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Master-Seminar – From Neuroscience to Neurotechnology - Brain Connectivity, Motor Control, Brain-Computer Interfaces, Haptics, and **Embodiment**

Prosthetic Embodiment

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Abstract

This paper review discloses the concept of embodiment in the context of prosthetic devices. Embodiment refers to the state of possessing a physical body and perceiving the external environment through it. In order to describe this process the main focus of research is the psychological and physiological integration of devices with the human body. This review aims to provide a comprehensive overview of the existing literature on prosthetic embodiment, highlighting the frameworks of body representation, ownership and agency. By synthesizing the available knowledge and discussing potential improvements, this review contributes to a better understanding of prosthetic embodiment and its implications for successful prosthesis adaptation and user satisfaction.

Contents

1 Introduction

Embodiment is a state of possessing a physical body and experiencing the environment through it from a unique perspective. This is achieved by developing a sense of what and where one's boundaries are [1]. The sense of embodiment happens for most people unconsciously and is integrated into all sensory experiences, thoughts, and behaviors. However, the sense of embodiment can be disrupted. Reasons for that can be psychological conditions, injuries of the nervous system, or serious injuries to the body, such as major limb amputation, the embodiment is further disrupted or changed by adding a prosthetic limb. [2]

In the field of prosthetic design, the concept of embodiment is of the particular focus area, as embodiment contributes to the user's satisfaction with the prosthetic device and is, therefore, a crucial factor for a successful prosthesis adaption. The satisfaction is achieved by the psychological (e.g., cosmetic aspects) and physiological (e.g., functional aspects) integration of the prosthesis within the body, shaping the user's acceptance and utilization. [3]

Due to the advances in prosthetic technology, improvements in control and sensory feedback have enabled the user to better perceive their artificial limbs [4]. Therefore, the concept of prosthetic embodiment has grown in popularity. As shown in Figure 1.1, there has been a significant increase in the number of scientific papers published in this field.

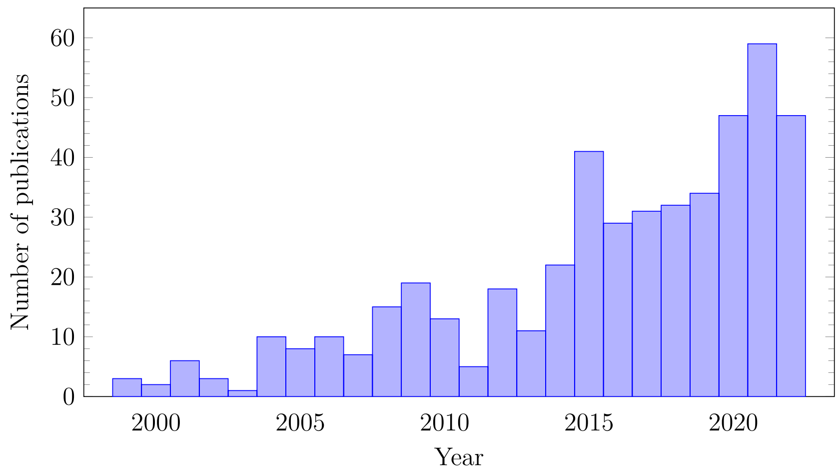

Figure 1.1: Number of prosthetic embodiment related publications listed in the ScienceDirect database.

Apart from prosthetic embodiment, the concept of embodiment has also been applied in other fields, such as philosophy to discuss the way how we experience ourselves and in neuroscience when studying how the brain senses the body. This multidisciplinary influence on the term embodiment and the lack of shared understanding leads to confusion in the research community and complicates the comparison of studies since there is no common understanding of how to measure embodiment as a metric of success. [5]

In this paper, we focus on the prosthetic embodiment. The literature research was conducted on the scientific databases Scopus and Pubmed. As keywords the terms "prosthetic embodiment", "agency", "ownership", "body image" and "body schema" were used. Titles and abstracts were screened and only papers relevant to the research were selected. For further comparison of the literature, the impact score of the papers was calculated via the online platform Resurchify. This helped us to better assess the relevance of the individual papers and we focused on the most relevant work in the field of prosthetic embodiment.

In our review of prosthetic embodiment, we established the framework by defining the keywords and their relations. Furthermore, we examine various methods of measuring embodiment, providing insights into the diverse approaches used to understand the relationship between the perception, body and environment. Finally, we discussed relevant points and potential improvements in prosthetic embodiment research in order to give an outlook on future developments regarding this topic.

2 Background

2.1 Prosthesis embodiment framework

In order to successfully formalize the process of prosthetic embodiment, the following section outlines frameworks and their relevant definitions. The process of embodiment is multi-disciplinary, as well as their measuring embodiment span fields. Therefore, this review contains research outcomes across psychology, neural engineering, and cognitive neuroscience. The overall aim is to shape the user's utilization and acceptance of the prosthetic devices within the body due to psychological and physiological integration [3].

Among various methods of capturing the embodiment, this paper is focused on psychophysical or experimental phenomenological strategies due to its scientific investigability.

