize phonological features at scale; Rodriguez et al. (2023) proposed a phonological distance metric ("phdist") over fourteen phonological specifications in NGT and used it to analyze deep sign embeddings; and Kezar et al. (2023) demonstrated that incorporating phonological representations improves isolated sign recognition performance on the Sem-Lex benchmark. These works highlight increased attention toward phonologically grounded representations in computational modelling of sign similarity.

Our work differs in that it focuses on symbolic phonological similarity across multiple sign languages using HamNoSys. By constructing large-scale similarity matrices and performing analytical studies, we aim to uncover structural patterns in sign language phonology that are both linguistically meaningful and computationally tractable.

## 3 Dataset Construction

The dataset used in this study is derived from the publicly available **Dicta-Sign Language Resources** (Efthimiou et al., 2012), a multilingual repository of sign language data developed as part of the Dicta-Sign project. The resource provides a curated list of over 1000 concepts, each annotated with corresponding signs and phonological representations in four European sign languages: British Sign Language (BSL), German Sign Language (DGS), French Sign Language (LSF), and Greek Sign Language (GSL).

For each of the four languages, we selected 1000 signs corresponding to a shared set of concepts. Each sign is associated with a HamNoSys transcription that encodes its phonological structure, including handshape, location, orientation, and movement. These symbolic representations serve as the foundation for computing phonological similarity.

To quantify phonological similarity, we compute the normalized Levenshtein distance (Yujian and Bo, 2007) between HamNoSys strings. Given two signs $i$ and $j$ with HamNoSys representations $H_i$ and $H_j$, the similarity score $S_{ij}$ is defined as:

$$S_{ij} = 1 - \frac{d_{\text{lev}}(H_i, H_j)}{\max(|H_i|, |H_j|)} \quad (1)$$

where $d_{\text{lev}}$ denotes the Levenshtein edit distance between the two strings, and $|H_i|$ is the length of the string. This results in a similarity score in the range $[0, 1]$, where 1 indicates identical phonological structure.

For each language, we construct a $1000 \times 1000$ similarity matrix $\mathbf{S}^{(l)}$ capturing all pairwise phonological similarities. These matrices form the basis for the analytical tasks described in the next section.

## 4 Analysis and Results

We present a comprehensive analysis of phonological similarity patterns within and across four sign languages: British Sign Language (BSL), German Sign Language (DGS), French Sign Language (LSF), and Greek Sign Language (GSL). Each language's dataset consists

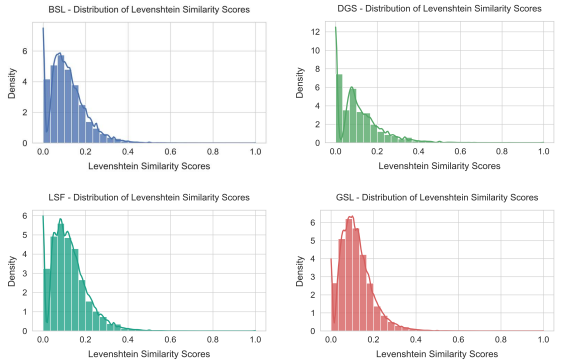


Figure 3: Intra-language phonological similarity distributions for BSL, DGS, LSF, and GSL.

of 1000 signs, and a $1000 \times 1000$ similarity matrix was computed using normalized edit distance over HamNoSys representations.

### 4.1 Intra-Language Similarity Distributions

Figure 3 shows the distribution of similarity scores within each language. All distributions are left-skewed, indicating that most sign pairs are moderately dissimilar, with a smaller proportion of highly similar signs. Notably, DGS and LSF exhibit slightly higher concentrations of high-similarity pairs, suggesting more phonologically compact lexicons.

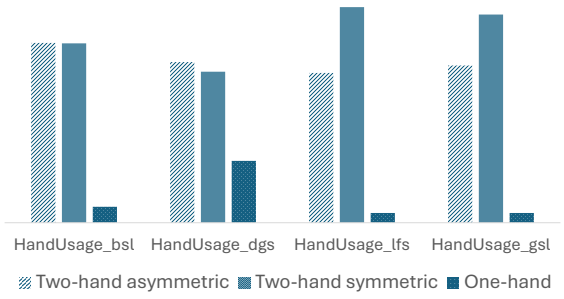


Figure 4: Intra-language hand-usage frequency for BSL, DGS, LSF, and GSL.

### 4.2 Phonological Clustering

To explore the internal structure of each language's phonological space, we applied hierarchical clustering on each similarity matrix. Figure 5 show the resulting clusters (only for the sake of clear visualization, we show the clustering results on a $100 \times 100$ subset). Clear block structures emerge, indicating the presence of phonological families—groups of signs that share similar handshapes, locations, or movements.

| Language | Mean | Std Dev | Min | Max |
|---|---|---|---|---|
| BSL | 0.115 | 0.084 | 0.000 | 1.000 |
| DGS | 0.112 | 0.106 | 0.000 | 1.000 |
| LSF | 0.122 | 0.085 | 0.000 | 1.000 |
| GSL | 0.118 | 0.075 | 0.000 | 1.000 |

Table 1: Summary statistics of phonological similarity scores

Table 1 present the mean, standard deviation, and range of similarity scores for each language. LSF and GSL show the highest average similarity, while DGS exhibits the widest spread, indicating greater phonological diversity.

### 4.3 One-hand vs Two-hand Sign Analysis

The Figure 4 presents the distribution of signs based on hand usage—categorized into one-handed signs, two-handed symmetric signs, and two-handed asymmetric signs—across British Sign Language (BSL), German Sign Language (DGS), French Sign Language (LSF), and Greek Sign Language (GSL). A clear trend emerges: all four languages predominantly use two-handed signs, with symmetric and asymmetric configurations being nearly equally represented. For instance, BSL shows a near-even split between symmetric (461) and asymmetric (462) two-handed signs, while LSF and GSL lean slightly toward symmetric usage. In contrast, one-handed signs are significantly less frequent, especially in LSF and GSL (only 25 each), whereas DGS shows a relatively higher count (159), suggesting a greater preference or flexibility for one-handed articulation in German Sign Language. This distribution highlights both universal tendencies and language-specific variations in sign formation, which may reflect linguistic, cultural, or ergonomic factors influencing sign language structure.

