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ORIGINAL ARTICLE

Embodied Cognition in Substance Use Disorder: Evaluation of Implicit Muscle Activity in Forearms with Surface Electromyography

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Main Points

- Significant electromyography (EMG) activity was observed when participants discussed substance-related topics, suggesting a link to unconscious drug cravings.
- Electromyography activities of dominant and non-dominant forearms were similar during substance-related conversations.
- The study supports the idea that language processing can activate motor areas, potentially reflecting cravings in substance use disorder.
- Suppressed gestures may have contributed to increased forearm muscle activation during substance use discussions.

Abstract

This study investigates the role of embodied cognition in substance use disorder by examining involuntary forearm muscle activity, measured through surface electromyography, during conversations on substance-related and non-substance-related topics. Conducted with 16 participants undergoing detoxification, the research aimed to determine whether discussions about substance use would elicit greater electromyography responses, indicative of implicit motor imagery or unconscious cravings. Results revealed a significant increase in electromyography activity during substance-related conversations across all participants, regardless of forearm dominance, supporting our initial hypotheses. This suggests that discussions about substance use may trigger subconscious processes linked to past use experiences. The observed effect sizes were substantial, underscoring the robustness of these findings. Our research contributes to the understanding of substance use disorder by demonstrating how embodied cognition manifests in affected individuals and provides insights into implicit cravings, highlighting the potential of using electromyography to explore these unconscious processes. The study emphasizes the need for further research into the embodied cognition aspect of substance use disorder, ideally with larger sample sizes and control groups, to gain a more comprehensive understanding.

Keywords: Embodied cognition, implicit cravings, motor imagery, substance use disorder, surface electromyography

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Introduction

Mental images are perceptions that are created in the mind either from memory or simulated without external stimuli (Pearson, 2007). These mental images play an important role in various cognitive processes, such as recalling memories of specific events, planning for the future, spatial orientation, planning navigation, and fostering creativity (Palmiero et al., 2019). Mental imagery is used in

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daily life to support various activities, from simple tasks like visualizing a shopping list to more complex tasks such as mentally rehearsing musical material and movements while playing an instrument (Clark et al., 2012). Mental images can be intentionally created, but they can also arise involuntarily, such as in dreams, hallucinations, and post-traumatic stress disorder (PTSD) (Nanay, 2021; Palmiero et al., 2019).

Mental imagery can be conducted through different sensory modalities, including visual, auditory, tactile, kinesthetic, olfactory, and gustatory, or a combination of these senses (Floridou et al., 2022). Motor imagery, a specific type of mental imagery, involves mentally simulating a motor task without actual physical movement (Driskell et al., 1994). The psychoneuromuscular theory proposes that the same neural pathways used to perform a specific movement are activated during mental imagery of that movement, leading to the activation of relevant muscles (Driskell et al., 1994).

In a series of studies conducted by Jacobson, one of the pioneers in motor imagery research, it was demonstrated that minimal involuntary movements (ranging from 0.07 to 0.32 mm on the mechanogram) occurred in the muscles related to the movement during the imagination of various motor tasks (Jacobson, 1932). Jacobson provided evidence suggesting that various muscle activities during the imagery process resembled those during actual movement but at a lower magnitude (Jacobson, 1932). Recent studies have shown increased electromyography (EMG) activity during motor imagery (Bakker et al., 1996; Wehner et al., 1984; Weiss et al., 1994). These findings suggest that EMG activity is specific to the muscles involved in the imagined action (Magill & Lee, 1998; Schmidt et al., 2018). Furthermore, it has been observed that the increase in EMG activity is proportional to the imagined effort; for instance, imagining lifting 9 kg dumbbells results in greater EMG activity compared to imagining lifting 4.5 kg dumbbells (Bakker et al., 1996; Wehner et al., 1984).

