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Perceived peripersonal space in unilateral segmentary exclusion of the upper limb

Pierrick Herbé

pierrick.herbe@ugecam.assurance-maladie.fr

Louis Pierquin Centre of the Regional Institute of Rehabilitation, UGECAM Nord-Est

Marion Birck

Louis Pierquin Centre of the Regional Institute of Rehabilitation, UGECAM Nord-Est

Amélie Touillet

Louis Pierquin Centre of the Regional Institute of Rehabilitation, UGECAM Nord-Est

Jonathan Pierret

Louis Pierquin Centre of the Regional Institute of Rehabilitation, UGECAM Nord-Est

Nathanaël Jarrassé

Sorbonne University, UPMC Univ Paris 06, CNRS, UMR 7222, INSERM U1150

Jean Paysant

Louis Pierquin Centre of the Regional Institute of Rehabilitation, UGECAM Nord-Est

Hadrien Ceyte

Aix Marseille Université, CNRS, ISM

Article

Keywords: segmentary exclusion syndrome, limb disuse, peripersonal space, body representation

Posted Date: May 29th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9678214/v1

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Additional Declarations: No competing interests reported.

Abstract

Peripersonal space (PPS) refers to the multisensory representation of the space surrounding the body and is shaped by motor experience and body representation. Upper limb segmentary exclusion syndrome (UL-SES) is characterized by underuse of a limb segment without identifiable neurological lesion and is associated with altered body perception. Fifteen participants with UL-SES and 27 non affected participants completed a previously validated reachability judgment task assessing perceived maximum reachable distance (P-MRD) relative to objective maximum reachable distance (O-MRD). Body perception disturbances were evaluated using the BATH scale. Contrary to our hypothesis, PPS perception did not differ between affected and unaffected limbs in UL-SES in participants, nor between UL-SES and healthy participants. These findings may be explained by the focal nature of UL-SES, which mainly involved isolated fingers. However, body perception disturbances were significantly associated with reachability judgment accuracy on the affected side, with greater disturbances linked to more accurate estimations of reachable space. These results provide novel insights into the complex interplay between body representation, limb disuse, and PPS perception in UL-SES, offering potential avenues for therapeutic interventions and highlighting the enduring impact of limb exclusion on spatial perception.

Introduction

Since motor action is the only way for biological organisms to interact with the environment, the cognitive processes necessary to perform an adapted action must take into account not only the characteristics of the external world, but also the state of the body and the potentialities offered by acquired motor experiences[1]. For each action the central nervous system is able to integrate sensory signals allowing individual to perceive itself and its environment[2–4], and to interact with the nearest space called the peripersonal space (PPS), *i.e* the space close to the body where all physical interactions with objects in our environment take place[5, 6]. Perceived PPS has been studied in various populations, for instance in asymptomatic participants who were asked to handle a tool, or in individuals with peripheral and central traumatic injuries[1–4].

Several studies showed that the perceived PPS is flexible and plastic: flexible because perceived PPS can be modulated in response to changes in the environment or changes in an individual's internal state[1, 7], plastic because it can evolve with training, learning and can be modified by a physical injury such as a limb amputation[8, 9]. Indeed, in case of amputation, contraction of the PPS around the residual limb have been reported[8], suggesting that perceived PPS and the individual's body perception are strongly linked.

In clinical practice, a phenomenon characterized by the non-use or under-use of a body segment in individuals without identifiable peripheral or cerebral lesions, or external physical constraints, has been described by Andre et al. [10] as segmentary exclusion syndrome (SES). This condition has been compared to a neglect-like behavior of peripheral origin that may occur following a triggering event such as trauma, infection, inflammation, or surgery. In SES, the affected limb is typically under-used, whereas

the non-affected limb is often over-used as a compensatory strategy[11]. Body perception disturbances are frequently reported in individuals with upper limb SES, although their severity is rarely quantified. Individuals with SES may describe sensations of strangeness toward the affected limb or a feeling that the limb does not belong to the rest of the body. In some cases, these perceptions may intensify to feelings of disgust or even requests for amputation of the troublesome limb[10]. Although the syndrome may initially be transient, its persistence can lead to marked functional impairment and prolonged disuse of the affected limb[12].

No study to date has raised the question of the alteration of the perceived PPS in SES.