### 4.4 Phonological analysis across language

Table 2 showing the top 5 handshapes, movements, non-manual signs, and sign locations across British Sign Language (BSL), German Sign Language (DGS), French Sign Language

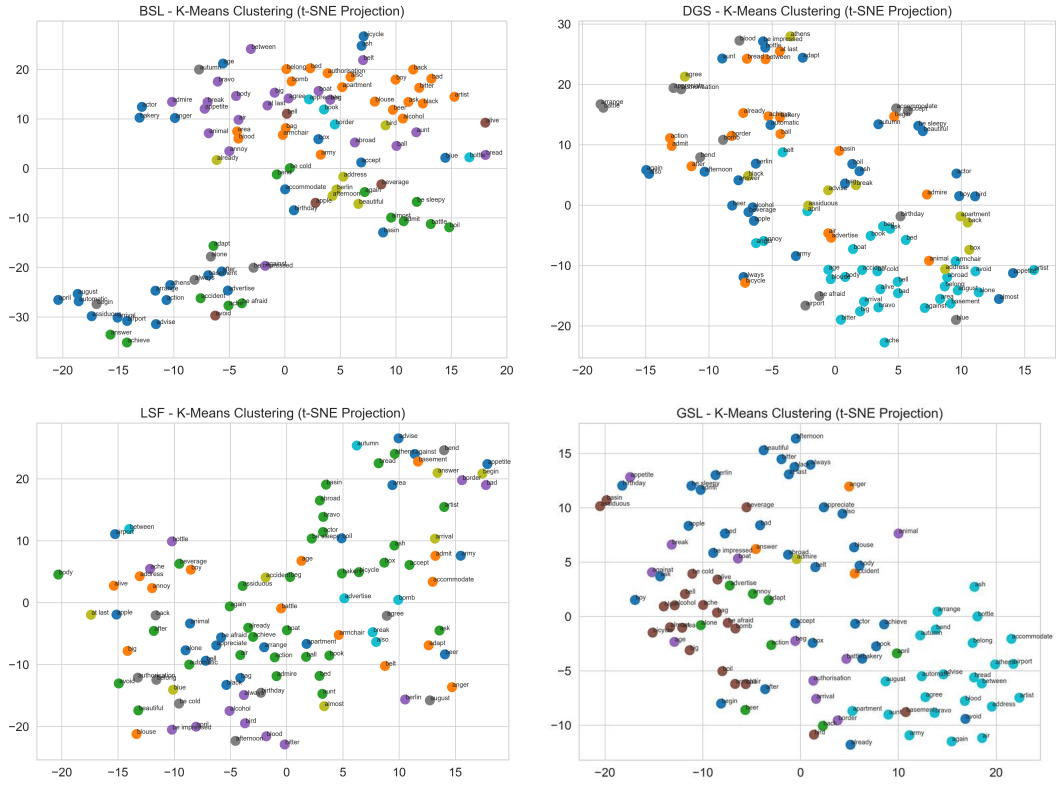


Figure 5: Phonological similarity using k-means clustering across languages. Same colored points belong to same cluster.

(LSF), and Greek Sign Language (GSL). The data reveals both shared and language-specific preferences in phonological features across the four sign languages.

**Handshapes (HS):** The handshapes hamthumboutmod, hamflathand, and hamfinger2 appear consistently across all languages with hamthumbacrossmod appearing in BSL, LSF, and GSL, indicating a core set of frequently used configurations. BSL and LSF favor hamthumboutmod most prominently. DGS and GSL show a high preference for hamflathand. DGS uniquely includes hamfist in its top 5, suggesting a more frequent use of closed hand configurations.

**Movements (MOV):** Universal dominance: hamrepeatfromstart is the most frequent movement across all four languages, highlighting repetition as a common linguistic strategy. hammoved and hammoveo are consistently present, but their ranks vary. GSL shows a higher frequency of hamfast, possibly reflecting a faster signing tempo or stylistic variation. LSF and GSL include hamrepeatfromstartseveral, suggesting more complex repetition patterns.

**Non-Manual Features (NMA):** BSL, LSF, and GSL emphasize hamshoulders and hamchest, indicating upper torso involvement. Moreover, GSL shows the highest counts for hamchest and hamshoulders, suggesting strong reliance on torso-based non-manual cues. DGS has lower counts overall and includes hamchin and hamhead, pointing to more facial involvement.

**Sign Locations (LOC):** hambetween (likely referring to the space between hands or between signer and viewer) is dominant in BSL and GSL, suggesting spatial articulation is central. DGS and LSF favor hampalml and hampalmd, indicating signs are often articulated near the palm or lower body. hamsymmlr and hamextfingeru appear across multiple languages, reflecting symmetrical and extended finger placements.

These patterns suggest that while there is a shared phonological core across sign languages—especially in handshapes and movements suggesting inter-language phonological similarity—each language exhibits

unique tendencies in non-manual features and spatial articulation. This supports the idea that sign languages, though visually grounded, are shaped by distinct linguistic and cultural norms.