Mental images can be conscious or unconscious (Nanay, 2021; Pearson, 2007). A study on individuals diagnosed with PTSD revealed that they displayed strong EMG responses in their brow muscles to trauma-related cues, suggesting that some automatic reactions that participants may struggle to verbalize can be detected through subtle muscle activations (Pole, 2007). In another study, Dimberg and colleagues used the backward masking technique to unconsciously present participants with pictures of happy and angry facial expressions for only 30 milliseconds. The participants reacted to the images with corresponding EMG reactions in facial muscles, indicating their response to happy (zygomaticus major) and angry (corrugator supercilii) facial expressions (Dimberg et al., 2000).

Numerous studies have indicated that verbal instructions alone, without incorporating mental imagery, can strongly elicit sensory-motor responses (Mertens et al., 2020). For instance, through the use of functional imaging techniques, researchers have shown that listening to or silently reading sentences containing action verbs associated with mouth, hand, and leg movements activates the somatomotor regions linked to those actions (Hauk et al., 2004).

In recent years, the embodied cognition approach has provided a new perspective on the nature of mental imagery (Palmiero, 2014; Wilson, 2002). According to this theory, the body is embedded in a world with specific purposes and needs, and it cannot be separated from cognition as it shapes and structures it (Fridland & Wiers, 2018). This approach suggests that mental imagery is based on the reactivation of sensorimotor brain patterns involved during accurate perception (through experience) (Fridland & Wiers, 2018).

Recent studies have indicated that subtle cues related to substance use can activate the brain's reward system without conscious awareness (Childress et al., 1999; Gómez et al., 2008). Visual images and memories associated with substance use, whether triggered explicitly or implicitly, often intensify individuals' cravings for substances. These may include sensory images such as a positive first-time experience with the substance (Fridland & Wiers, 2018; Littel et al., 2016).

Just like we use our hands to perform many tasks in our daily lives, individuals with substance use disorder (SUD) also use their hands for various cognitive and motor functions such as acquiring, carrying, and using substances. In these individuals, focused bodily motor responses, particularly involving the hands (arms), may occur as a direct result of mental imagery formed during certain implicit verbal tasks or due to an increase in substance cravings, whether consciously or unconsciously (Littel et al., 2016).

There are no studies in the literature that aim to directly measure the conscious or unconscious motor responses of individuals with SUD triggered by various verbal processes through their hands. In this study, we focused on this specific area to investigate the effects of motor imagery and language processing on substance use desires and aimed to provide a new perspective for identifying the potential bodily manifestations of implicit substance use cravings in individuals with SUD.

In our study, we aimed to examine the right and left forearm EMG activities while discussing personal information other than substance use histories (such as marital status, occupation, educational background, etc.) and substance use histories with patients undergoing inpatient detoxification treatment at our clinic. Additionally, we aimed to compare the EMG activities of patients between their dominant and non-dominant forearms. Our first hypothesis for the study is that during conversations about their substance use histories, the forearm EMG activities of participants will be higher than the EMG levels during conversations unrelated to substance use. Our second hypothesis is that the EMG activity of the dominant forearm will differ from that of the non-dominant forearm.

Material and Methods

Study Sample

The participants in the study were individuals who had sought treatment at the Ankara Training and Research Hospital Alcohol and Drug Addiction Treatment Center for Substance Use Disorder as diagnosed by DSM-5 and had been using substances for more than 1 year. Volunteers for the study had to be 18 – 45 years old, literate, and had received treatment for SUD in the last month. Additionally, participants were required to score higher than 23 on the mini-mental test, and were not diagnosed with orthopedic, neurological, or systemic diseases that could interfere with the study evaluations. Those with uncorrectable vision or hearing problems, as well as individuals currently taking medication for any other condition, were excluded from the study. Prior to the evaluations, the purpose and content of the study were explained to all individuals approved to participate by the psychiatrists, and written informed consent was obtained from each individual. The study was ethically approved by the Health Sciences Ethics Committee of Ankara Training and Research (dated October 27, 2023, No. 392-08).