The main objective of our study was to assess the perceived PPS in individuals suffering from SES of the upper limb (UL-SES) during use of their affected and unaffected upper limb. We expected that individuals with UL-SES contract their perceived PPS when they use their affected limb. We also compared perceived PPS between individuals with UL-SES and healthy participants and explored the effect of limb dominance on this spatial perception. At last, we checked the relation between perceived PPS and body perception.

Materials and methods

Ethics statement

The study protocol was approved by the Comité de Protection des Personnes Ile-de-France VIII ethics committee (CPP 21.06.57; ID-RCB 2021-A01432-39). All procedures were performed in accordance with the ethical standards of the institutional and national research committee and with the 1964 Declaration of Helsinki and its later amendments. Oral and written informed consent was obtained from all participants prior to inclusion in the study. Participants can revoke their consent at any time.

Participants & Eligibility Criteria

The inclusion criteria in the UL-SES group were being adults aged 18 years or older presenting with UL-SES and no contraindication to intense work in daily living activities due to current injuries. The diagnosis of UL-SES was based on the 400-points score carried out by an occupational therapist[13]. This assessment evaluates four functional criteria of the hand thanks to independent tests: mobility (test 1), strength (test 2), monomanual grip and object movement (test 3), and bimanual function (test 4). Each dimension is scored out of 100 points, with the total score expressed as a percentage of the maximum 400 points. This test assesses both the ability to perform the movement and the quality of its execution. The minimum number of disturbed items (due to exclusion) was set at a minimum of 2 results for tests 3 and 4, meaning that the limb was either non-used or under-used. Participants were not included if they had visual impairment, a history of sensory, cognitive, or psychological impairment, or central neurological pathology.

Participants unable to give informed consent, with visual impairment, having a history of sensory, cognitive, or psychological impairment and/or central neurological pathology, adults under legal protection measures or those unable to provide informed consent were not included.

Dominant hand was determined by self-reporting, verified by observation when signing the informed consent.

UL-SES participants were questioned about the details of their condition: date of onset, duration of evolution, level of exclusion, occupation, hobbies. A clinical examination was then performed to check in UL-SES participants the presence of sensory disorders, trophic disorders, joint stiffness, or tendon adhesions. We conducted assessments to evaluate both pain and thymia. Specifically, we utilised two questionnaires and clinical examinations. The DN4[14] questionnaire was used to screen for neuropathic pain, and the HADS (Hospital Anxiety and Depression scale[15]) was used to evaluate symptoms of anxiety and depression.

Healthy participants (HP) were recruited through local advertisement and among volunteers at the rehabilitation institute. Inclusion criteria were being adults aged 18 years or older, had confirmed their non-opposition to participate, did not meet any of the non-inclusion criteria described above, and were not receiving antidepressant treatment.

Required sample size

The sample size was estimated based on the study by Gouzien et al.[9], which used the same experimental paradigm in participants with upper limb amputation. In this study, the reachability judgement (RJ) error was 3.71% ± 5.44% in healthy participants (n = 30) and 9.11% ± 5.92% in participants with UL-SES (n = 11), yielding a large effect size (Cohen's d = 0.95). Based on these values, a two-sided independent samples t-test with $\alpha = 0.05$ and 80% power required a minimum of 18 participants per group. Given the exploratory nature of the study and the difficulty in recruiting participants with UL-SES, we aimed to include at least 15 participants with UL-SES and 27 healthy participants. While the UL-SES group was slightly below the calculated requirement, the healthy group exceeded it, providing sufficient statistical power for the primary between-group comparison.

Experimental protocol

The experimental set-up used for this study is the same as for the study of Gouzien et al.[9]. It consists of a table of 1.15m wide and 1.50m deep, supporting a cardboard cabin limiting the external visual disturbances. In addition, participants wore noise-cancelling headphones to reduce the risk of sound disturbance. A projector was mounted on a tripod on one side of the table and allowed computer-generated images, here a green circle of 10mm in diameter (the target) to be projected on the table at different positions.

During the experimental protocol, the participants were seated on a chair whose height was adjusted so that each participant's abdomen rested against the table. The participant's trunk and shoulder movements were reduced by positioning his head on a chin strap fixed to the table, perfectly aligned with his sagittal body midline. The middle finger of their tested upper limb was placed on a luminous square (the start area) on the table located at 23cm in front of the sagittal body midline axis, as illustrated in Fig. 1.