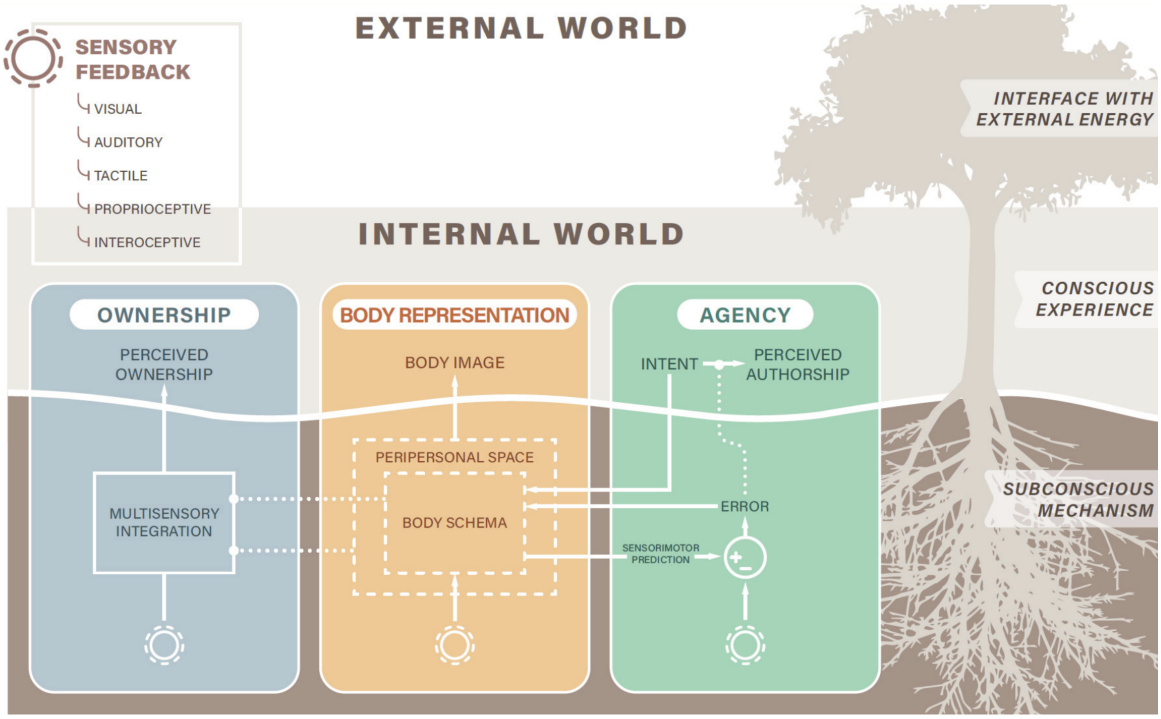

Figure 2.1: Measuring embodiment: A review of methods for prosthetic devices, [2]

Psychophysics is commonly associated with stimuli and perception, but the concept of empirically measuring and correlating brain states and sensory experience can also be applied to volition and action. Therefore, in a psychophysical, or experimental phenomenological framework, embodiment can be divided into the sense of ownership and agency, which makes it quantifiable, thus providing operable outcome measures within artificial limb development [5]. To enhance the ongoing discourse, we establish a multi-dimensional framework that includes many disciplines to facilitate the understanding and research of prosthetics.

For our conceptualization of embodiment, we consider a model with three main components: ownership, body representation, and agency (see Figure 2.1). A similar three-domain approach is used in research by [6] and [3]. An alternative framework describes the construct of embodiment within two components, especially ownership and agency [5].

The three components of the model can be distinguished phenomenologically, as subjective encounters with each domain can appear to be independent of the others, i.e. each domain can be independently invoked, transformed, or damaged without the need for involvement in the remaining domains [6], [7].

For example, in experimental situations, they feel a sense of control over the movement of the prosthesis, despite a simultaneous sense of ownership over the prosthesis itself [8]. These domains are not separate at the level of neurophysiological processes [5], [9]–[11]. To achieve a complex motor interaction, often all three dimensions are operating at multiple levels.

2.2 Body representation

The brain has multiple representations of the body. Afferent inputs from the skin and proprioceptive receptors project to maps of the body surface and body segments respectively in the primary somatosensory cortex [12]. These somatotopic maps reflect the distribution of sensory receptors within the body and underpin somatic sensation [13].

Evidence from neurophysiological, neuropsychological, and neurophysiological studies all support the idea that these early sensory inputs are further processed to form more complex and higher-order representations of the body. It is important to make a distinction between body image and body schema. Body image refers to beliefs, attitudes, and perceptions about one's body [14]. This is in contrast to the body schema, which is a system that determines the functions involved in motor control. These are considered to be unconscious and have no (conscious) awareness of the body [15].

2.2.1 Body schema

The term *body schema* was originally introduced by Sir Henry Head to describe the impaired spatial representation of the body due to damage to the posterior muscles [16]. However, this term has various definitions in cognitive science. In this paper, the *body schema* is a neural representation of the body used for spatial sensorimotor processing [17].

Updated during the movement, the body schema represents the spatial locations of its parts. Typically, when the body system operates outside of conscious awareness, it serves the purpose of organizing the basic aspects of action. Consequently, body schema plays a role as an indicator of the spatial properties of the body, with features such as the length of the organ segments, their hierarchy, the spatial arrangement of segments, and the shape of the body surface [17].

2.2.2 Body image

Body image refers to a conscious visual representation of the way the body appears from the outside, typically in a canonical position [14], [18], [19]. In addition, BI (Body Image) is associated with the multidimensional psychological experience of embodiment [20]. Therefore BI influence the way human beings interact with the world through their bodies [21].

The scientific concept corresponds roughly to the everyday use of the term. The term was introduced by Paul Schilder in 1935, who defined BI as the mental representation of one's body that everyone develops. The developmental process of BI is dynamic and is influenced by the physical (e.g., body size or shape) as well by psychological (e.g., perfectionism, low self-esteem) characteristics of an individual. Additionally, BI is built also by lifestyle and cultural contexts (e.g., perceptions of beauty, and media pressure to produce) [22], [23].

2.3 Phenomenology

Phenomenology is defined as the perception of the prosthesis as part of the body. This alternative approach combines ownership and agency, becoming a quantifiable metric that can be used in translational research [4]. "Experimental" phenomenology stands for its subjective experiential correlation.

The endeavor to collect a phenomenological idea of embodiment led to its decomposition into subelements of this experience, which makes it possible to define it more precisely. The components, which represent conceptual representations include a sense of agency and a sense of ownership [24], [25].