| Category | Features | BSL | DGS | LSF | GSL |
|---|---|---|---|---|---|
| HS | hamthumboutmod | 666 | 216 | 543 | 646 |
| | hamthumbacrossmod | 464 | 0 | 490 | 631 |
| | hamflathand | 448 | 343 | 350 | 656 |
| | hamfinger2 | 345 | 219 | 326 | 445 |
| | hamfinger2345 | 298 | 0 | 0 | 401 |
| | hamfist | 0 | 208 | 0 | 0 |
| | hamfingerstraightmod | 0 | 269 | 289 | 0 |
| MOV | hamrepeatfromstart | 232 | 298 | 260 | 232 |
| | hammoved | 210 | 211 | 187 | 216 |
| | hammoveo | 134 | 105 | 115 | 165 |
| | hammover | 134 | 103 | 115 | 0 |
| | hammoveu | 109 | 0 | 0 | 0 |
| | hammoveor | 0 | 81 | 0 | 0 |
| | repeatfromstartseveral | 0 | 0 | 125 | 160 |
| NMA | hamshoulders | 341 | 91 | 376 | 456 |
| | hamchest | 259 | 81 | 377 | 495 |
| | hamshouldertop | 99 | 0 | 115 | 135 |
| | hamneck | 75 | 0 | 0 | 0 |
| | hamstomach | 66 | 0 | 48 | 75 |
| | hamchin | 0 | 58 | 0 | 0 |
| | hamhead | 0 | 27 | 0 | 0 |
| | hamlips | 0 | 25 | 56 | 49 |
| LOC | hambetween | 903 | 0 | 318 | 937 |
| | hampalml | 543 | 401 | 494 | 543 |
| | hampalmd | 509 | 317 | 498 | 491 |
| | hamextfingeru | 462 | 0 | 448 | 413 |
| | hamsymmlr | 375 | 330 | 320 | 552 |
| | hamextfingerol | 0 | 336 | 0 | 0 |

Table 2: Frequency distribution of the most frequent sign language phonological features across languages.

### 4.5 Intra-Phonological Co-occurrences

Insights derived from the co-occurrence (pointwise mutual information, PMI) table across four sign languages—BSL, DGS, LSF, GSL—focusing on phonological feature interactions revels that Across all languages, high PMI values are observed between compound or modified handshapes (e.g., hamthumboutmod, hamceeopen, hamfingerside), indicating that these handshapes frequently co-occur in signs with complex articulatory configurations. DGS shows strong co-occurrence between hamfingerpad and hamthumbball (PMI = 5.59±0.035), suggesting a preference for precision grip-like configurations. LSF and GSL both show high PMI between hamceeopen and hamfingerside, indicating a shared structural tendency toward open, lateral hand articulations. GSL also exhibits strong co-occurrence between hamceeopen and hamfingernail, hinting at a visual emphasis on finger extension and orientation.

The highest PMI values in hand-location category are found in LSF (hamextfingerdi-hamextfingeri, PMI = 6.91±0.043) and DGS (hamarmextended-hamextfingerdi, PMI = 5.91±0.037), suggesting frequent use of extended arm and finger configurations in spatial articulation. GSL shows strong co-occurrence between hamarmextended and hamextfingerir (PMI = 5.59±0.035), indicating a preference for distal articulation zones. Across all languages, combinations involving hamhandback, hamwristback, and hamextfinger variants suggest a consistent use of backward or lateral orientations in sign production.

Movement features show the highest PMI values overall, with DGS (hamclockdr-hamclocku, PMI = 9.91±0.061) and GSL (hamcircleil-hamstirccw, PMI = 8.91±0.055) demonstrating highly structured temporal motion patterns. Circular and clock-like movements (hamcircle, hamclock, hamstir) dominate across all languages, indicating a shared visual rhythm in sign articulation. These patterns suggest that cyclic and directional movements are central to sign semantics and may serve as phonological markers for verb or action-related signs.

Non-manual features show lower PMI values overall, indicating more diffuse or context-dependent usage. BSL shows the strongest co-occurrence (hameyes-hamnose, PMI = 4.30±0.027), suggesting facial articulation plays a significant role in sign contrast. LSF and GSL show moderate co-occurrence between hamchin, hamhead, and hamneck, pointing to a layered use of facial and neck gestures. DGS shows relatively low PMI values, possibly reflecting a more manual-centric phonological system or less reliance on facial features.

### 4.6 Inter-Phonological Co-occurrence

As depicted in Table 3 We also analyze how different category of phonological features interact among themselves. For example, how handshapes interact with movements, or locations in a particular language's signing space. We found BSL and GSL show higher co-occurrence between hamthumboutmod and