The study recorded the demographic and physical characteristics of all individuals, along with information about their substance use, including the first substance tried, the type of substance they attempted to quit, the frequency of substance use, and the duration of exposure to the substance. The cognitive status of the individuals was assessed using the mini-mental state test, which efficiently evaluates cognitive performance in a standardized manner. The test examines functions such as registration, recall, language, orientation, attention, calculation, and the ability to follow simple commands. Each correct answer is awarded 1 point, with a maximum score of 30. In the study, a score below 24 points was considered an indicator of cognitive impairment, and individuals with scores of 24 and above were included (Folstein et al., 1975; Güngen et al., 2002).

Electromyography Data Collection and Analysis

Electromyography data were collected using the Noraxon Ultium EMG sensor system (Noraxon USA, Inc., Scottsdale, Arizona) with a sampling frequency of 4000 Hz per channel, gain set at 1000 (signal to noise ratio of 1 μV RMS), common mode rejection rate (CMRR) of −100 dB, and input impedance greater than 100 mΩ. Any hair on the skin was removed, and the area was cleansed with an alcohol swab before electrodes were connected to detect EMG signals. The electrodes were placed on both sides of the flexor carpi radialis (FCR), along a line on the palm side of the forearm between the medial epicondyle of the humerus and the capitate carpal bone, on the flexor carpi ulnaris (FCU) along a line from the medial epicondyle to the ulnar styloid process, on the brachioradialis (BHR) along the line from the radial styloid process to just below the elbow joint, and on the extensor digitorum (EXD) at the midpoint on the back of the forearm, three-quarters down its length, in the direction of the muscle alignment as shown in Figure 1 (Gomez-Correa & Cruz-Ortiz, 2022). The data were sampled at a rate of 2000 Hz. Two filters were used: a band-pass filter with a range of 10 – 500 Hz, implemented using a first-order high-pass filter and a fourth-order low-pass Butterworth filter, to eliminate unwanted artifacts; and a 60 Hz notch filter to remove noise. Root mean square (RMS) values were calculated using a moving 100-ms window. The Noraxon MyoResearch XP program (version 3.16, Noraxon Inc, Scottsdale, AZ, USA) was used for data processing. The data from each trial were represented as a percentage of the calculated mean RMS of the maximal voluntary isometric contraction (MVIC) (%MVIC), and the average %MVIC of three trials was used for analysis (Hermens et al., 2000).

Procedures

Each muscle was subjected to a MVIC, and the EMG signal amplitude was recorded to normalize the EMG data. Participants were requested to carry out three repetitions of 5-second maximal contractions against manual resistance in specific muscle test positions. These positions were where the muscle exhibits the highest activation for the surface EMG measurements of the MVIC values of the forearm muscle groups on both sides. There was a 30-second rest period between each repetition. The MVIC value of each muscle was measured three times with a 1-minute rest period between repetitions.

After the MVIC assessment, participants were given a 5-minute rest period. Then, two different conversations were held with the individuals. The first conversation served as a control condition and was non-addiction-related. It lasted for 3 minutes and did not include any addiction-related keywords or cues (Basal Level—BL). The content of the conversation consisted of standardized structured interview questions, such as the participants' place of birth, number of siblings, their parents' profession, marital status, who they live with, and whether they have children. The

