Event structure reflected in muscle activation differences in Austrian Sign Language (ÖGS) verbs: First evidence from surface electromyography

Julia Krebs* (Department of Linguistics,
Centre for Cognitive Neuroscience (CCNS), University of Salzburg)
julia.krebs@plus.ac.at
Isabella Fessl* (Department of Sport and Exercise Science,
University of Salzburg)
isabella.fessl@plus.ac.at
Ronnie B. Wilbur (Department of Linguistics, Department of Speech,
Language, and Hearing Sciences, Purdue University)
wilbur@purdue.edu
Evie A. Malaia (Department of Communicative Disorders,
University of Alabama)
eamalaia@ua.edu
Hans-Peter Wiesinger (Department of Linguistics, University of Salzburg)
hans-peter.wiesinger@plus.ac.at
Hermann Schwameder (Department of Sport and Exercise Science
University of Salzburg)
hermann.schwameder@plus.ac.at
Dietmar Roehm (Department of Linguistics,
Centre for Cognitive Neuroscience (CCNS), University of Salzburg)
dietmar.roehm@plus.ac.at

*The authors contributed equally to this work.

Abstract

This paper aims to introduce kinematic motion capture analysis and electromyography (EMG) methodology in the context of experimental investigations involving sign languages. While motion capture has been employed in previous sign language research, the application of EMG is relatively novel. We utilized both motion capture and EMG techniques to examine the disparities in muscle activation associated with the production of telic verb signs (with boundary marking, e.g. the verb *arrive*) and atelic verb signs (lacking boundary marking, e.g. the verb *run*) in Austrian Sign Language (ÖGS). The data analysis revealed that the visual boundary marking inherent in the production of telic signs, which is kinematically characterized by heightened acceleration, jerk, and deceleration at the conclusion of a sign, is generated by increased

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activation in upper arm muscles during the sign and hold interval for telics compared to atelics. In contrast, the majority of atelics exhibited a repeated movement, which contributed to more pronounced muscle activation in the forearm compared to telics. The EMG/motion capture combined method applied to sign language production offers novel insights into linguistics of sign language that were previously inaccessible.

Keywords: sign language kinematics, muscle activation, electromyography (EMG), motion capture, telicity

1 Introduction

Sign languages are expressed through both manual and non-manual components across four dimensions: the movement of the arms/hands unfolds in time within the three-dimensional signing space – the area in front of the signer dedicated to sign language production. In the process of sign language production, distinct manual (involving hands and arms) and non-manual elements (position and/or movement of the upper body, shoulders, head, eye gaze, as well as the motion of eyebrows, mouth, lips, cheeks, and nose) co-occur. Consequently, the recipient simultaneously interprets different components or visual cues that offer varied informational fragments, all processed simultaneously (Wilbur 2000). In contrast, spoken languages, generated by the vocal tract and primarily perceived through the auditory system, are perceived sequentially (although in spoken languages, some degree of simultaneity still exists: for instance, tonal languages like Mandarin utilize suprasegmental features to convey meaning).

The production of sign language constitutes a complex visual dynamic signal that differs quantitatively from everyday visual environments and gestures (Malaia, Borneman, and Wilbur 2016; Borneman, Malaia, and Wilbur 2018). Analyzing this complex visual-linguistic signal is a challenge for a number of methodological reasons (Krebs et al. 2022). The distinction in language modality between signed and spoken languages (vocal-auditory versus (non)manual-visual) gives rise to modality-induced differences in grammatical structure and processing. However, it's important to note that both language modalities are governed by grammatical principles, processed in language-relevant brain regions, and acquired through analogous acquisition processes (for an overview see Corina and Lawyer 2019; Emmorey 2021; Cardin et al. 2020; Hickok and Bellugi 2023). The distinction in the nature of the language signal between signed and spoken languages (auditory versus visual signal) requires clear approaches for data analysis as well as different analytical methods. The development of such analysis tools for sign languages required broadening our understanding about the sign language signal, including its visual and dynamic characteristics.