Experimental assessments

First, positioned on the experimental set-up, with their eyes closed, all participants had to push a small plastic cart equipped with a tape measure as far as possible in front of them, successively with one of their two upper limbs in order to determine the maximum objective achievable distance (O-MRD) on the median axis of the sagittal body for each of the two upper limbs.

Then, they were asked to estimate for each upper limb separately if they were able to reach different target positions (n = 25; ± 9.6cm, in 8mm increments, from the O-MRD) placed along their sagittal body midline axis without moving their hand positioned in the start area: if the projected target is estimated reachable ("yes, I can reach this target"), they had to press the green button with the hand of their non-tested upper limb if not ("no, I cannot reach this target") they had to press the red button. Once the response was delivered, the next target position appeared after a randomised delay of 500 to 1000ms. Each target position was randomly tested 5 times per upper limb. Thus the furthest target position from the body perceived as reachable allowed us to determine the perceived maximum reachable distance (P-MRD) on the sagittal body midline axis for each of the two participant’s upper limbs.

A computer recorded the positions of the targets and associated responses (O-MRD, P-MRD).

Before installing the UL-SES participants in front of the experimental setup, each of them was asked to respond to a French translation of the BATH CRPS Body Perception Disturbance Scale[16]. This survey, designed to evaluate body perception disorders in individuals with Complex Regional Pain Syndrome (CRPS), consisted of two main parts. The first part focused on the individuals' perceptions of their affected limb, while the second part explored their internal representation of both the affected and unaffected body parts. The total sum of the different items of the survey on the disturbance of body perception gives a global score. A higher score indicates a greater disturbance, 57 being the maximum score.

Data processing and statistical analysis

The RJ for each participant and for both upper limbs was determined by an individual logistic regression model for binomial distribution, calculated based on the percentage of "yes, I can reach this target" responses over the total number of responses for each target position. The intercept of this curve (p = 0.5) corresponds to RJ. The percentage error of the RJ relative to the O-MRD was calculated. A positive

RJ means that the P-MRD is greater than the O-MRD and thus that the participant overestimates his O-MRD. A negative RJ means that the participant underestimates his O-MRD.

Quantitative data were expressed as the mean (M) ± standard deviation (SD) often associated with range [min-max]. For each group, the data were normally distributed (Shapiro-Wilk test, ps > 0.05) and homogeneity of group-variances occurred (Levene's test, ps > 0.05). Therefore, parametric statistical analyses were computed. In order to explore the effect of the upper limb dominance on the RJ a Student's t-test was performed only in the healthy group. Then a mixed-design analysis of variance was performed in order to assess the effects of dominance side factor (Yes, No) and of tested side factor (affected, no-affected) in the UL-SES group on the RJ data. Furthermore a Student's t-test was used to compare the RJ between the groups whatever the dominance.

At last, in order to assess the relationship between the body perception disorders in participants with UL-SES and the RJ, a Spearman's correlation between score at the adapted BATH Scale and their RJ-error was performed.

All statistical analyses and graphs were performed using R software® (version 4.1.2). The threshold for statistical significance (α) was at 0.05.

Results

Descriptive data

15 participants with UL-SES (including 9 females, aged from years, mean age = 44.9 ± years old [22 to 63]) and 27 HP (including 21 females, mean age = 37.6 ± years old [20 to 62]) were included in this study performed at the Regional Rehabilitation Institute in Nancy, France.

Twenty-four HP (88%) and 14 UL-SES were right-handed (93%), 3 HP and 1 UL-SES were left-handed. Complete characteristics of UL-SES participants are reported in Table 1.

Table 1
Characteristics of the UL-SES participants and healthy participants. n (%); Mean {SD}; Range []; N/A : not applicable; * significant difference at $p < 0.05$, F1 : finger one (thumb), F2, 3, 4 & 5 : finger two, three, four and five (fifth being the little finger).