2.3.1 Ownership

The experience of the body as one's own is referred to as the sense of "body ownership" [14], [25]. This is a fundamental aspect, which allows human beings consciously move their body parts.

The process of ownership occurs by receiving different types of signals from the limb. Namely, temporal, spatial, somatic and visual. Ownership is assumed to rely on the integration of sensory signals from different modalities [25]–[27] or so-called "multisensory integration" [16], [28].

The model of ownership forward by Tsakiris [29] is presented at Figure 2.2. Parts of the afferent sensory feedback related to the prosthesis are consecutively compared in a three-step comparator process: visual feedback of prosthesis, postural and anatomical feedback of prosthesis properties and event-related feedback. The first step is a comparison of a representation of how a biological limb should look in the body model. The second feedback is a comparison of the current estimated postural state of the body, stored in the body schema. The last step is the sensory integration of the remaining afferent feedback. In the case of three consistent comparator stages, ownership arises, which later will be used to update the body representation. It includes body image and body schema, which is used for congruent visual, postural, and anatomical feedback. Together with event-related feedback a sense of ownership is being formed.

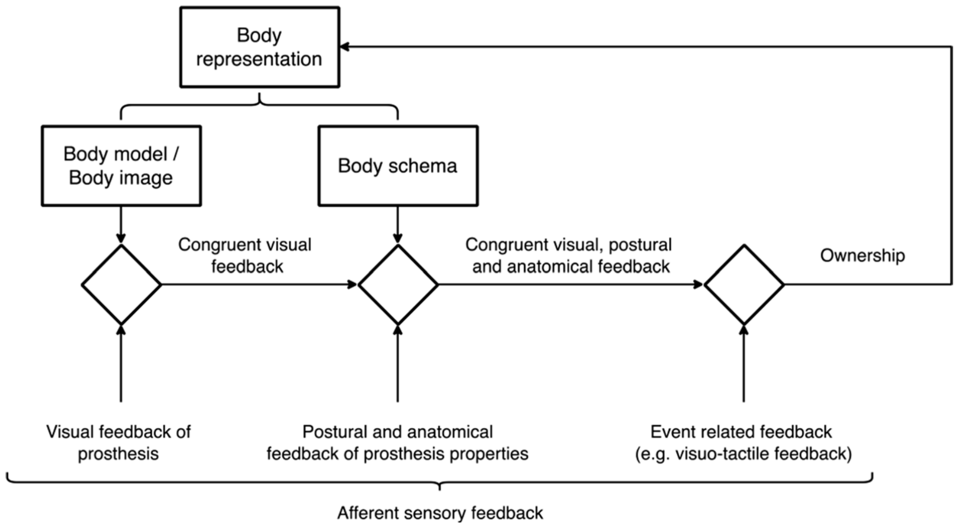

Figure 2.2: Prosthetic embodiment: a systematic review on definitions, measures, and experimental paradigms. Model of ownership [5]

2.3.2 Agency

During the body movement, ownership includes a perception that it is our body moving. In other words: the feelings of initiation and control over bodily action movement (volition). Ownership and agency are aspects of self-awareness [14]. Agency differs from ownership in that it can be felt beyond one's body. In addition, the perceptual constraints have historically been charted through experiments investigating the feeling of control over external events (e.g. studies on intentional binding) [4].

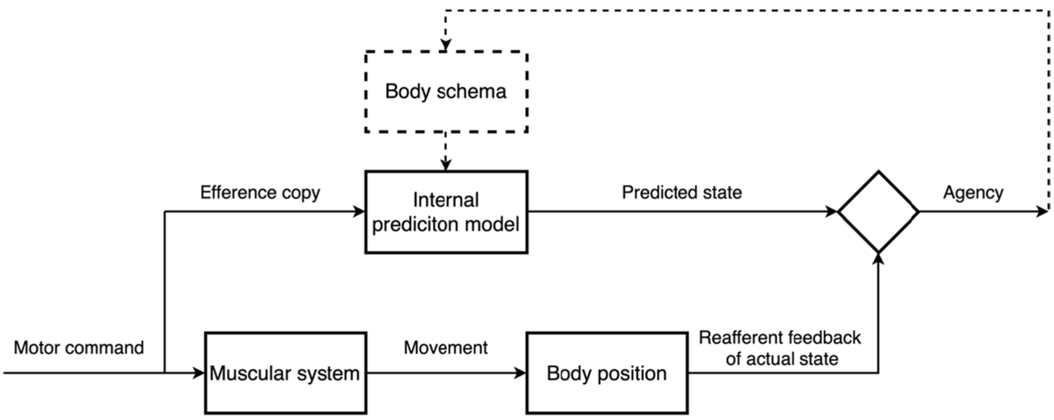

Figure 2.3: Prosthetic embodiment: systematic review on definitions, measures, and experimental paradigms. Model of agency [5]

The details of the process are described in a popular comparison model, represented in Figure 2.3. This model is a prediction model of the motor position of the body [30]. By the time a motor command is generated, an efference copy is sent to the internal prediction model. If the predicted state is congruent with the reafferent feedback of the actual body movement triggered by the motor command, a sense of agency is formed. This state of agency updates the state of the body schema. Parallel to this process the generated motor command leads within the muscular system to the movement, which changes the body position. As a result, reafferent feedback of the actual state is sent together with the predicted state to form a sense of agency.

Frith [31] in 2000 showed that the comparator/ central monitoring process used for the optimal sensorimotor control of action [32] may also be responsible for generating the sense of agency. This model is based on the premise that every voluntary movement is accompanied by an efferent copy, which is used to compute the expected sensory consequences. If the perceived feedback clearly violates the expected outcome, then the participant becomes aware of this. Therefore, there will be no sense of agency formed [33].