As previously mentioned, the sign language signal is composed of various components. In this paper, our focus is on analyzing the movement of the hand(s) and arm(s) during sign language production. Most signs (though not all) have a distinct (primary) movement, in addition to a specific handshape formation, a particular hand orientation (referring to the palm and/or fingertips), and a designated place of articulation (indicating where the sign is produced within signing space or on the signer's body) (Brentari 1998). This movement can serve not only as a phonological or lexical element of a sign, but can also express grammatical marking. For example, reduplication of the movement in a specific manner can indicate plurality, convey aspectual meanings, or provide prosodic cues (Fischer 1973; Klima and Bellugi 1979; Wilbur 2005, 2009). However, an exhaustive analysis of the movement component and its potential grammatical functions within the broader context of sign language grammar remains lacking.

In analyzing the movement within sign language production, a variety of spatial and dynamic kinematic parameters of articulation can be explored (Malaia and Milković 2021). For instance, displacement measure quantifies the path traced in signing space by the hand(s). Dynamic parameters of interest include duration of a sign, velocity (how fast the hands move, i.e. displacement divided by time), deceleration (how rapidly the hands stop - i.e. displacement divided by time, squared), etc. During signing, the hand(s) move in three dimensions: horizontal (side to side), vertical (up and down), and depth (forward and backward), each of which can be independently analyzed for dynamic kinematic features.

The application of the motion capture method allows for precise experimental investigation into the dynamic and kinematic characteristics of sign language production. Additionally, to quantify the activation of arm muscles during sign language production, the electromyography (EMG) methodology can be used. Given that interpreting EMG data requires contextual information about the kinematic features of the signal, we will outline both the motion capture and EMG methods below. In this proof-of-concept study, we examined disparities in arm muscle activation when a proficient user of Austrian Sign Language (ÖGS) produced telic and atelic verbs. Before describing our study and the findings, we first introduce the motion capture and EMG methods.

1.1 Kinematic/3D-Motion Capture Analysis

Kinematic analysis captures, analyzes and illustrates spatio-temporal characteristics of movements and postures. However, the causes (e.g. internal forces and torques) of the movements are disregarded by kinematic analysis. The kinematic base parameters are time (t) and distance (d). Other parameters (e.g. velocity, acceleration, etc.) are calculated from time and distance. These parameters are used to characterize postures and movements in translational and rotational motion.

Several methods allow for kinematic analysis - video, motion capture, radar recordings, etc.. The 3D-Motion Capture Systems (active camera system) is the gold standard for the kinematic analysis, as it provides 3D information with high precision. In 3D motion capture systems, infrared arrays are located around the camera lens, which send infrared light that is reflected by the markers on a moving participant (the markers are placed on the person or object of interest beforehand). The location of the marker depends on the target of the kinematic analysis (Schwameder and Dengg, 2021b).

A limited number of studies have explored the kinematic attributes of sign languages using motion capture. For instance, research has been conducted on American Sign Language (ASL) and Croatian Sign Language (HZJ), investigating the kinematic distinctions between telic and atelic signed verbs. Telic verbs, like ARRIVE, involve a natural conclusion point, whereas atelic signs can potentially terminate while lacking a definitive endpoint. Across several sign languages, evidence indicates that telicity is reflected in the phonological structure of verb signs (Malaia and Wilbur 2012; Malaia, Wilbur, and Milković 2013; Strickland et al. 2015; Krebs et al. 2021). Telic and atelic verbs exhibit distinct movement patterns, observable in their phonological attributes and syllable structure. Studies utilizing motion capture in ASL and HZJ concurred in some kinematic findings. For example, in telic signs, the endpoint of the event is signified by a notably faster deceleration at the sign's end, in contrast to atelic signs, which do not show such a rapid deceleration to a stop at the end of the sign. In HZJ, apart from a rapid deceleration at the sign's end, telic verbs also exhibited a higher peak velocity compared to atelic signs (see Malaia and Wilbur 2012 for ASL, and Malaia, Wilbur, and Milković 2013, for HZJ analyses).

1.2 Electromyography (EMG)

Electromyographic analysis pertains to the origin, detection, and analysis of myoelectric signals, which arise from biochemical and physiological changes in the muscle fiber membrane (Basmajian and De Luca 1985; Konrad 2005). In the field of (sports) biomechanics, surface EMG is used as a non-invasive technique to measure muscle-internal electric signals. It is particularly valuable for identifying the start and end of muscle activities, their duration, the relative magnitude of muscular contractions, intermuscular coordination patterns, etc. (Schwameder and Dengg, 2021a).