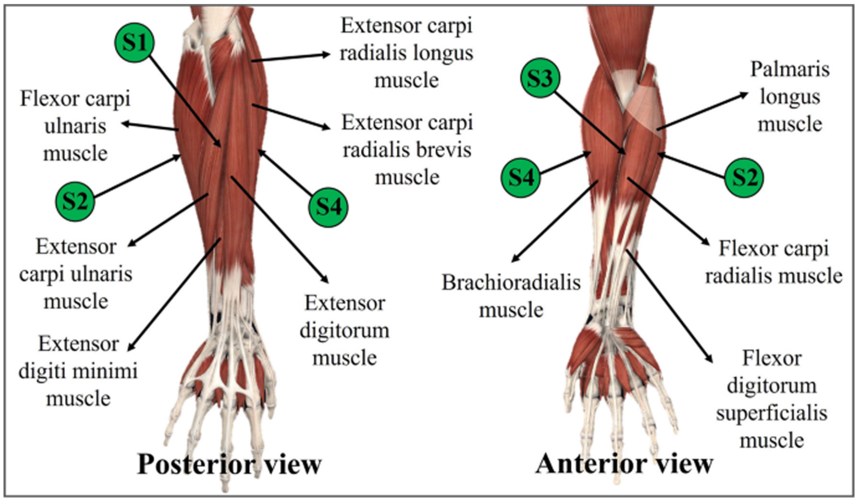

Figure 1. Superficial EMG Electrode Placements According to SENIAM Criteria (Gomez-Correa & Cruz-Ortiz, 2022).

questions were: 1. Where is your birthplace? Can you tell us a little about this place? 2. How many siblings do you have? 3. What is your parents' profession? 4. What is your marital status? If you are married, do you have children? 5. Who are you currently living with? After another period of rest, the second stage introduced a 3-minute speech delivered by a psychiatrist specifically addressing drug addiction (substance-related topics-SRT).

During the conversation, we used a standard structured interview form with questions about the patients' first substance use, including their age at first use, the type of substance they started with, their initial feelings when they used it, the duration of their substance use, the current types of substances they use, frequency of use, their feelings while using the substance, how they use it, and how they feel when they don't use it. Each question was designed to gather specific information: 1. At what age did you use substances for the first time and what was the first substance you used? 2. Can you talk about what you felt when you first used substances? 3. How long have you been using substances, and what substance(s) do you use now? 4. How often and in what ways do you use substances, and what are your feelings about the substance you use now? 5. Can you talk about your feelings when you don't use substances?

We also recorded synchronized video footage using a Logitech Web camera alongside EMG measurements to monitor participant responses. Participants were instructed to maintain a neutral position with their arms resting comfortably on the table without moving their forearms and hands. Electromyography signals were continuously recorded from their forearm muscles during both stimuli presentations (Figure 2).

Statistical Analysis

The data analysis was conducted using IBM SPSS Statistics 26. The normality of the variables was assessed both visually (using histograms and probability plots) and analytically (using Kolmogorov – Smirnov and Shapiro – Wilk tests). Descriptive statistics were presented as mean ± standard deviation, median (minimum; maximum) for numerical variables, and frequency (percentage) for categorical variables. The Wilcoxon signed-rank test was used to determine the difference in repeated measurements between the two factors on %MVIC for individuals with SUDs and to compare the dominant and non-dominant sides. The effect size was interpreted as "small" (0.10 – <0.30), "medium" (0.30 – <0.50), and "large" (0.50 and above). Statistical significance was set at $p < .05$ (Field et al., 2012).

A post-hoc power analysis of our study was performed with G*Power software, using the right FCR muscle as the primary outcome. According to the analysis, with an effect size of 1.761 and $\alpha = 0.05$, the study power was estimated to be 99% (Field et al., 2012).

Results

This cross-sectional study involved 16 individuals with SUD, including one woman and 15 men, all of whom were right-handed. The average age and body mass index of the participants were 29.38 ± 5.25 years and 23.16 ± 2.74 kg/m^2, respectively. The average mini-mental state test score for the individuals was 28.63 ± 1.54. Upon examining the duration of substance use, it was found that the minimum duration was 3 years, the maximum was 25 years, and the average duration was 12.5 ± 6.26 years. All individuals reported using substances daily. The socio-demographic data and substance use characteristics of individuals are shown in Table 1.