Number of female	**UL-SES group (n = 15)**	**Healthy participants (n = 27)**
	9	**21**
Age	44 [22–63]	37.6 [20–62]
Mean 400 points score	227.4 {46.1}	N/A
Dominant side	Right, N = 14 Left, N = 1	Right, N = 27 Left, N = 3
Affected side		
Right	5 (35.7%) 1 (100.0%)	N/A
Left	9 (64.3%)	N/A
Affected segment		
F1	1 (7.7%) 0 (0.0%)	N/A
F2	7 (53.8%) 0 (0.0%)	N/A
F3	2 (15.4%) 1 (100.0%)	N/A
F3, F4, F5	2 (15.4%) 0 (0.0%)	N/A
F4, F5	1 (7.7%) 0 (0.0%)	N/A
Unknown	1	N/A
Mean exclusion delay (month)	8 [7–30] 7 [7–7]	N/A
HAD score		
Mean Anxiety (/21)	10.73 [2–18]	5 (0–17)
Mean Depression (/21)	5.53 [2–15]	1.47 (0–7)
Pain (0–10)		
Mean at rest	2.4 [0–8]	0
Mean at use	4.7 [0–10]	0.05 [0–3]

Effects of affected and dominance side on RJ in UL-SES participants

The RJ of UL-SES, according to the affected side and according to the dominance side are depicted in Fig. 2.

There was an overall overestimation of P-MRD. No significant difference in RJ was observed between the affected and non-affected side sides (7.5% ± 5 for the affected side vs 5% ± 6 for the non-affected side, t(14) = 1.62 *p* = 0.13).

There was no significant difference in RJ-errors according to the dominant side (6% ± 5 for the dominant side vs 6% ±6 for the non-dominant side, t(14) = 1.62 p = 0.13)

A mixed design analysis of variance (dominance side * tested side) revealed no significant interaction effects ([F(1,26) = 0.22, p > 0.05]).

Effect of limb dominance on RJ in healthy participants

For RJ in HP, there was an overall non-significant overestimation of the P-MRD compared with the O-MRD. No significant difference was observed between the dominant and non-dominant sides, regardless of handedness ([t(26) = 1.74; p = 0.09]).

As for UL-SES participants, there was an overall overestimation of P-MRD.

Comparison of RJ between UL-SES and healthy participants

No difference on the RJ between HP and UL-SES groups was shown ([t(24,73) = -1.96 p > 0.061]) Fig. 2.

Relationship between the body perception disturbances and the RJ in UL-SES participants

In the UL-SES group, the mean BATH score was 15.53 ± 9.55. A moderate-to-strong significant correlation between the BATH score and the RJ was observed on the affected side (; r = − 0.65; p = 0.009). This result indicates that participants with greater disturbances in body representation tended to estimate their reachable distance more accurately.

Table 2
Relationship between the body perception disorders in participants with UL-SES and the RJ-error in UL-SES participants, using Spearman's correlations.

Spearman's Correlations		
Variable		RJ-Error
BATH	Spearman's rho	-0.650
	p-value	0.009

Discussion

The main aim of our study was to compare the forward perceived PPS between participants with UL-SES and healthy participants. Our results highlight several important facts.

First, no significant difference was found between the affected and non-affected side in UL-SES participants. This result is against our initial hypothesis. Indeed, the affected limb is underused in UL-SES, while the contralateral limb may be overused as a compensatory strategy[10, 11]. In line with this idea, Bassolino et al.[17] showed that immobilisation of a limb resulted in a contraction of PPS representation around that limb and an unaltered PPS representation on the overused contralateral side. However, it was difficult in our study to assess whether the affected limb was underused and the contralateral limb overused as upper limb activity in daily life was not measured. Moreover, it is challenging to speak of complete immobilisation in our case because we observe more of a hypomobility in one or several fingers rather than the immobility of the entire upper limb. Indeed, in our study the majority of UL-SES involved only one finger (including 7 participants with affected index finger). Previous research demonstrated the existence of PPS representation specific to different body parts, identifying hand-centred PPS, arm-centred PPS, face-centred PPS and trunk-centred PPS[18]. Regarding more precisely upon upper limb-centered PPS, most of the data focus on the representation of arm- or hand-centred PPS [3, 18]. To our knowledge, there are no studies that report a different PPS representation depending on the fingers of a hand. It is more commonly accepted that PPS representation is centred on the whole hand because actions performed in this space require a global perception of the upper limb.

Second, the comparison of perceived PPS between the UL-SES group and the HP group did not show significant results. These results could also be explained with the hypothesis mentioned above that the SES was highly focal. Indeed, in most participants the condition affected only a single finger rather than the entire hand, which may not be sufficient to induce measurable changes in hand-centred PPS representation.