3 Methods

The selection of RHI (Rubber Hand Illusion) experiment and prosthesis in the loop as the primary topics of investigation in this paper is driven by their pivotal role in the study of prosthetic embodiment. The RHI is a well-known experimental paradigm that explores the malleability of body ownership and body representation. By studying RHI, we can gain insight into the underlying mechanisms of the integration of artificial limbs or prosthetic devices with the human body. Furthermore, prosthesis in the loop represents an emerging field that explores two-way communication between humans and their prosthetic devices, with the aim of creating a seamless and natural integration.

3.1 Rubber Hand Illusion (RHI)

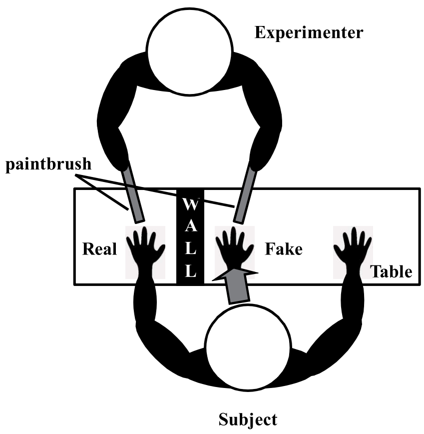

Figure 3.1: Overview of the RHI experiment [34]

The most popular and widely used method for studying ownership and agency is the RHI paradigm [5]. This method is based on an illusion by Botvinick and Choen in 1998 that relates tactile sensations to a rubber hand. The setup of their illusion is that a subject sits at a table and rests his left arm on it. As shown in Figure 3.1, a life-size rubber model of the left hand and arm is placed within the subject's view, while a panel hides the real hand from the subject's view. While looking at the rubber hand, two small brushes are used to stroke both the artificial hand and the subject's hidden hand. During this stimulation, the focus is on synchronizing the brush movements as precisely as possible. After this illusion, the subject is asked to complete a questionnaire about the occurrence of certain perceptual effects during the experiment. The completed questionnaire of Botvinivk and Choen's study indicated that the subjects felt the touch of the visible brush as if the artificial hand perceived the touch, and not through the hidden brush on the subject's hand. [12]

3.1.1 Influences on embodiment during RHI

Understanding how the brain perceives sensory information and establishes a sense of body ownership is critical in the field of prosthetic embodiment. The RHI provides valuable insights into the influence of visuotactile, visuomotor and visuoproprioceptive stimuli on the experience of ownership and embodiment.

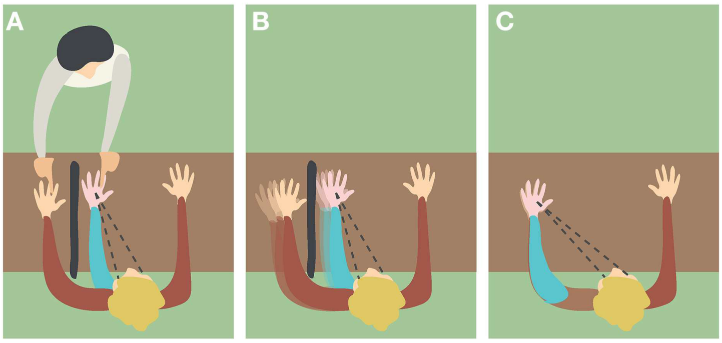

Figure 3.2: Body Ownership Illusions [35]

For the perception of our body and the surrounding space, visuotactile integration, meaning perception using vision and touch, is considered fundamental (see Figure 3.2 A). In a study, the effect of temporal matching revealed stimulation delays smaller than 300 ms strong illusory feelings. The subject experienced the hand stimulation as if the touch came from the prosthetic hand. For longer delays, the illusion reduced significantly [36]. Other studies show, that for simultaneous stimulation but with different locations (e.g., index vs. little finger) the illusion stops [37]. This shows that for a successful RHI temporal alignment alone is not sufficient.

Visuomotor stimuli, as shown in Figure 3.2 B, refer to a relationship between seeing and coordinating movement and are also essential for body ownership illusions. Studies represent that modified visual movements of the rubber hand relative to real movements reduce the corresponding illusion. In the case of visuomotor triggers, the results of the experiments assume a spatial and temporal correspondence between the visual and the tactile motor movements [38].

Another type of stimuli are visuoproprioceptive triggers, which are caused by the person's own body movements and their relations to the environment (see Figure 3.2 C). Studies have shown that subjects perceive their hand to be in a single location that is between the seen and felt positions. The perceived position tends to be closer to the seen position. The results showed that as long as the artificial body part is perceived in a realistic anatomical position and supported by congruent visuotactile or visuomotor stimulation, the illusion of body ownership can occur without the need for spatial congruence in visuoproprioceptive signals. [35]

These different influences are an important reference on how a human is perceiving its own body. Ownership illusion like the rubber hand paradigm is therefore a crucial instrument to measure the embodiment of a prosthesis. However, the evidence from studies about the presented ownership triggers suggests that ownership illusions, like RHI, are influenced by the visual appearance of the artificial body. This includes the shape and the anatomical plausibility, meaning the structure and spatial configuration. As mentioned, certain anatomical violations (e.g., larger or smaller hands/fingers, longer or multiple limbs) can be tolerated and overcome with congruent stimulation, but other forms of abnormalities (e.g., spatial arrangement) may not [39]. The boundaries of acceptable violations are still a matter of debate [35].

3.1.2 RHI studies and measurements

RHI is a sufficient method the receive important measurements and findings related to ownership and embodiment, which can be used in order to incorporate these results into prosthetic research. Therefore, Studies perform various measurements and tasks before and after experiment.