Less is known about the arm muscle activity in sign language production. Some reports describe specific sign language structures that exhibit increased muscle tension, more pronounced articulation, or are marked by distinct dynamic qualities or manner of movement (Klima and Bellugi 1979). However, qualitative descriptions of manner of movement are mainly based on visual inspection of 2D videos. The use of the EMG method offers a more precise measure, as opposed to subjective observations. Existing EMG studies that focus on sign language production, to our knowledge, primarily use this method for developing Sign Language Recognition Systems (e.g., Kosmidou, Hadjileontiadis, and Panas 2006; Zhang et al. 2011).

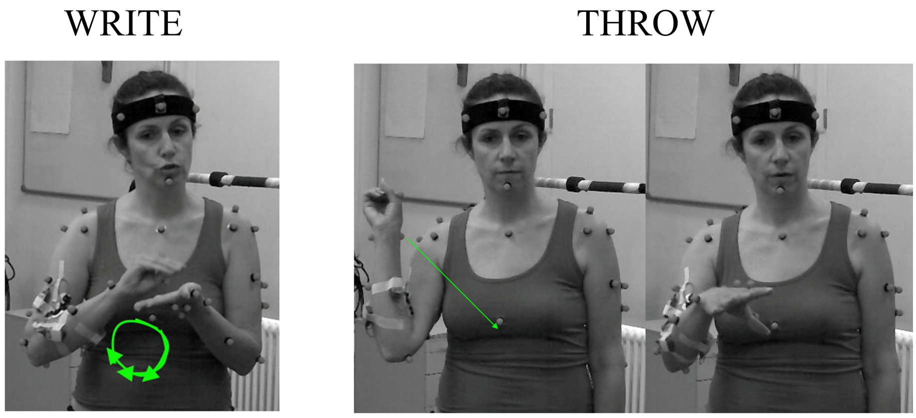
2 The present study

In the present work, we used EMG measurements to evaluate arm muscle activation for telic and atelic verbs in ÖGS. Based on 2D video analysis, Schalber 2006 noted that the two verb types differ in phonological structure. Telics show a rapid movement (deceleration) to a complete stop (EndState morpheme) which is realized in changes of handshape and orientation of the hand(s) or changes of setting/place of articulation (cf. Wilbur 2008, 2010). First experimental evidence confirming this observation regarding ÖGS verbs is provided by motion capture and EMG data that we present in this paper. The EMG data reported below was collected simultaneously with kinematic data reported in Krebs et al. 2021.

2.1 Stimulus material

The telic and atelic signs (10 per category) were produced by a Deaf fluent signer. Verbs were selected based on fieldwork interview data from four Deaf fluent signers, where verb types (telic, atelic) were identified using converging results of three linguistic tests (cf. Borik 2006). The telic verbs used in the study were THROW, CATCH-UP, TAKE, DISAPPEAR, CHANGE, ARRIVE, DIE, RELAX, STEAL, SUGGEST. The atelic verbs used in the study were TRAVEL, COLLECT, SHAVE, CHASE, WRITE, PAINT, SEW, EXAMINE, ANALYZE, SWIM. An example of a telic and an atelic verb sign is illustrated in Fig. 1.

Figure 1: Examples for atelics (WRITE) and telics THROW in ÖGS. The atelic sign WRITE shows a repeated circular path movement; the telic sign THROW shows a single linear path movement as well as a handshape change (closed to open).



2.2 Kinematic/3D-Motion Capture Analysis

2.2.1 Data acquisition and analysis

The investigation was conducted in the biomechanics laboratory at the Department of Sport and Exercise Science at the University of Salzburg. The kinematic analysis was performed as follows: Body kinematics of the trunk, head, and upper extremity including hands were recorded using a custom-built marker set (Figure 2). 57 reflective markers (silver spheres Ø.12 mm screwed on a 10 mm plastic base) were placed on the participant's body (Figure 1) using tape located at the marker base. The trajectories of the markers during sign production were recorded by a 12-camera infrared motion capture system (Qualisys AB, company located in Göteborg, Sweden) with a sampling frequency of 300 Hz. A 2D video of the participant (frontal plane) was recorded simultaneously at 150 Hz frequency (Qualisys AB, Göteborg, Sweden). Marker trajectories were low-pass filtered using a sond-order zero-lag Butterworth filter with a cutoff frequency of 25 Hz. Segment positions and orientations were determined using an inverse kinematics algorithm (V3D; C-Motion, Rockville, MD, USA). Joint centers of the wrist and elbow were defined as virtual landmarks at 50% of the line between the lateral and medial joint marker.