| | BSL | | DGS | | LSF | | GSL | |
|---|---|---|---|---|---|---|---|---|
| Type | Pairs | Freq | Pairs | Freq | Pairs | Freq | Pairs | Freq |
| HS + LOC | hamthumboutmod-hampalml | 259 | hamflathand-hamextfingerol | 122 | hamthumboutmod-hampalml | 211 | hamthumboutmod-hambetween | 259 |
| | hamthumboutmod-hambetween | 249 | hamflathand-hampalml | 107 | hamthumbacrossmod-hampalmd | 180 | hamthumboutmod-hamsymmlr | 248 |
| | hamthumboutmod-hamsymmlr | 227 | hamflathand-hampalmd | 102 | hamthumboutmod-hampalmd | 172 | hamflathand-hambetween | 229 |
| | hamthumboutmod-hampalmd | 208 | hamfist-hampalml | 97 | hamthumbacrossmod-hamextfingeru | 165 | hamflathand-hamsymmlr | 229 |
| | hamthumbacrossmod-hamextfingeru | 190 | fingerstraightmod-hamsymmlr | 97 | hamthumbacrossmod-hampalml | 143 | hamthumboutmod-hampalml | 225 |
| HS+ NMA | hamthumboutmod-hamrepeatfromstart | 111 | hamfingerstraightmod-hamrepeatfromstart | 89 | hamthumboutmod-hamrepeatfromstart | 104 | hamthumboutmod-hamrepeatfromstart | 90 |
| | hamthumboutmod-hammoved | 99 | hamfist-hamrepeatfromstart | 75 | hamthumbacrossmod-hamrepeatfromstart | 91 | hamthumbacrossmod-hamrepeatfromstart | 87 |
| | hamthumbacrossmod-hamrepeatfromstart | 95 | hamflathand-hamrepeatfromstart | 65 | hamfingerstraightmod-hamrepeatfromstart | 79 | hamflathand-hamrepeatfromstart | 86 |
| | hamflathand-hamrepeatfromstart | 75 | fingerstraightmod-hammoved | 62 | hamthumboutmod-hammoved | 79 | hamthumboutmod-hamfast | 84 |
| | hamfinger2-hamrepeatfromstart | 67 | hamfinger2-hamrepeatfromstart | 62 | hamthumbacrossmod-hammoved | 75 | hamthumboutmod-hammoved | 79 |
| HS+ NMA | hamthumboutmod-hamshoulders | 166 | hamthumboutmod-hamchest | 29 | hamthumboutmod-hamchest | 163 | hamthumbacrossmod-hamshoulders | 181 |
| | hamthumboutmod-hamchest | 139 | hamfinger2345-hamchest | 25 | hamthumboutmod-hamshoulders | 137 | hamthumboutmod-hamchest | 173 |
| | hamthumbacrossmod-hamshoulders | 101 | fingerstraightmod-hamshoulders | 22 | hamthumbacrossmod-hamshoulders | 133 | hamflathand-hamchest | 166 |
| | hamflathand-hamshoulders | 99 | hamflathand-hamshoulders | 22 | hamflathand-hamchest | 113 | hamthumboutmod-hamshoulders | 159 |
| | hamflathand-hamchest | 90 | hamthumboutmod-hamshoulders | 21 | hamthumbacrossmod-hamchest | 105 | hamthumbacrossmod-hamchest | 155 |
| MOV+ LOC | hamrepeatfromstart-hampalml | 119 | hamrepeatfromstart-hampalml | 124 | hamrepeatfromstart-hampalml | 108 | hamrepeatfromstart-hambetween | 135 |
| | hamrepeatfromstart-hambetween | 113 | hamrepeatfromstart-hamsymmlr | 101 | hamrepeatfromstart-hamextfingeru | 100 | hamrepeatfromstart-hamsymmlr | 124 |
| | hammoved-hamsymmlr | 90 | hammoved-hampalml | 92 | hamrepeatfromstart-hampalmd | 92 | hamrepeatfromstart-hampalml | 113 |
| | hamrepeatfromstart-hamextfingeru | 88 | hamrepeatfromstart-hamextfingerol | 90 | hammoved-hampalml | 83 | hamfast-hambetween | 113 |
| | hammoved-hampalml | 88 | hammoved-hamextfingerol | 79 | hammoved-hampalmd | 78 | hammoved-hambetween | 112 |
| MOV+ NMA | hamrepeatfromstart-hamshoulders | 76 | hammoved-hamshoulders | 35 | hammoved-hamshoulders | 81 | hammoved-hamchest | 93 |
| | hammoved-hamshoulders | 56 | hamrepeatfromstart-hamshoulders | 20 | hamrepeatfromstart-hamshoulders | 78 | hamrepeatfromstart-hamchest | 88 |
| | hammoved-hamchest | 53 | hamrepeatfromstart-hamchin | 20 | hammoved-hamchest | 73 | hammoved-hamshoulders | 81 |
| | hamrepeatfromstart-hamchest | 53 | hamrepeatfromstart-hamchest | 20 | hamrepeatfromstart-hamchest | 65 | hamhalt-hamshoulders | 80 |
| | hammover-hamshoulders | 34 | hammoved-hamchest | 13 | repeatfromstartseveral hamshoulders | 53 | hamrepeatfromstart-hamshoulders | 77 |
| NMA+ LOC | hamshoulders-hambetween | 168 | hamshoulders-hamsymmlr | 46 | hamshoulders-hampalml | 148 | hamchest-hambetween | 260 |
| | hamshoulders-hampalml | 151 | hamchin-hampalml | 42 | hamshoulders-hampalmd | 146 | hamchest-hamsymmlr | 236 |
| | hamshoulders-hamsymmlr | 142 | hamchin-hamextfingerul | 37 | hamchest-hampalmd | 140 | hamshoulders-hamsymmlr | 235 |
| | hamchest-hambetween | 137 | hamchest-hampalml | 35 | hamchest-hampalml | 129 | hamshoulders-hambetween | 229 |
| | hamshoulders-hampalmd | 121 | hamshoulders-hamextfingeruo | 34 | hamchest-hamextfingero | 122 | hamchest-hampalml | 206 |

Table 3: Frequency distributions of co-occurrences of phonological features across different sign languages.

spatial locations like hampalml, hambetween, and hamsymmlr, suggesting that this handshape is highly versatile and frequently used in central signing space. DGS favors combinations like hamflathand-hamextfingerol and hamflathand-hampalml, indicating a preference for flat hand configurations in extended or lateral orientations. LSF shows similar patterns to BSL, with hamthumboutmod and hamthumbacrossmod frequently paired with hampalml and hampalmd, reflecting a balanced use of thumb-based handshapes in mid-body locations.

Across all languages, hamrepeatfromstart is the most frequent movement paired with dominant handshapes (hamthumboutmod, hamthumbacrossmod, hamflathand), reinforcing its role as a core phonological motion. BSL and LSF show strong pairings of hamthumboutmod with both hamrepeatfromstart and hammoved, suggesting a dynamic use of thumb-based signs. GSL includes hamfast in its top co-occurrences, indicating a tendency toward rapid articulation in certain handshape-movement combinations.

BSL, LSF, and GSL show strong co-occurrence between hamthumboutmod and upper-torso cues, while GSL uniquely favors hamthumbacrossmod-hamshoulders and hamflathand-hamchest, reflecting rich manual–non-manual integration. DGS, with lower overall frequencies and modest pairings like hamfinger2345-hamchest, suggests a more manual-centric system.

hamrepeatfromstart usually co-occurs with hampalml, hambetween, and hamsymmlr across all languages, confirming its central role in spatially anchored sign articulation. GSL shows strong pairings of hamfast with hambetween, suggesting a preference for fast, centrally located signs. BSL, DGS and LSF include extended finger orientations (like hamextfingeru, hamextfingerol) in frequent pairings, indicating a nuanced use of directional movement.