A sensory perception task involving two sensory stimuli is the TOJ (temporal order judgment) task. For the rubber hand illusion, the stimuli are presented in mirrored positions on the two hands. The participant has to identify which of the stimuli is applied first. Delay variation is also used to determine how the timing of the stimuli affects the order of perception. Quantitative measurements are the PSS (Point of Subjective Simultaneity), where the participant perceived the stimuli to be simultaneous, and the JND (Just Noticeable Difference), which refers to perceiving the smallest detectable stimulus by the subject. It is assumed that increased use of the prosthesis will reduce the PSS and JND, indicating more equal sensory processing between the prosthetic limb and the intact limb [2]. A study found that synchronous input resulted in a lower JND than asynchronous and mismatched conditions. This suggests that providing amputees with synchronous feedback through a prosthesis can improve tactile information processing [40].

Painful stimuli (e.g., thermal skin conduction or infrared laser probes) are generated in the pain perception measurement, where subjects report their perceived pain intensity on a scale [2]. In a recent study, a laser single pulse was induced to the back of the real hand, while a LED flash is indicating an upcoming pain stimulus on the rubber hand. After the stimulus, the participant should rate the pain intensity, pain unpleasantness and the RHI strength (see Figure 3.3). Results indicate that RHI can effectively reduce pain perception. In a high RHI condition, there was a significant reduction in pain intensity and unpleasantness ratings.[41] Such an experiment has not yet been conducted with prosthesis wearers. However, a change in pain perception between the residual limb and the intact limb could serve as an indicator of changes in prosthesis ownership [2].

Figure 3.3: Laser pain stimulation experiment setup [41]

In a crossmodal congruency task, subjects receive tactile stimuli (e.g., touch or vibration) on two different locations(e.g., fingers) and should identify which part was stimulated. Also, two visual distractors light up, either congruent (same location as tactile stimuli) or incongruent (second, different location). While incongruent visual stimulation slow down the localization of the tactile target, congruent stimuli improve this process [42]. The different performance outcome occurring during the two procedures is known as the CCE (Crossmodal Congruency Effect). Higher CCE vaules suggest that more processing time is required to respond to incongruent stimuli compared to congruent stimuli, indicating the need to ignore distractions and focus on the target. The CCE score serves as a measure of limb ownership, with higher scores reflecting a stronger sense of ownership. [2]

Sensory attenuation is the phenomenon of perceiving self-generated touch as less intense than external touch. It has evolved as an important ability for self-identification. It allows individuals to distinguish between harmless self-touch and potentially threatening touch from others. In a recent RHI study, touches delivered to the rubber hand are perceived with a reduced force similar to self-generated touches, indicating a sense of ownership of the rubber hand [43]. Another study, adapted for use with a prosthesis, showed a significant reduction in force for the self-touch and prosthesis-touch conditions compared to a stranger's touch. An increased sense of embodiment with the prosthesis led to an increased similarity between the forces experienced in the self-touch condition and those experienced in the prosthesis-touch condition. Suggesting the users' sensorimotor system represents an embodied prostheses as an actual limb. [44]

Some studies show a correlation between ownership of a limb and its skin temperature. A decrease in ownership results in a decrease in limb temperature. In one study, increased ownership after RHI was associated with increased limb temperature [40]. However, this effect is not fully understood and has not been confirmed in other studies [2].

Ownership can also be measured by the change in skin conductance that is caused by potentially painful stimuli (e.g., hitting the artificial hand with a hammer). This effect leads to increased sweat production. In one study, the SCR (Skin Conductance Response) was measured with electrodes before and after inducing a RHI and confirmed a significant increase in the SCR after the RHI, suggesting an increase in ownership [34].

Botvinivk and Choen suggested that there is a sort of distortion in the human's sense of position during their illusion. They investigated this theory by conducting an experiment where before and after the viewing and stimulation of the rubber hand the subject performs reaching movements using both hands. The participant should move the right index finger below the table to the believed position of the participant's left index finger, which is rested on the table during the whole illusion. After experiencing the rubber RHI, participants' reaching movements were shifted to the right, bringing them closer to the rubber hand. The longer participants perceived the illusion, the more their reaching movements were pulled toward the rubber hand [12]. A similar experimental setup is shown in Figure 3.4. This measurement is known as proprioceptive drift and is common in the frequent literature [2]. However, recent research suggests a separation between proprioceptive drift and ownership because of inconsistent results. Findings suggest that the asynchronous stroking, which was part of the control condition, has a negative effect on proprioceptive drift [45]. This may account for the variations in the drift observed in previous studies. Results from another study contribute to existing research by demonstrating that questionnaire measures and proprioceptive drift measures capture different RHI metrics, contradicting previous findings that suggested a correlation between the two [46].

Figure 3.4: Measurement of the proprioceptive drift [47]

3.2 Interviews and questionnaires

One common procedure after the Rubber Hand Illusion or other embodiment-involved experiments is conducting either semi-structured or structured interviews. Semi-structured interviews provide participants with several open questions [48], while structured interviews often deal with all kinds of questionnaires or scales [49]. The participation form includes FTF (Face-To-Face) talks [50], [51], Email [48], and phone calls [52].

Before a detailed investigation and refinement of the Ownership-Agency-Location framework, Longo et al. did fundamental work on determining such basic 3 components of the embodiment using a psychometrics approach [6]. Psychometric means objectively measuring latent constructs that cannot be directly observed, and in our case, the ambiguous embodiment concept in the RHI experiment is a latent construct. Methodologically Participants in Longo's experiment observed a rubber hand being stroked either in sync or out of sync with their own hand. Afterward, they assessed the position of their own hand based on their proprioceptive sense and used Likert scales to rate their level of agreement or disagreement with 27 statements pertaining to their subjective experience of the illusion. Upon conducting a PCA (Principal Component Analysis) on the synchronous dataset, four primary components of the experience were identified across various conditions, which had been interpreted as the embodiment of rubber hand, loss of own hand, movement, and effect. After the PCA in the asynchronous dataset, an additional fifth component, deafference, was found. Also, in their secondary analysis of the embodiment of the rubber hand component, it was discovered that three subcomponents, namely ownership, location, and agency, were present in both conditions. Without this brilliant interpretation of the primary components in this work, there will not exist subsequent investigations on the refinement of this ternary framework.