The sign production was divided into 4 phases:
1. *preparation phase*: the interval from the time point when the velocity of the right wrist joint center (vertical component) was greater than 0.1 m/s to the time point sign onset was defined;
2. *sign phase*: the interval from sign onset to hold onset;
3. *hold phase*: hold onset (last local minimum of the resultant velocity) to sign offset;
4. *down phase*: the interval from sign offset to the time point when the velocity of the right wrist joint center (vertical component) was lower than 0.1 m/s.

The onset and offset of the sign phase were marked by a skilled signer (J.K). Sign onset was marked when the target handshape reached target place of articulation from where

Figure 2: Motion capture marker set.

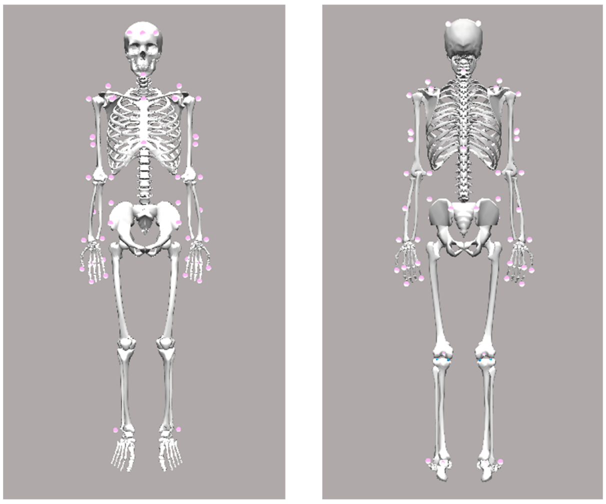


Table 1: Kinematic features; standard deviations in parentheses; only significant results are reported in the table.

Parameter	Atelics	Telics	p-value
Sign duration in s	1.69 (0.36)	1.19 (0.30)	< 0.01
Deceleration (max) in m/s^2	6.2 (2.9)	12.3 (5.2)	< 0.01
Acceleration (max) in m/s^2	6.4 (2.6)	11.7 (5.7)	< 0.05
Jerk (max) in m/s^3	765 (537)	1933 (1598)	< 0.05
Relative hold duration in %	16.88 (11.51)	40.07 (13.30)	< 0.001

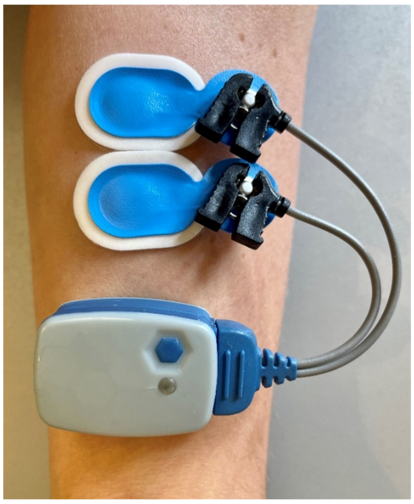
sign movement started. Sign offset was marked when the handshape or hand orientation changed, or when the hand moved away from the final place of articulation. Onset of the hold was operationalized by the research team as the last local minimum of the resultant velocity (Malaia and Wilbur 2012; Malaia, Wilbur, and Milković 2013). The 2D video and velocity of the right wrist joint center (vertical component) was used in marking of sign onset and offset. For each sign, duration, peak velocity, maximum/minimum acceleration and maximum jerk (i.e. the rate of change in acceleration within the sign) were calculated for the sign phase. The data are presented as group means (telic vs. atelic) and standard deviations (SD). A group samples t-test was performed to evaluate the differences between the telic and atelic verbs by using IBM SPSS Statistics (SPSS Inc, Chicago, IL, USA) [1].