Third, there was no influence of the dominant side on perceived PPS in both UL-SES and healthy groups. Previous studies have highlighted an asymmetry in this space based on a person's dominant hand [19, 20], particularly when examining the PPS representation. In our study, PPS was assessed along the sagittal axis directly in front of the body (referred to as right straight ahead), focusing in the peri-trunk PPS rather than focusing on right or left hemispaces. It is worth mentioning that there are differing opinions on whether PPS representation differs or remains consistent across all directions. For instance, research has explored PPS representation at the back of the body using audio-tactile or visual-tactile stimuli, revealing asymmetry between the front and back of the body, with studies suggesting that the PPS in the front of the body tends to be larger than at the back[4]. In contrast, Serino et al.[18] studied PPS representation around the trunk in the front and back spaces with visual-tactile stimuli and found that the peri-trunk PPS is symmetrical between the front and back spaces. Similarly, Matsuda showed no difference in the representation of the right and left peri-trunk PPS in healthy participants[21]. Taken together, these findings suggest that dominance-related asymmetries in PPS may primarily emerge when PPS is measured in limb-centred reference frames rather than trunk-centred spaces. The absence of

dominance effects observed in the present study may therefore reflect the trunk-centred nature of the PPS assessed in our paradigm.

During the experiment, a protective attitude of the UL-SES participants towards their affected finger(s) was observed. While such protection is legitimate just after an early lesion but the persistence of this protective attitude after wound healing may be considered maladaptive. This observation may reflect an increased vigilance toward the space surrounding the affected limb. The functional organisation of PPS proposed by de Vignemont et al.[22] may provide a useful framework for interpreting these observations. Indeed, they proposed that PPS can be divided into two functional components: a defensive PPS, involved in protecting the body from potential threats, and a goal-directed action PPS, involved in planning and guiding voluntary actions. Previous studies have suggested that these two PPS representations may be dissociated in certain clinical populations. For example, Gouzien et al.[23] showed that individuals with depression overestimated their goal-directed action PPS but underestimated their defensive PPS. Conversely, Sambo et al.[24] reported that individuals with higher anxiety levels exhibited an enlarged defensive PPS, suggesting that anxious individuals perceive potentially threatening stimuli as closer to their body than they really are. In our study, UL-SES participants showed higher anxiety level as measured with the HAD scale, with mean score reaching the threshold suggestive of an anxiety disorder (mean A score = 11 vs 5 in HP, significant score if ≥ 11). However, no correlation was found between HAD score and RJ, perhaps due to lack of statistical power. Although the difference in RJ between groups did not reach statistical significance, values tended to be higher in UL-SES participants, suggesting a trend toward overestimation of their O-MRD. Taken together, these findings may support the hypothesis of an increased defensive PPS in UL-SES, potentially driven by heightened anxiety and persistent protective behavior.

Although the BATH questionnaire was originally designed to assess body perception disturbances in individuals with CRPS, it allowed us to capture alterations in body representation in UL-SES participants. Importantly, we observed that higher BATH scores were associated with P-MRD closer to O-MRD. In other words, UL-SES participants with greater disturbances of body representation tended to provide more accurate RJ. One possible explanation is that the initial lesion may have altered the individual's self-representation, which could influence how individuals interact with their surrounding environment. From this perspective, disturbances in body representation may modulate the PPS. Given that defensive PPS is thought to support body protection against potential threats in the space surrounding the body, a more accurate estimation of reachable space may reflect an increased vigilance toward the environment. However, the present study did not specifically distinguish between defensive and goal-directed action PPS. Therefore, this interpretation remains speculative.

Several limitations of the present study should be acknowledged. First, the sample size of the UL-SES group was relatively small, which may have limited the statistical power of some analyses, particularly regarding the relationship between anxiety levels and reachability judgments. Another limitation concerns the use of the BATH questionnaire, which has mainly been validated in individuals with CRPS. Although it allowed us to capture variations in body representation in UL-SES participants, its

interpretation in this population should be considered with caution. In addition, the present paradigm did not allow us to distinguish between defensive and goal-directed action PPS. Future studies using paradigms specifically designed to dissociate these two functional components of PPS would help clarify the mechanisms underlying the observed changes in reachability judgments.