Since the work of Longo et al. has a focus on a general psychometric structure of bodily self-consciousness, participants in their experiment are all able-bodied. After the ternary Ownership-Agency-Location framework has been well-known in the prosthesis field, several further investigations on the embodiment of amputees were performed. Giummarra et al. investigated phantom-limb experience in 283 amputees and discussed the relation between prosthesis embodiment and the phantom-limb in their devised questionnaire named CIBS-Questionnaire (Changes in Body Sensation Following Limb Loss Questionnaire) [53]. More specifically, many participants in this work reported that their phantom limb "becomes the prosthesis" or vice versa, the others reported their phantom limb disappears when wearing the prosthesis, and statistics showed prosthesis embodiment did not pose an impact on the perception of phantom pain or the pain intensity. Dunne et al. recruited 30 lower limb amputees from a rehabilitation program and performed semi-structured interviews via telephone or in person [52]. In these interviews, "It didn't feel part of me" indirectly highlights the sense of ownership, "I feel confident with this leg" shows the affection, location, and agency sense. Graczyk et al. focused on the daily experience of upper limb amputees with sensory restoration system [54]. They used a semi-structured daily survey and conducted a more detailed interview after the home-use period. In the data analysis, they concluded key concepts, or what they call coding structures, in interview transcripts, concluding embodiment, reduced focus and attention (cognitive load), sensation location, etc. Using these key concepts they aimed to develop a complex, holistic understanding of participants' experience with the SRS (Sensory Restoration System). Middleton et al. employed semi-structured deep interviews to understand the lived phenomena of uninterrupted, unmonitored home use of the neuromusculoskeletal limb prostheses[51]. In their interviews, the 3 participants expressed feeling that their neuromusculoskeletal prosthesis was (at times) part of their body (embodied), they did not necessarily consider it a part of their “self". Their work nicely derived seven key themes from participants interviews: Mechanical attachment, control, sensory feedback, daily life use, relation to the phantom limb, self-image/esteem, and social relations.

All of the works discussed above performed a qualitative approach to the embodiment of amputees, with different emphasizes (on the daily use, on the phantom limb, on the sensory restoration, etc.) Mostly they performed semi-structured interviews and summarized key concepts from these interviews that includes embodiment. However, one of the first influential quantitative methods to calculate exact embodiment value, or more specifically the ownership and agency values, is proposed by Bekrater-Bodmann in 2020 [49]. As shown in Figure 6.2, Embodiment in the amputation participants was assessed by the PEmbS-LLA (Prosthesis Embodiment Scale for Lower Limb Amputees), which was developed based on Longo's questionnaire. In this scale it calculates ownership/integrity, agency, and anatomical plausibility (sense of location) by taking the means of several items which has a scale from -3 to +3. Another quantitative method is Sturma's work, which explicitly inquired about the participant's ownership and agency towards their prosthesis after having undergone bionic reconstruction after a brachial plexus injury [55]. Figure 3.5 shows the individual ratings of the patients regarding their prosthetic embodiment.

Patient ID	P 1	P 2	P 3	P 4	P 5	P 6
Prosthesis wearing time in the last week	Not within the last week (only for social events)	Less than twice per week	Every second day	Almost daily	Almost daily	Almost daily
I had the feeling that the prosthesis was part of my body	7	5	5	6	4	8
I felt the prosthesis only as a tool, and not as a part of my body	1	5	7	8	6	0
I did bimanual tasks with my intact arm/hand together with my prosthesis	5	5	4	5	5	0
I felt that I had full control over the prosthesis	7	5	5	8	4	8
I liked wearing the prosthesis	9	4	3	8	5	10
I felt that my prosthesis looked like a real part of the body	10	7	2	3	4	9

Figure 3.5: Individual ratings of prosthetic embodiment [55]

3.3 Prosthetics in the loop

In Bekrater-Bodmann's work, participants were required to do some actions (stare at their prosthesis, stand up and walk around the room) and fill in the scale. This raises up a new question: What functional tests should perform when we want to investigate the ownership and agency attribute of the prosthesis? Are there better ways for prosthesis users to reflect on these capabilities than just staring at the prosthesis or walking around? Furthermore, instead of doing functional tests and measuring the ownership and agency ad-hoc, are there explicit ways to investigate ownership and agency? In this section, different functional tests and explicit ways to investigate the embodiment will be discussed.

3.3.1 Functional tests

For the upper-limb amputation case, the Box and Blocks Test is a commonly used assessment tool to evaluate manual dexterity and functional performance in individuals with upper limb amputations or other upper limb impairments. It is a standardized test that measures the ability to reach, grasp, transport, coordinate, and release small objects using the prosthesis. During the test, the individual sits at a table with a partition placed vertically down the middle, creating two sections. A box containing a set of standardized blocks is placed on one side, and an empty space is provided on the other side. The goal is to transfer as many blocks as possible from one side to the other within a specific time frame, typically one minute. The blocks are moved one at a time using the prosthesis. It provides a quantitative measure of performance by counting the number of blocks successfully moved within the given time limit. The test can be used to track progress over time, compare outcomes between individuals, or evaluate the effectiveness of interventions or prosthetic devices.