In our study, we found a statistically significant difference in individuals' basal EMG activities and EMG activation when they were exposed to substance-related topics ($p < .001$). This difference had a significant effect size, as shown in Table 2.

No statistical difference was found when comparing the differences between basal level and exposure to substance-related

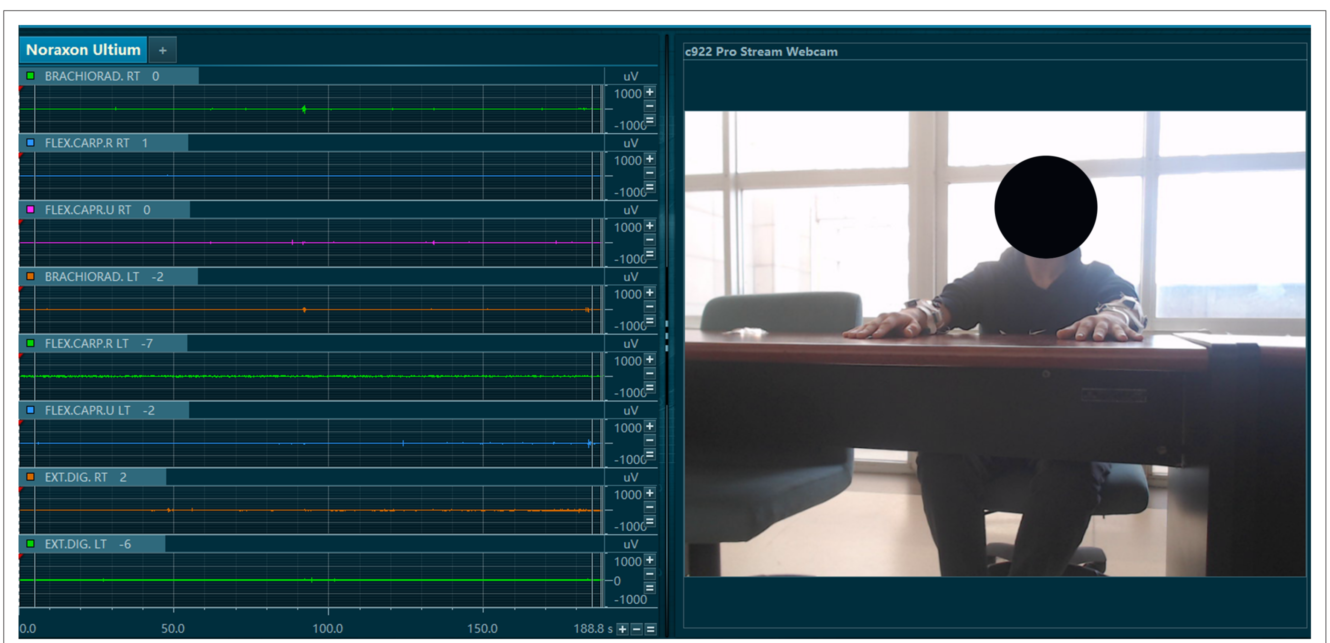

Figure 2. Participant Position and EMG Recordings during Two Different Sound Conversations.

Table 1.
Socio-Demographic Data and Substance Use Characteristics of Individuals

N = 16	Mean ± SD	Min – Max
Age (year)	29.38 ± 5.25	23 – 37
BMI (kg/m^2)	23.16 ± 2.74	18.92 – 29.04
Mini mental state test score	28.63 ± 1.54	24 – 30
Substance use duration (year)	12.50 ± 6.26	3 – 25
	n	%
Gender		
Male	15	93.75
Female	1	6.25
Dominance		
Right	16	100
Left	0	0
Education level		
Primary school	1	6.25
Secondary school	4	25.00
High school	10	62.5
University	1	6.25
Marital status		
Single	11	68.75
Married	5	31.25
The substance currently used		
Poly-drug	5	31.25
Metamphetamine	5	31.25
Synthetic cannabis	1	6.25
Cocaine	1	6.25
Heroin	4	25.00
The first substance use		
Cannabis	14	87.50
Metamphetamine	1	6.25
Heroin	1	6.25

Note: BMI = Body mass index; *N* = number; SD = standard deviation.

topics of dominant and non-dominant forearm EMG activities ($p > .05$), as indicated in Table 3.