In conclusion, this study explored the perception of perceived PPS in individuals with UL-SES. Contrary to our initial hypothesis, perceived PPS did not differ between affected and non-affected sides, nor between UL-SES participants and healthy individuals. However, disturbances in body representation were associated with changes in RJ, with UL-SES participants showing a more accurate estimation of their reachable distance as body perception disturbances increased. This finding suggests that alterations in body representation may influence how individuals estimate the limits of their perceived PPS. Further studies are needed to determine whether these changes reflect a modulation of defensive mechanisms within PPS in individuals with UL-SES.

Declarations

Acknowledgements

The authors thank all the participants for their participation in the study, the paramedical staff, Dr Anne Foisneau Lottin and Anne-Gabrielle François of the Louis Pierquin Centre of the Regional Rehabilitation Institute, and the University Institute for Health Engineering (Paris Sorbonne Universities).

Author's contribution:

Marion Birck carried out the experiment. Jonathan Pierret and Hadrien Ceyte analysed the data. Pierrick Herbé, Marion Birck and Hadrien Ceyte wrote the manuscript with support from Amélie Touillet, Jonathan Pierret and Nathanael Jarrassé. Jean Paysant supervised the project.

Additional information

Competing Interests: The authors declare no competing financial or non-financial interests related to this work.

Funding: The author received No Funding for this work.

Data Availability

The datasets generated and analysed during the current study are available from the corresponding author on request.

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Figures

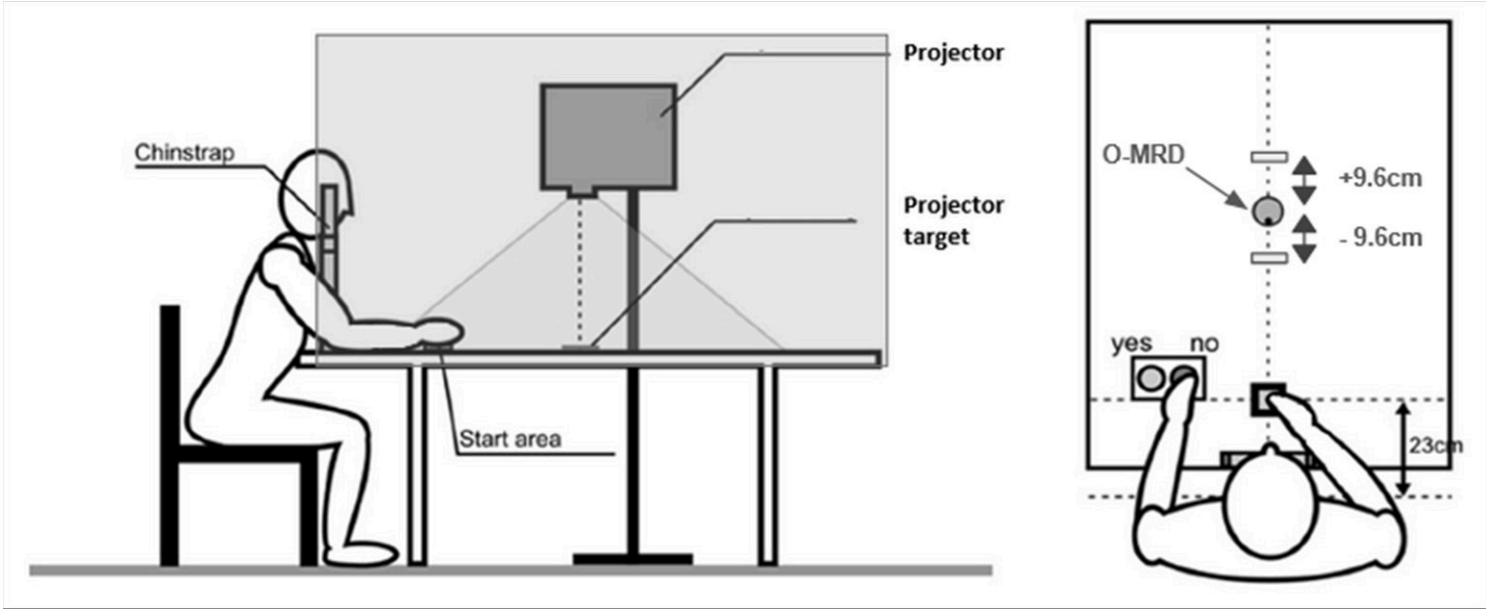


Figure 1

Experimental setup and reachability judgment task (adapted from Gouzien et al.[9]). Participants were seated with the head stabilized by a chin strap aligned with the sagittal body midline. The tested hand was positioned on a start area located 23 cm in front of the midline. Targets (green circle, 10 mm

diameter) were projected along the sagittal axis. The objective maximum reachable distance (O-MRD) was first measured, and multiple target positions were then presented within ± 9.6 cm around the O-MRD. Participants judged by pressing a button (“yes” or “no”) whether each target was reachable, allowing the determination of the perceived maximum reachable distance (P-MRD).