Another test is called SHAP (Southampton Hand Assessment Procedure) from Schiefer et al., which is a validated assessment of upper limb function that has been applied to myoelectric prosthetics. As shown in Figure 3.6 SHAP involves manipulating both abstract shapes and common household objects. Each task is timed, and the duration is utilized to calculate an IoF (Index of Functionality). This index serves as a measure of the subject's prosthetic dexterity, providing an assessment of their capacity to perform various ADLs (Activities of Daily Living) that require different grip types. After this test and the other 2 functional tests (forced-choice object detection test and modification of box and blocks test), participants were asked to finish the questionnaire adapted from the RHI questionnaire. The embodiment result showed an improved sense of integration of the prosthesis in the self-body image with sensory feedback.

Figure 3.6: SHAP(the Southampton Hand Assessment Procedure) [56]

For the lower-limb amputation case, the functional tests include overground walking, stair tasks, and obstacle avoidance tasks, whose content can be easily inferred literally.

3.3.2 An explicitly focus on ownership and agency

In recent times, there has been a notable emergence of studies that proposed new paradigms explicitly focusing on ownership and agency. A noteworthy experiment in this domain is the PIC (Prosthesis Incorporation) assessment [57], targeting ownership over a prosthesis. The PIC assessment utilizes the cross-model congruency paradigm (Figure 3.7), which examines participants' ability to prioritize one form of feedback over another. In a study conducted by Marasco et al., two prosthesis users underwent targeted motor and sensory reinnervation. During the experiment, the participants received tactile stimulation on the reinnervated skin that was either congruent or incongruent with the visual feedback indicating the stimulation location while grasping an object. When the visual feedback location aligned with the tactile feedback location, participants were able to discern the stimulation location more quickly compared to when they received incongruent feedback.

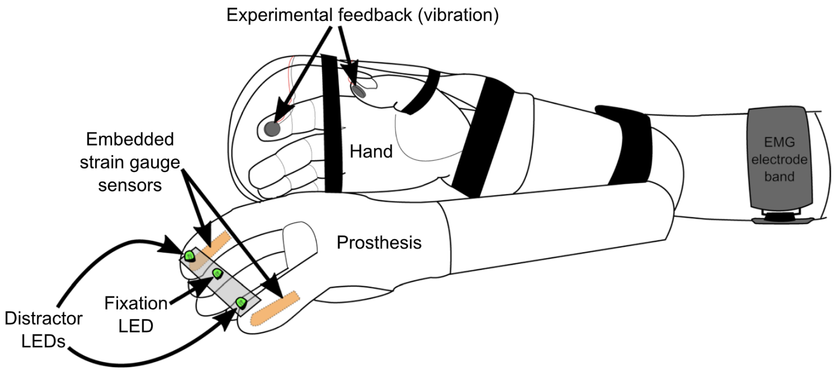

Figure 3.7: Cross-model congruency pradiagm [57]

Besides the explicit investigation of ownership, Libet Clock Experiment [8] focuses on agency over a prosthetic limb. Before the experiment, participants with upper-limb amputation underwent a surgical procedure to redirect the nerve endings in their residual limb. This redirection allowed the nerves to reinnervate the skin and muscles on the upper arm. By applying vibrations at 90 Hz to the reinnervated residual muscle at various locations, the researchers induced kinesthetic sensations of digit flexion and extension. In the actual experiment, the participants were presented with a virtual prosthetic hand controlled by electromyography. They were instructed to touch a virtual ball, which triggered a stimulation corresponding to a percept of cylinder-grip, accompanied by a tone played with a random delay. The participants were then asked to estimate the time delay. When the participants received congruent feedback through their intent, kinesthetic sensations, and visual cues, they tended to estimate shorter time delays compared to situations where these feedback modalities were incongruent.

4 Discussion

4.1 Framework convention

As alluded to previously, the concept of embodiment encompasses a wide range of research across scientific disciplines, resulting in the development of different frameworks. In our literature review, the main focus was on prosthetic embodiment. However, even within this specifications, there are various frameworks, including two-dimensional, three-dimensional and multi-dimensional ones. In reality, the attainment of embodiment involves the integration of multiple disciplines, such as genetics, neural activity research, psychiatry, and the study of complex psychological functions. This interdisciplinary nature leads to an increase of further frameworks, which causes hinders effective multidisciplinary interaction. Therefore, there is a pressing need for the establishment of a conventional framework that enables interaction among different research fields.

4.2 Disciplinary boundaries

One of the main challenges of integrated embodied research is that different scientific disciplines differ in their standards of what qualifies as embodied experiences. If different methods of discovery and data are used to analyze and determine, these values can require additional conceptual discussions. It is therefore important to clarify discipline-specific criteria to establish the relationship between physiological models and physiological methods.

In order to comprehensively elucidate and attain embodiment, it is important to investigate its various levels. Every level of embodiment entails distinct areas of study, specific methodologies, and corresponding data types. As a result, the process of understanding embodiment necessitates the examination and analysis of data at each respective level.

On a genetic and epigenetic level, for example, the type of data are DNA sequence (genetic polymorphisms), RNA expression levels, etc. Level of neural connectivity patterns can be studied by proceeding EEG, fMRI, resting state MRI, hormone levels, and diverse measurements of basic metabolic functions. Sensory and motor activity levels can be captured by EEG, fMRI, behavioral observation of movement patterns and reaction time to sensory stimuli. The level of complex psychological functions and psychiatric symptoms widely varies from the previously mentioned data structure: behavioral data (field observation, experimental induction), psychological and psychiatric diagnostics (test, interview), self-reports and health records. Levels of social and cultural interactions are measured with qualitative interview data, discourse analysis and behavioral data. [58]

It is clear that the type of data and approach to its measurement varies depending on the level of embodiment and therefore, research disciplines. In order to prevent encapsulating of knowledge and provide communication between them, it may be advantageous at first to create a discipline specific criteria. As a next step is to establish a knowledge bridge, which enables to build a relationship between different disciplines.