Discussion

In our study examining implicit muscle activity in individuals with SUD, we found that when discussing their substance use histories, the EMG activities of the BHR, FCU, FCR, and EXD muscles were significantly higher compared to conversations unrelated to substance use. While various studies exist on muscle activation during different imagery methods, ours is the first to explore muscular activations during dialogue about substance use histories in individuals with SUD. We believe that the results of our original study offer a new perspective on identifying potential physical signs of implicit substance cravings in substance users.

Several studies have shown that when people imagine performing a physical action, similar brain networks are activated as when they actually perform the action. These brain networks include the primary motor cortex, premotor cortex, cerebellum, and somatosensory cortex. This activation leads to the involvement of various muscles related to the imagined action (Bakker et al., 1996; Wehner et al., 1984; Weiss et al., 1994). In our study, participants may have engaged in mental imagery of past substance use experiences, such as searching for, purchasing, carrying, and using substances, even if they were not directly instructed to do so. This could have resulted in increased forearm muscle activity, as measured by EMG.

Research on tasks such as motor imagery has demonstrated that there is a slight increase in EMG activity in the muscles involved in the imagined action (Magill & Lee, 1998; Schmidt et al., 2018). Furthermore, studies have indicated that this phenomenon is related to whether the muscle involved is the dominant or non-dominant one. In a particular study, participants were instructed to mentally visualize hand movements using either their right or left hand, and disparities were observed in the lateralization of the motor cortex between those who used their right hand and those who used their left hand during the mental imagery of hand movements (Willems et al., 2009). In our study, participants were not given specific imagery tasks for either arm. Due to reasons such as individuals often using both arms for tasks like purchasing, carrying, operating devices, and using substances, an increase in activation may have been observed in the EMG of both forearms. A study on tennis players found that muscle activation differed between the dominant and non-dominant extremities during different phases of a backhand stroke performed with both hands (Tai et al., 2022).

In our study, we found that during conversations about substance use, there was a noticeable difference in muscle activation between the dominant and non-dominant sides for certain muscles. The BHR, FCU, and EXD muscles showed more pronounced activation in the dominant side, while the FCR muscle had more pronounced activation in the non-dominant side. Our findings suggest that the increased activity in the non-dominant FCR muscle, which is responsible for grasping, may be related to the specific support needs for non-dominant forearm functions, such as grasping, during substance use processes like procurement, preparation, and usage.

Traditional models state that language processing occurs in specialized brain areas, such as the Broca and Wernicke areas, as an abstract, rule-based system (Pulvermüller, 2005). However, recent neuroimaging evidence shows connections between language areas like the dorsal/ventral premotor cortex and the left inferior frontal (Broca's area) and superior temporal (Wernicke's area), suggesting potential information flow between cortical systems for language and motor action (Pulvermüller, 2005). Recent theories of embodied language processing propose that brain structures traditionally linked to perceptual and motor processes are also involved in processing language related to perception and action (Hauk et al., 2004).