Co-occurrence between hamrepeatfromstart and hamshoulders or hamchest is common in BSL, LSF, and GSL, reinforcing the idea that repetitive movements are often accompanied by expressive non-manual cues. GSL shows the highest integration, with hammoved-hamchest and hamrepeatfromstart-hamchest appearing frequently, suggesting a significant coupling of motion and torso-based expression. DGS shows lower frequencies and more facial-centric pairings (e.g., hamrepeatfromstart-hamchin), indicating a different balance of articulatory features.

BSL and GSL show high co-occurrence between hamshoulders and hambetween, suggesting that upper-body non-manual features are often used in central signing space. LSF shows high frequencies for hamchest-hampalml and hamshoulders-hampalmd, indicating a preference for mid-body articulation zones. DGS includes more facial and lateral pairings (e.g., hamchin-hampalml, hamchin-hamextfingerul), reflecting a more distributed use of non-manual features.

In summary we observe that BSL and GSL exhibit strong centralization in signing space, with frequent use of hambetween and upper torso non-manuals. DGS shows a more distributed and facially oriented phonological structure, with lower integration of non-manuals and more lateral articulations. LSF balances manual and non-manual features with a preference for mid-body locations and thumb-based handshapes. These patterns reveal universal tendencies and regional variations in phonological feature co-occurrence, offering insights into the structural and cultural shaping of sign languages.

## 5 Conclusion

We analyzed phonological similarity across four sign languages using HamNoSys-based symbolic representations. By comparing 1000 signs per language, we identified consistent patterns in handshape, movement, and spatial usage, along with notable differences in non-manual features and articulation styles. Co-occurrence analysis revealed strong intra- and inter-feature dependencies, suggesting both universal phonological structures and geo-linguistic variation. LSF and DGS show higher internal consistency, and sign clustering reveals phonological families—laying the groundwork for multilingual sign language modeling and cross-linguistic phonological transfer. All these observations are based on raw frequency counts; formal statistical testing will be included in future work.

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## A HamNoSys Explanations

Table 4 shows the detailed explanation and category of what each HamNoSys symbol means along with its unicode (Neves et al., 2020).

| HamNoSys | Unicode | Explanation | Category |
|---|---|---|---|
| hamspace | 0020 | Space separator (used to separate symbols or words). | Other |
| hamexclaim | 0021 | Punctuation marker (e.g., exclamation, comma, full stop, question) for transcriptions. | Other |
| hamcomma | 002C | Punctuation marker (e.g., exclamation, comma, full stop, question) for transcriptions. | Other |
| hamfullstop | 002E | Punctuation marker (e.g., exclamation, comma, full stop, question) for transcriptions. | Other |
| hamquery | 003F | Punctuation marker (e.g., exclamation, comma, full stop, question) for transcriptions. | Other |
| hamaltbegin | 007B | Alternative/parenthetical markers used to bracket alternate transcriptions or metadata. | Other |
| hammetaalt | 007C | Alternative/parenthetical markers used to bracket alternate transcriptions or metadata. | Other |
| hamaltend | 007D | Alternative/parenthetical markers used to bracket alternate transcriptions or metadata. | Other |
| hamfist | E000 | Fist handshape (closed hand). | Hand Shapes |
| hamflathand | E001 | Flat handshape (palm and fingers extended and close together, like a flat hand). | Hand Shapes |
| hamfinger2 | E002 | Two-finger configuration (usually index+middle extended). | Hand Shapes |
| hamfinger23 | E003 | Two adjacent fingers extended (index+middle) in non-spread configuration. | Hand Shapes |
| hamfinger23spread | E004 | Two adjacent fingers extended and spread apart (index+middle spread). | Hand Shapes |
| hamfinger2345 | E005 | Fingers 2 5 extended (index through little finger), excluding thumb. | Hand Shapes |
| hampinch12 | E006 | Pinch-like handshape (thumb and one or more fingers pinching together). | Hand Shapes |
| hampinchall | E007 | Pinch-like handshape (thumb and one or more fingers pinching together). | Hand Shapes |
| hampinch12open | E008 | Pinch-like handshape (thumb and one or more fingers pinching together). | Hand Shapes |
| hamcee12 | E009 | C-shaped hand configuration (curved hand like letter 'C'). | Hand Shapes |
| hamceeall | E00A | C-shaped hand configuration (curved hand like letter 'C'). | Hand Shapes |
| hamceeopen | E00B | C-shaped hand configuration (curved hand like letter 'C'). | Hand Shapes |
| hamthumboutmod | E00C | Thumb pointed outwards (thumb extended away from palm) a thumb position modifier. | Hand Shapes |
| hamthumbacrossmod | E00D | Thumb lying across the palm or fingers a thumb position modifier. | Hand Shapes |
| hamthumbopenmod | E00E | Thumb held open (not tucked in) modifier for thumb openness. | Hand Shapes |
| hamfingerstraightmod | E010 | Handshape specifying particular fingers extended. | Hand Shapes |
| hamfingerbendmod | E011 | Handshape specifying particular fingers extended. | Hand Shapes |
| hamfingerhookmod | E012 | Handshape specifying particular fingers extended. | Hand Shapes |
| hamdoublebent | E013 | Modifier for double-bent or double-hooked finger shapes (complex finger bend). | Hand Shapes |
| hamdoublehooked | E014 | Modifier for double-bent or double-hooked finger shapes (complex finger bend). | Hand Shapes |
| hamextfingeru | E020 | Finger direction marker extended finger points up (used to show finger orientation). | Location/Orientation |
| hamextfingerur | E021 | Finger direction marker extended finger points up-right (used to show finger orientation). | Location/Orientation |