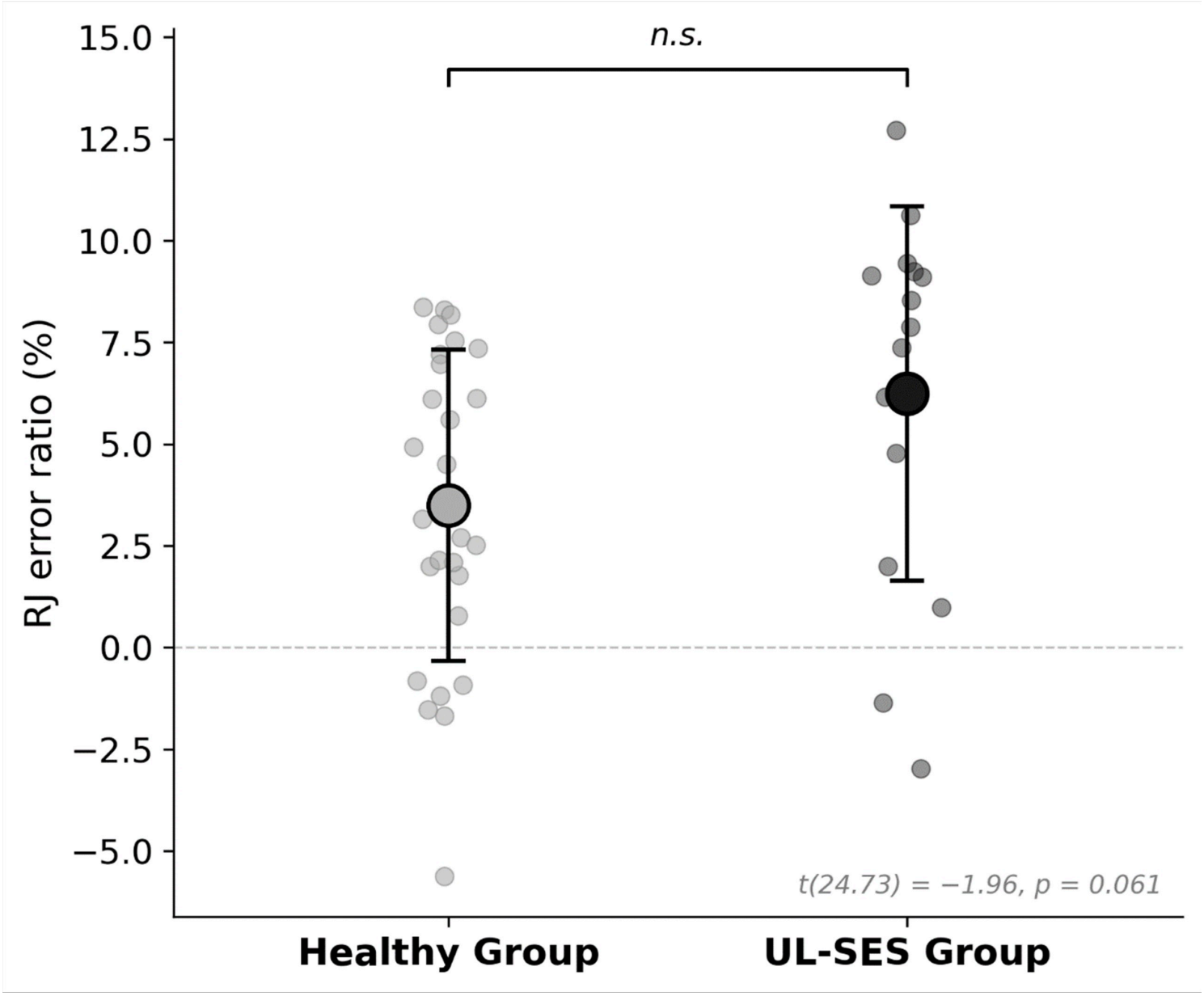


Figure 2

Ratio of reachability judgment error in healthy group and UL-SES group. Distribution of the reachability judgment error ratio (RJ error ratio) for healthy group and UL-SES group. Each dot represents an individual participant, and large dots indicate group means. No significant difference (n.s.) was found between groups (t(24.73) = −1.96, p = 0.061).