According to research, the processing of verbal materials can engage neural structures associated with motor control for

Table 2.
Analysis of the Individuals' Basal EMG Activities and EMG Activation during Exposure to Substance-Related Topics

***N* = 16**	**Basal Level EMG**		**EMG Activation During Exposure to SRT**				
	Mean ± SD	**Min – Max**	**Mean ± SD**	**Min – Max**	***p***	***Z***	**Effect Size**
Brachioradialis-right	1.41 ± 1.31	0.19 – 5.15	10.02 ± 7.65	2.47 – 34.30	<.001	−3.516	1.372
Brachioradialis-left	1.48 ± 1.15	0.30 – 4.78	9.66 ± 6.90	3.54 – 28.00	<.001	−3.516	1.350
Flexor carpi ulnaris-right	3.67 ± 2.99	0.03 – 9.89	11.54 ± 6.48	3.45 – 24.80	<.001	−3.517	1.385
Flexor carpi ulnaris-left	2.69 ± 2.50	0.70 – 9.66	9.63 ± 4.20	3.47 – 16.40	<.001	−3.517	1.821
Flexor carpi radialis-right	2.34 ± 1.96	0.30 – 7.03	7.94 ± 3.05	4.01 – 14.00	<.001	−3.517	1.761
Flexor carpi radialis-left	2.30 ± 1.72	0.42 – 5.74	9.18 ± 3.91	3.54 – 16.90	<.001	−3.516	2.532
EXD-right	4.75 ± 3.69	1.13 – 12.90	13.84 ± 9.96	5.67 – 41.20	<.001	−3.516	1.039
EXD-left	5.15 ± 3.97	1.15 – 13.10	12.20 ± 6.32	4.65 – 26.40	<.001	−3.517	1.318

Note: EMG = Electromyography; EXD = Extensor digitorum; *N* = Number; SD = Standard deviation; SRT = Substance related topic.

action verbs, even when individuals are concurrently involved in distracting tasks (Hauk et al., 2004; Pulvermüller, 2005). In a study involving the passive reading of action words such as "lick," "pick," or "kick," functional magnetic resonance imaging revealed that reading these words activates specific structures (left inferior frontal cortex, motor cortex, and premotor cortex) similar to those engaged during the actual performance of corresponding movements (Hauk et al., 2004). Several studies using electroencephalography and magnetoencephalography have indicated that the pattern of activation in the cortex when processing action verbs related to concrete actions corresponds to the cortical representation of the action indicated by the word (Hauk et al., 2004; Shtyrov et al., 2004).

In our study, we found that when participants discussed their substance use experiences, there was increased activity in the motor cortices and relevant muscles, even though they were not intentionally imagining physical movements. This raised the question of why the increase in muscle activation when talking about substance use was more significant compared to other past physical activities, like work. This could be because people used more action-oriented words when discussing their substance use or because it triggered cravings.

When a person uses drugs, their brain may link certain cues, like where they use the drug or who they use it with, to the effects of the drug. This can cause the person to pay more attention to these cues and automatically feel a stronger urge to use the drug when they encounter them, even if they are not aware of it (Fridland & Wiers, 2018). This automatic and rapid response to drug-related cues is known as drug approach bias. It is a common phenomenon among people who use substances like drugs or alcohol (Field et al., 2013; Fridland & Wiers, 2018). As per the drug approach bias model, approach behavior is seen as an integral part of the desire to use drugs rather than a separate and independent response (Fridland & Wiers, 2018). In this context, the rise in EMG activation in the forearms while participants discuss their substance use histories may indicate their conscious or unconscious drug cravings and implicit drug-seeking or usage behaviors that can be gauged through forearm muscles.

People often use gestures when describing their mental images (Hostetter & Alibali, 2008). Gestures made during speech are spontaneous movements of the hands and arms that closely represent the meaning in the accompanying speech. Various gestures involving hand and arm movements are widely accepted as valid evidence of the bodily representations of language and cognition (Hostetter & Alibali, 2008). Gestures directly convey spatial or motor features rather than through verbal or propositional codes (Morsella & Krauss, 2004).