| HamNoSys | Unicode | Explanation | Category |
|---|---|---|---|
| hamextfingerr | E022 | Finger direction marker extended finger points right (used to show finger orientation). | Location/Orientation |
| hamextfingerdr | E023 | Finger direction marker extended finger points down-right (used to show finger orientation). | Location/Orientation |
| hamextfingerd | E024 | Finger direction marker extended finger points down (used to show finger orientation). | Location/Orientation |
| hamextfingerdl | E025 | Finger direction marker extended finger points down-left (used to show finger orientation). | Location/Orientation |
| hamextfingerl | E026 | Finger direction marker extended finger points left (used to show finger orientation). | Location/Orientation |
| hamextfingerul | E027 | Finger direction marker extended finger points up-left (used to show finger orientation). | Location/Orientation |
| hamextfingerol | E028 | Finger direction marker extended finger points out-left (used to show finger orientation). | Location/Orientation |
| hamextfingero | E029 | Finger direction marker extended finger points out/away (used to show finger orientation). | Location/Orientation |
| hamextfingeror | E02A | Finger direction marker extended finger points out-right (used to show finger orientation). | Location/Orientation |
| hamextfingeril | E02B | Finger direction marker extended finger points in-left (used to show finger orientation). | Location/Orientation |
| hamextfingeri | E02C | Finger direction marker extended finger points in/toward (used to show finger orientation). | Location/Orientation |
| hamextfingerir | E02D | Finger direction marker extended finger points in-right (used to show finger orientation). | Location/Orientation |
| hamextfingerui | E02E | Finger direction marker extended finger points up-in (used to show finger orientation). | Location/Orientation |
| hamextfingerdi | E02F | Finger direction marker extended finger points down-in (used to show finger orientation). | Location/Orientation |
| hamextfingerdo | E030 | Finger direction marker extended finger points down-out (used to show finger orientation). | Location/Orientation |
| hamextfingeruo | E031 | Finger direction marker extended finger points up-out (used to show finger orientation). | Location/Orientation |
| hampalmu | E038 | Palm orientation indicator (which way the palm faces: up/down/left/right or variants). | Location/Orientation |
| hampalmur | E039 | Palm orientation indicator (which way the palm faces: up/down/left/right or variants). | Location/Orientation |
| hampalmr | E03A | Palm orientation indicator (which way the palm faces: up/down/left/right or variants). | Location/Orientation |
| hampalmdr | E03B | Palm orientation indicator (which way the palm faces: up/down/left/right or variants). | Location/Orientation |
| hampalmd | E03C | Palm orientation indicator (which way the palm faces: up/down/left/right or variants). | Location/Orientation |
| hampalmdl | E03D | Palm orientation indicator (which way the palm faces: up/down/left/right or variants). | Location/Orientation |
| hampalml | E03E | Palm orientation indicator (which way the palm faces: up/down/left/right or variants). | Location/Orientation |
| hampalmul | E03F | Palm orientation indicator (which way the palm faces: up/down/left/right or variants). | Location/Orientation |
| hamhead | E040 | Head (general) indicates head as location or non-manual articulator. | Non-Manual Features |
| hamheadtop | E041 | Top of the head (specific location). | Non-Manual Features |
| hamforehead | E042 | Forehead (location; often for non-manuals like eyebrow movement). | Other |
| hameyebrows | E043 | Eyebrows (non-manual feature raise/lower etc). | Non-Manual Features |
| hameyes | E044 | Eyes (gaze direction or eye activity). | Non-Manual Features |
| hamnose | E045 | Nose (facial location). | Non-Manual Features |
| hamnostrils | E046 | Nostrils (specific part of nose). | Other |
| hamear | E047 | Ear (location). | Other |
| hamearlobe | E048 | Earlobe (location). | Other |
| hamcheek | E049 | Cheek (facial location). | Other |
| hamlips | E04A | Lips / mouth area (non-manual/mouthings). | Non-Manual Features |
| hamtongue | E04B | Tongue (mouth articulation reference). | Other |
| hamteeth | E04C | Teeth (mouth reference). | Other |