2.2.2 Results

Kinematic data analysis showed that telic verbs were characterized by shorter duration, higher acceleration and jerk, and higher deceleration at the end of the signs compared to atelic verbs (Krebs et al. 2021). Furthermore, telic verbs had ~ 2.5 times longer holds at the end of the signs, as compared to atelic verbs (see Table 1).

1. No significant differences were observed in maximal/peak velocity.

Figure 3: EMG electrodes and Noraxon EMG Sensor.



2.3 Electromyography

2.3.1 Data acquisition and analysis

The EMG analysis was performed simultaneously with the kinematic analysis by using the Qualisys Track Manager (Qualisys AB, Göteborg, Sweden). EMG data was collected at 2000 Hz. EMG signals were recorded from four arm muscles: m. extensor digitorum, m. flexor digitorum, m. biceps brachii and m. triceps brachii of the dominant (right) arm. Therefore, EMG electrodes were placed on the participant's skin, which was prepared beforehand (by shaving and disinfecting the skin to remove skin scales, hair, and skin oil to get the best possible EMG signal) at specific anatomical places (e.g. thickest part of the muscle of interest) according to the recommendations of SENIAM (http://www.seniam.org/). At each muscle the EMG sensor (Ultium(TM) EMG, Noraxon, Scottsdale, AZ, USA) was linked to the EMG electrodes (Figure 3). EMG data was post processed by using V3D (C-Motion, Rockville, MD, USA). Raw EMG data was filtered (Butterworth low at 300 Hz, then high at 10 Hz), and smoothed (root mean square with a moving window of 151 data points (0.0755 s)). Standard EMG measures (Konrad 2005) were computed: EMG mean (averaged EMG signal), EMG max (peak in EMG signal) and EMG integral (area under the EMG signal curve) were analyzed for sign phase (time interval between sign onset and sign offset) as well as hold phase (time interval after sign movement ended and the hands were held in space, i.e. before sign offset).

The data are presented as group means (telic vs. atelic) and standard deviations (SD). For statistical analysis a group samples t-test was performed to evaluate the differences between the telic and atelic verbs by using IBM SPSS Statistics (SPSS Inc, Chicago, IL, USA).

To interpret the EMG data, both the corresponding kinematic data and the phonological structure of the signs are necessary. The current phonological analysis focused on movement type (path or local), movement direction, repetition, finger flexion, contact of hands, and sign location.

Table 2: Muscle activation. EMG-values in %; standard deviations in parentheses; only significant results are reported in the table.

Muscles (phase of sign production)	**Upper arm muscles**			**Forearm muscles**	
	biceps EMG max (sign phase)	biceps EMG mean (sign phase)	triceps EMG mean (hold phase)	extensor digitorum EMG integral (sign phase)	flexor digitorum EMG integral (sign phase)
atelics	33.4 (14.0)	15.7 (6.3)	2.2 (0.9)	46.6 (19.0)	20.4 (11.5)
telics	51.2 (26.3)	21.7 (7.8)	3.0 (0.4)	25.1 (7.1)	8.7 (2.7)
***p*-value**	0.04	0.03	0.01	0.003	0.001

2.3.2 Results

Data analysis revealed that the upper arm muscles showed higher muscular activity in telic than atelic verbs: For the sign phase, significant effects were observed in EMG max and EMG mean, such that more activation was revealed in the biceps for telic signs compared to atelic signs. EMG mean value in the hold phase after the sign in the triceps for telic signs was also higher than for atelics. For atelics, higher muscle activity was found in the forearm: higher activation was observed in the EMG integral in the extensor and flexor digitorum in the sign phase (see Table 2)[2].

The phonological analysis of the signs showed that most of the telic signs involved local movement (with and without additional path movement), but no repeated movement. Most of the atelics, on the other hand, had a repeated movement (reduplication) component. The two signs which lacked a repeated movement (the signs TRAVEL and SEW) show a straight linear path movement. In contrast to telics, of which most involved a local movement, only four of the atelics showed a local movement; the same four atelic signs also had a repeated movement component. Table 3 presents the relevant part of phonological structure analysis results for the atelic and telic signs, providing information on the presence or absence of the three phonological features related to the movement component for each sign: path movement, local movement and repeated movement.