When someone says, "Turn left after the light" while moving their hand to the left, this gesture helps convey the concept of "left" and reflects the speaker's mental image. Research indicates that gestures work with speech to facilitate communication about mental images (Hostetter & Alibali, 2008). The lexical access hypothesis

Table 3.
Comparison of the Differences between Basal Level and Exposure to Substance-Related Topics of Dominant and Non-Dominant Forearm EMG Activities

***N* = 16**	**Right**		**Left**			
	Mean ± SD	**Min – Max**	**Mean ± SD**	**Min – Max**	***p***	***Z***
Brachioradialis	8.61 ± 7.22	0.71 – 30.98	8.18 ± 6.63	2.43 – 26.61	.756	−0.310
Flexor carpi ulnaris	7.87 ± 5.25	1.78 – 17.90	6.94 ± 2.99	2.62 – 12.07	.959	−0.052
Flexor carpi radialis	5.60 ± 2.76	2.62 – 11.23	6.88 ± 3.83	1.93 – 12.69	.109	−1.603
Extansor digitorum	9.09 ± 8.21	4.40 – 30.93	7.05 ± 3.85	1.84 – 15.47	.326	−0.982

Note: *N* = Number; SD = standard deviation.

suggests that people use more gestures when word retrieval is difficult (e.g., when trying to name something challenging or unfamiliar). Conversely, speech becomes less fluent when gestures are prohibited (Morsella & Krauss, 2004). In our study, participants were asked to refrain from making gestures while discussing their substance use experiences, which resulted in suppressed gestures that would normally accompany their speech. This suppression may have caused implicit muscle activation in both forearms. However, the significant increase in activation during conversations unrelated to substance use, compared to those related to substance use within the same timeframe, suggests that other factors may contribute to this phenomenon.

Our study on embodied cognition in SUD revealed significant findings but had some limitations. These included a small sample size of 16, which may affect the generalizability of the results. The focus on forearm EMG responses to conversational cues may only partially represent SUD's broader embodied cognition responses, potentially missing other manifestations of substance cravings. The absence of a non-SUD control group also hinders our ability to determine if the observed EMG activations are specific to SUD. Furthermore, the study's cross-sectional design limits our ability to conclude causality or changes in embodied cognition responses over time. This suggests a need for more extensive, diverse, and longitudinal studies to deepen our understanding of these phenomena.

In summary, the significant increase in EMG activation observed when discussing substance-related topics suggests a potential connection between conscious or unconscious motor imagery and the conversation content, language processing, or substance cravings. A complementary study involving individuals in remission from substance use could help determine if these EMG responses indicate latent cravings associated with SUD. This study hypothesizes that the cravings experienced by individuals with SUD may be subconsciously expressed through forearm muscle activations. It's important to note that participants were unaware of the study's objectives and received no guidance or instructions that might influence their focus on motor-related activities. Conversely, they were explicitly instructed to remain still, supporting our belief that the recorded muscle activation patterns were not due to intentional motor preparation or execution.

In future research focusing on embodied cognition in SUD, it is important to include a wider range of participants and larger sample sizes to ensure more comprehensive results. Additionally, incorporating control groups without SUD is crucial for comparison, and expanding muscle activity monitoring to areas beyond the forearms will provide a more detailed view of embodied cognition responses. Longitudinal studies can help in understanding changes in EMG activity over time, especially in relation to treatment interventions. Further exploration into the roles of motor imagery and substance use cravings, as well as the impact of language processing on EMG responses, could yield significant insights. The utilization of advanced EMG analysis techniques, such as wavelet analysis or machine learning, may reveal more intricate data patterns. Comparative studies across different substance types could shed light on the distinct effects of various substances on embodied cognition. Lastly, investigating the potential preventive and therapeutic applications of understanding embodied cognition responses in SUD could lead to the development of new treatment approaches, advancing both theory and practice in the field.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Ethics Committee Approval: The study was ethically approved by the ethics committee of Health Sciences Ethics Committee of Ankara Training and Research Hospital dated October 27, 2023, No. 392-08).

Informed Consent: Written informed consent was obtained from the participants who agreed to take part in the study.

Peer-review: Externally peer-reviewed.

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