| HamNoSys | Unicode | Explanation | Category |
|---|---|---|---|
| hamchin | E04D | Chin (location reference). | Non-Manual Features |
| hamunderchin | E04E | Under-chin (location). | Other |
| hamneck | E04F | Neck (location / non-manual). | Non-Manual Features |
| hamshouldertop | E050 | Top of the shoulder (location). | Non-Manual Features |
| hamshoulders | E051 | Shoulders (body reference). | Non-Manual Features |
| hamchest | E052 | Chest (body location). | Non-Manual Features |
| hamstomach | E053 | Stomach/abdomen area (location). | Non-Manual Features |
| hambelowstomach | E054 | Lower stomach/abdomen (location). | Other |
| hamlrbeside | E058 | Location: left/right beside (side position next to body). | Other |
| hamlrat | E059 | Location: left/right at (side location marker) indicates side-relative placement. | Other |
| hamcoreftag | E05A | Coreference tag (used for referencing another element or anchor in notation). | Location/Orientation |
| hamcorefref | E05B | Coreference reference (points to a previously defined anchor or location). | Location/Orientation |
| hamneutralspace | E05F | Neutral signing space in front of the signer (space away from body). | Location/Orientation |
| hamupperarm | E060 | Upper arm (location reference). | Other |
| hamelbow | E061 | Elbow (location). | Other |
| hamelbowinside | E062 | Inner side of the elbow (specific location). | Other |
| hamlowerarm | E063 | Lower arm / forearm (location). | Other |
| hamwristback | E064 | Back of the wrist (location). | Location/Orientation |
| hamwristpulse | E065 | Wrist pulse area (location). | Location/Orientation |
| hamthumbball | E066 | Bulbous part of thumb (thumb pad/ball) used as a location reference. | Hand Shapes |
| hampalm | E067 | Palm orientation indicator (which way the palm faces: up/down/left/right or variants). | Location/Orientation |
| hamhandback | E068 | Back of hand (dorsal side). | Location/Orientation |
| hamthumbside | E069 | Thumb-related handshape or modifier. | Hand Shapes |
| hampinkyside | E06A | Pinky-side (ulnar side) of hand. | Location/Orientation |
| hamthumb | E070 | Thumb-related handshape or modifier. | Hand Shapes |
| hamindexfinger | E071 | Index finger (reference) used as location/orientation reference. | Other |
| hammiddlefinger | E072 | Middle finger used as location/orientation reference. | Other |
| hamringfinger | E073 | Ring finger used as location/orientation reference. | Other |
| hampinky | E074 | Little finger / pinky used as location/orientation reference. | Location/Orientation |
| hamfingertip | E075 | Handshape specifying particular fingers extended. | Hand Shapes |
| hamfingernail | E076 | Handshape specifying particular fingers extended. | Hand Shapes |
| hamfingerpad | E077 | Handshape specifying particular fingers extended. | Hand Shapes |
| hamfingermidjoint | E078 | Handshape specifying particular fingers extended. | Hand Shapes |
| hamfingerbase | E079 | Handshape specifying particular fingers extended. | Hand Shapes |
| hamfingerside | E07A | Handshape specifying particular fingers extended. | Hand Shapes |
| hamwristtopulse | E07C | Top/inner wrist near the pulse location reference. | Location/Orientation |
| hamwristtoback | E07D | From wrist top toward back of wrist orientation reference. | Location/Orientation |
| hamwristtothumb | E07E | Thumb-related handshape or modifier. | Location/Orientation |
| hamwristtopinky | E07F | Orientation/position from wrist toward pinky side. | Location/Orientation |
| hammoveu | E080 | Hand movement direction: up (linear path in that direction). | Movements |
| hammoveur | E081 | Hand movement direction: up-right (linear path in that direction). | Movements |
| hammover | E082 | Hand movement direction: right (linear path in that direction). | Movements |
| hammovedr | E083 | Hand movement direction: down-right (linear path in that direction). | Movements |
| hammoved | E084 | Hand movement direction: down (linear path in that direction). | Movements |
| hammovedl | E085 | Hand movement direction: down-left (linear path in that direction). | Movements |
| hammovel | E086 | Hand movement direction: left (linear path in that direction). | Movements |
| hammoveul | E087 | Hand movement direction: up-left (linear path in that direction). | Movements |
| hammoveol | E088 | Hand movement direction: out-left (linear path in that direction). | Movements |
| hammoveo | E089 | Hand movement direction: out/away (linear path in that direction). | Movements |
| hammoveor | E08A | Hand movement direction: out-right (linear path in that direction). | Movements |
| hammoveil | E08B | Hand movement direction: in-left (linear path in that direction). | Movements |
| hammovei | E08C | Hand movement direction: in/toward (linear path in that direction). | Movements |

| HamNoSys | Unicode | Explanation | Category |
|---|---|---|---|
| hammoveir | E08D | Hand movement direction: in-right (linear path in that direction). | Movements |
| hammoveui | E08E | Hand movement direction: up-in (linear path in that direction). | Movements |
| hammovedi | E08F | Hand movement direction: down-in (linear path in that direction). | Movements |
| hammovedo | E090 | Hand movement direction: down-out (linear path in that direction). | Movements |
| hammoveuo | E091 | Hand movement direction: up-out (linear path in that direction). | Movements |
| hamcircleo | E092 | Circular movement path around out/away (circle in that orientation). | Movements |
| hamcirclei | E093 | Circular movement path around in/toward (circle in that orientation). | Movements |
| hamcircled | E094 | Circular movement path around down (circle in that orientation). | Movements |
| hamcircleu | E095 | Circular movement path around up (circle in that orientation). | Movements |
| hamcirclel | E096 | Circular movement path around left (circle in that orientation). | Movements |
| hamcircler | E097 | Circular movement path around right (circle in that orientation). | Movements |
| hamcircleul | E098 | Circular movement path around up-left (circle in that orientation). | Movements |
| hamcircledr | E099 | Circular movement path around down-right (circle in that orientation). | Movements |
| hamcircleur | E09A | Circular movement path around up-right (circle in that orientation). | Movements |
| hamcircledl | E09B | Circular movement path around down-left (circle in that orientation). | Movements |
| hamcircleol | E09C | Circular movement path around out-left (circle in that orientation). | Movements |
| hamcircleir | E09D | Circular movement path around in-right (circle in that orientation). | Movements |
| hamcircleor | E09E | Circular movement path around out-right (circle in that orientation). | Movements |
| hamcircleil | E09F | Circular movement path around in-left (circle in that orientation). | Movements |
| hamcircleui | E0A0 | Circular movement path around up-in (circle in that orientation). | Movements |
| hamcircledo | E0A1 | Circular movement path around down-out (circle in that orientation). | Movements |
| hamcircleuo | E0A2 | Circular movement path around up-out (circle in that orientation). | Movements |
| hamcircledi | E0A3 | Circular movement path around down-in (circle in that orientation). | Movements |
| hamfingerplay | E0A4 | Handshape specifying particular fingers extended. | Hand Shapes |
| hamnodding | E0A5 | General HamNoSys element (specific meaning depends on context). | Other |
| hamswinging | E0A6 | General HamNoSys element (specific meaning depends on context). | Movements |
| hamtwisting | E0A7 | General HamNoSys element (specific meaning depends on context). | Movements |
| hamstircw | E0A8 | General HamNoSys element (specific meaning depends on context). | Movements |
| hamstirccw | E0A9 | General HamNoSys element (specific meaning depends on context). | Movements |
| hamreplace | E0AA | General HamNoSys element (specific meaning depends on context). | Other |