Combined EMG results, kinematic data and the phonological structure of the signs indicated that endpoint marking in telic signs, which is characterized by higher acceleration, jerk and deceleration at the end of a sign, is produced by higher activation in upper arm muscles in the sign and hold interval in telics as compared to atelics. It is also noted that the repeated arm/hand movement used in the majority of the atelics (n=8), but absent in telics, requires more intense muscle activation in the forearm in the production of atelic as compared to telic signs.

2. For the biceps, no significant differences were observed regarding the EMG integral in the sign phase and the EMG mean in the hold phase. For the triceps, no significant differences were observed regarding the EMG integral, the EMG max and EMG mean in the sign phase. For the extensor digitorum, no significant differences were observed regarding the EMG max and EMG mean in the sign phase and the EMG mean in the hold phase. For the flexor digitorum, no significant differences were observed regarding the EMG max and EMG mean in the sign phase and the EMG mean in the hold phase.

Table 3: Phonological analysis: + indicates that certain phonological feature is present in the sign; - denotes feature absence.

Verb Type	Verb	Path Movement	Local Movement	Repeated Movement
Telics	THROW	+	+	-
	CATCH UP	+	+	-
	TAKE	+	+	-
	DISAPPEAR	+	+	-
	CHANGE	-	+	-
	ARRIVE	+	-	-
	DIE	-	+	-
	RELAX	+	-	-
	STEAL	-	+	-
	SUGGEST	-	+	-
Atelics	TRAVEL	+	-	-
	COLLECT	+	+	+
	SHAVE	+	-	+
	FOLLOW	+	+	+
	WRITE	+	-	+
	PAINT	-	+	+
	SEW	+	-	-
	EXAMINE	+	-	+
	ANALYZE	+	+	+
	SWIM	+	-	+

3 Discussion

This paper aimed to provide an introduction into the EMG methodology and kinematic/3D-Motion Capture analysis combined to interpret EMG data. EMG analysis provides new insight into sign articulation, and helps understand muscle activation that produces linguistically relevant markers in sign languages.

The study exemplifies how a linguistic research question can be investigated using kinesiological methods. The data presented reveal a difference in kinematic characteristics of telic compared to atelic signs, as well as a difference in arm muscle activation between the two verb types in ÖGS. These findings are consistent with earlier motion capture findings for ASL and HZJ, suggesting that the event structure of a verb is reflected in the visual verb form. This finding supports the Event Visibility Hypothesis proposing an iconic representation of event structure in sign languages via mapping between sign semantics and visual form/motion (Wilbur 2008, 2010). The results also provide corroborative evidence for the perceptual Event Segmentation Theory (EST), which focuses on the ability of humans to parse the continuous stream of sensory inputs into individualized, distinct events (Zacks and Swallow 2007; Zacks and Tversky 2001). Specifically, EST posits that humans rely on dynamic features of visual motion in both perception (identifying discrete events in their environment), and production (i.e. marking event boundaries by co-speech gesture). Studies on hearing non-signers show that changes in speed (increases and decreases of speed) of individual objects are highly correlated with action start and end times, as identified by participants (i.e. event boundary identification) (Zacks et al. 2006). As shown by sign language data, rate of deceleration is also one of the motion features used for differentiating telic from atelic verbs in sign language production.

Analyzing the sign language signal using EMG allows for a more detailed articulatory phonetic analysis of sign languages, and yields information about arm muscle activation during sign language production. The method also enables investigation of grammatical markers expressed by kinematic or dynamic properties of hand motion in signing. For example, for a number of sign languages imperative constructions have been described as produced "quicker" and with "more tensed movement" (e.g. Brunelli 2011; Donati et al. 2017). However, how the proposed marker of imperative intensification can be characterized quantitatively in the different sign languages, and the way arm muscle activation can quantify 'tensed movement', are open questions.

Quantitative information about the kinematic characteristics of sign language articulation and the arm muscle activation in sign language production is necessary for the development of analysis tools required for the analysis of the visually complex sign language signal, and for the development of sign language recognition systems. More knowledge about the kinematic characteristics of sign language production is also important for developing learning materials and learning tools for sign language learners.

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