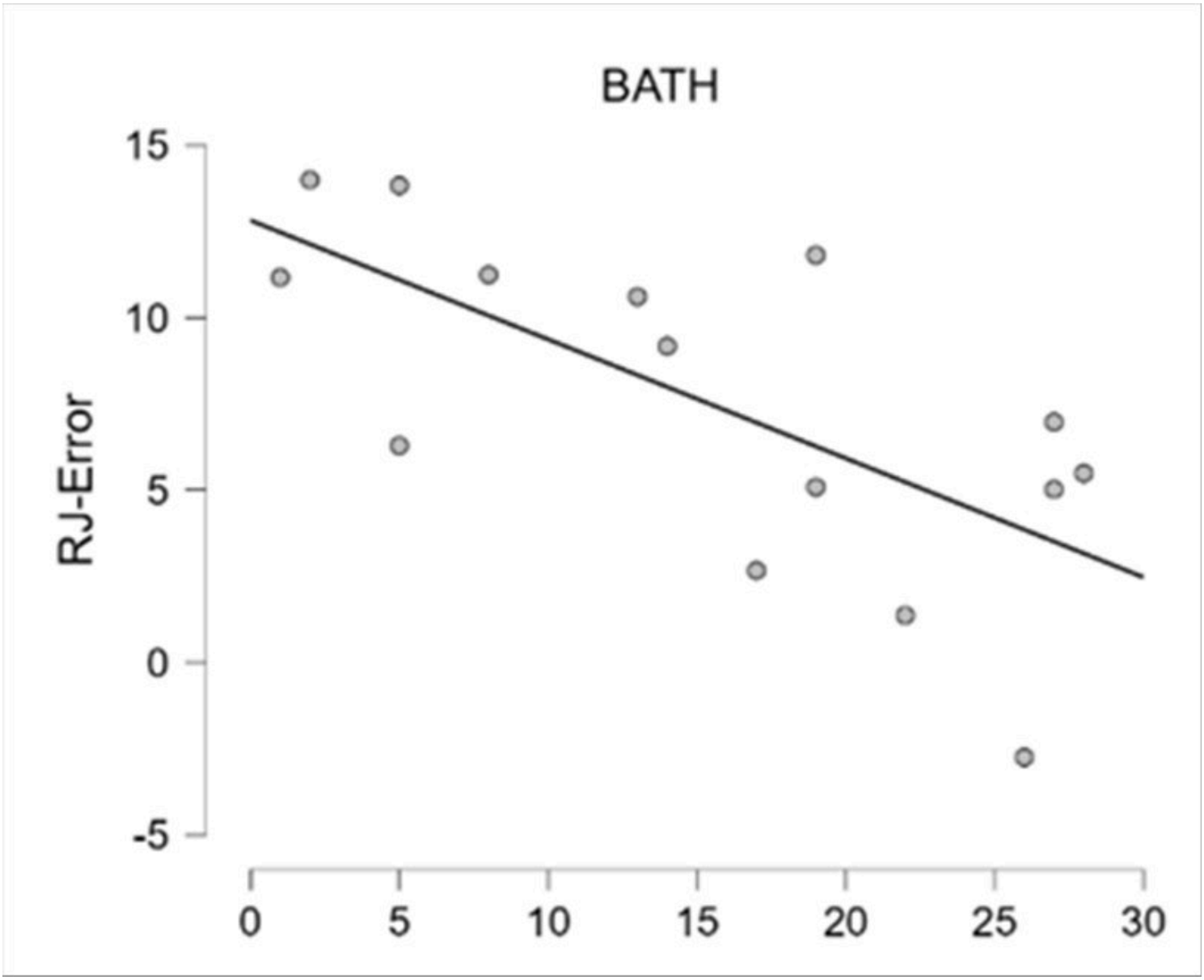


Figure 3

Correlation between the body perception disturbance scale (BATH) and the difference between O-MRD and P-MRD (RJ) on affected side in Upper Limb – Segmentary Exclusion Syndrome (UL-SES) participants.