| HamNoSys | Unicode | Explanation | Category |
|---|---|---|---|
| hammovecross | E0AD | Hand movement direction: directional movement (linear path in that direction). | Movements |
| hammoveX | E0AE | Hand movement direction: directional movement (linear path in that direction). | Movements |
| hamnomotion | E0AF | General HamNoSys element (specific meaning depends on context). | Other |
| hamclocku | E0B0 | Clockwise/counterclockwise circular motion indicated by clock position 'u'. | Movements |
| hamclockul | E0B1 | Clockwise/counterclockwise circular motion indicated by clock position 'ul'. | Movements |
| hamclockl | E0B2 | Clockwise/counterclockwise circular motion indicated by clock position 'l'. | Movements |
| hamclockdl | E0B3 | Clockwise/counterclockwise circular motion indicated by clock position 'dl'. | Movements |
| hamclockd | E0B4 | Clockwise/counterclockwise circular motion indicated by clock position 'd'. | Movements |
| hamclockdr | E0B5 | Clockwise/counterclockwise circular motion indicated by clock position 'dr'. | Movements |
| hamclockr | E0B6 | Clockwise/counterclockwise circular motion indicated by clock position 'r'. | Movements |
| hamclockur | E0B7 | Clockwise/counterclockwise circular motion indicated by clock position 'ur'. | Movements |
| hamclockfull | E0B8 | Full circular clockwise motion (full rotation). | Movements |
| hamarcl | E0B9 | Short arced movement (a small curved path). | Movements |
| hamarcu | E0BA | Short arced movement (a small curved path). | Movements |
| hamarcr | E0BB | Short arced movement (a small curved path). | Movements |
| hamarcd | E0BC | Short arced movement (a small curved path). | Movements |
| hamwavy | E0BD | Wavy oscillating movement (smooth wave-like motion). | Movements |
| hamzigzag | E0BE | Zig-zag oscillating movement (sharp alternating motion). | Other |
| hamellipseh | E0C0 | Elliptical (oval) movement path, specifying orientation of ellipse. | Movements |
| hamellipseur | E0C1 | Elliptical (oval) movement path, specifying orientation of ellipse. | Movements |
| hamellipsev | E0C2 | Elliptical (oval) movement path, specifying orientation of ellipse. | Movements |
| hamellipseul | E0C3 | Elliptical (oval) movement path, specifying orientation of ellipse. | Movements |
| hamincreasing | E0C4 | Movement or parameter increasing (e.g., amplitude growing). | Other |
| hamdecreasing | E0C5 | Movement or parameter decreasing (e.g., amplitude shrinking). | Other |
| hamsmallmod | E0C6 | Modifier: small (subtle / small-amplitude) movement. | Other |
| hamlargemod | E0C7 | Modifier: large (wide / large-amplitude) movement. | Other |
| hamfast | E0C8 | Modifier: fast speed. | Movements |
| hamslow | E0C9 | Modifier: slow speed. | Movements |
| hamtense | E0CA | Modifier: tense or stiff quality of movement/hand. | Movements |
| hamrest | E0CB | Rest position (hold without motion). | Movements |
| hamhalt | E0CC | Abrupt stop / halt in motion. | Movements |
| hamclose | E0D0 | Hand closing or coming together (close action). | Other |
| hamtouch | E0D1 | Touch/contact action (hand touches another part). | Other |
| haminterlock | E0D2 | Hands interlocking (fingers interlaced) action. | Other |
| hamcross | E0D3 | Crossing hands or crossing motion/placement. | Other |
| hamarmextended | E0D4 | Arm is extended away from body (extended-arm posture). | Location/Orientation |
| hambehind | E0D5 | Placed or moved behind body or another body-part. | Other |
| hambrushing | E0D6 | Brushing motion (light stroke across surface). | Other |
| hamrepeatfromstart | E0D8 | Repetition operator indicates repeating the movement or sequence. | Movements |
| hamrepeatfromstartseveral | E0D9 | Repetition operator indicates repeating the movement or sequence. | Movements |
| hamrepeatcontinue | E0DA | Repetition operator indicates repeating the movement or sequence. | Movements |
| hamrepeatcontinueseveral | E0DB | Repetition operator indicates repeating the movement or sequence. | Movements |

| HamNoSys | Unicode | Explanation | Category |
|---|---|---|---|
| hamrepeatreverse | E0DC | Repetition operator indicates repeating the movement or sequence. | Movements |
| hamalternatingmotion | E0DD | Alternating motion (hands or fingers alternate in action). | Movements |
| hamseqbegin | E0E0 | Sequence/grouping marker: begins/ends a sequence, parallel group, or fusion of actions. | Other |
| hamseqend | E0E1 | Sequence/grouping marker: begins/ends a sequence, parallel group, or fusion of actions. | Other |
| hamparbegin | E0E2 | Sequence/grouping marker: begins/ends a sequence, parallel group, or fusion of actions. | Other |
| hamparend | E0E3 | Sequence/grouping marker: begins/ends a sequence, parallel group, or fusion of actions. | Other |
| hamfusionbegin | E0E4 | Sequence/grouping marker: begins/ends a sequence, parallel group, or fusion of actions. | Other |
| hamfusionend | E0E5 | Sequence/grouping marker: begins/ends a sequence, parallel group, or fusion of actions. | Other |
| hambetween | E0E6 | Spatial relation: between (e.g., movement or placement between hands or body parts). | Location/Orientation |
| hamplus | E0E7 | Plus symbol: combines or adds elements (used in composite descriptions). | Other |
| hamsymmpar | E0E8 | Symmetry operator: indicates two-handed symmetry (how attributes mirror across hands). | Location/Orientation |
| hamsymmlr | E0E9 | Symmetry operator: indicates two-handed symmetry (how attributes mirror across hands). | Location/Orientation |
| hamnondominant | E0EA | Marker referring to the non-dominant hand (used to describe NDH behaviour). | Location/Orientation |
| hamnonipsi | E0EB | Marker meaning non-ipsilateral / opposite-side reference (side-related indicator). | Location/Orientation |
| hametc | E0EC | Placeholder: 'etc.' or miscellaneous/other elements not explicitly listed. | Other |
| hamorirelative | E0ED | Orientation/relative reference marker (indicates orientation relative to something else). | Location/Orientation |
| hammime | E0F0 | Mime or pantomime marker indicates mimed action rather than lexical sign. | Non-Manual Features |

Table 4: Explanations of HamNoSys symbols