4.3 From conscious to unconscious embodiment

In a famous passage of Being and Time, Martin Heidegger considers the foundational aspects of the use of tools: “The work produced [by tools] refers not only to the ‘toward-which’ of its usability and the ‘whereof’ of which it consists: under simple craft conditions it also has an assignment to the person who is to use it or wear it" [59]. Such a referential aspect of the involvement of users and tools inspires a non-representational understanding of tool use and embodiment. In a famous locution, tools are ready-to-hand for the Dasein [59] ; namely, users engage with tools, and tools are incorporated into the users' dynamics without requiring any conceptual work from them. Tools are ready to be used and, when that happens, they become tacitly integrated into the user. Such is the Heideggerian way to refer to something equivalent to tool embodiment. Also, he mentioned a tool will show its existence to the user only when it breaks or shows some dysfunctions. Besides this, the user will embody this tool unconsciously to produce work to which the tool is specifically directed.

In a similar way, Dunne's work [52] shows that participants also expressed an increased understanding of the significance of perceiving their prosthetic limb as an integral part of their body, even when it appeared dysfunctional. Such experiences strongly relate to the concept of the "dys-appearance of the body" described by Leder [60], which suggests that disability or dysfunction disrupts our usual lack of awareness regarding our bodies, thereby emphasizing our normal sense of embodiment or incorporation. In these situations, the body becomes prominent, while our conscious thoughts, systems of meaning, and connection to the "world of experience" fade into the background. In the context of using a prosthesis, an artificial limb may take center stage during moments of heightened awareness, such as when experiencing pain, discomfort, or a lack of balance.

In brief, an ideal embodiment process for the prosthesis should be the following: First, let the user be aware of their prosthetic limb by noticing the dysfunction of it, like lack of balance, or slow control response. Second, let the user operate the prosthesis smoothly such that the prosthesis moves to the background and the work that needs to be done moves to the foreground. In other words, the ideal prosthesis should move from conscious embodiment to unconscious embodiment.

4.4 Pros and cons of different measures in RHI and prosthetics in the loop experiments

As introduced in the Method part, there are different ownership and agency measures used in either RHI or closed-loop experiments. They can be classified into explicit measures (posterior judgment after the experiment) and implicit measures (pre-reflective feeling during the experiment). In the case of heterogeneous either explicit or implicit measures, what is the strength and weakness of certain measure and what should future research adopt?

For explicit ownership and agency measures, questionnaires are the common strategies. Although semi-structured questionnaires like [48] are more information-intensive than structured questionnaires and more convenient for participants to freely express their embodiment feeling, they often inquire about both explicit ownership and agency simultaneously such that making a separation between them becomes unpractical. Also, the lack of quantitative metrics makes it hard to compare different studies and different prosthetic technology. On the contrary, prosthesis-involved questionnaires, such as PEmbS-LLA by Bekrater-Bodmann [49], PEmbS-ULA by Fritsch, and PEM by Graczyk [54], provide quantitative metrics by rating answers on a 7-point Likert scale. Clear separation of ownership and agency score in these scales helps better reflect different aspects of embodiment and enables horizontal comparison between studies using the same scale. However, the use of questionnaires has faced criticism due to several reasons. Firstly, since the questionnaire requires participants to retrospectively judge their experiences, there are doubts about the accuracy of their reports in reflecting the true vividness of the experience. Instead, it is questioned whether the participants' judgments are convincing enough. Furthermore, it has been observed that the way questions are formulated can influence the measurement outcome. For instance, in the Rubber Hand Illusion experiments, participants rated the sensation of the rubber hand being a part of their body higher when phrased as a feeling compared to a belief [61].

Besides explicit methods, ownership can be assessed through implicit measures. The first common measure is proprioceptive drift. Despite being a reliable measure of the synchronous and asynchronous RHI, proprioceptive drift has been criticized for the reason that the absence of proprioceptive drift in the asynchronous RHI condition is caused by the asynchronous stimulation itself. Secondly, the skin temperature serves as another implicit measure. The normalization of temperature was attributed to the sense of ownership over the rubber hand. However, reproducing consistent changes in skin temperature during the RHI has proven challenging, casting doubts on the correlation between temperature changes and ownership. Last but not least, another implicit ownership measure is the phantom-limb length, where the perceived length of the phantom is measured before and after the intervention, but this is exclusive for amputees experiencing a phantom limb due to amputation.

As for agency, Intentional Binding, initially investigated within the Libet clock paradigm, serves as the primary measure for assessing implicit agency. Although it provides a standardized metric for assessing the sense of agency across different contexts, it faces criticism that various factors, including motor preparation, sensory feedback, or cognitive bias between participants, can influence intentional binding effects, requiring careful consideration and control to attribute the effect specific to the agency.

4.5 Challenges of prosthetic embodiment experiments

The field of prosthetic embodiment has witnessed significant advancements in recent years, aiming to develop prosthetic devices that seamlessly integrate with the user's body and provide a sense of ownership and control. This discussion compares two studies, Marasco et al. [40] and Di Pino et al. [62], that explored the challenges associated with achieving prosthetic embodiment using different approaches and experimental setups.

Marasco et al. focused on targeted reinnervation amputees, where the limb nerves remaining after amputation are surgically redirected to new skin and muscle sites, and investigated the impact of robotic touch on the perception of embodiment. Therefore, the G10 tactor (a miniature haptic robot) was positioned over the reinnervated skin to project pressure onto the skin of the residual limb to evoke sensation at the missing hand, see Figure 6.3. In the study two amputee subjects conducted a RHI with a questionnaire, TOJ task and residual limb temperature measurement. Their findings revealed that sensory feedback provided by the prosthetic limb shifted the users' perception, enhancing their sense of ownership and control. However, limitations remained, such as the need for improved sensory feedback fidelity to achieve a more realistic embodiment.

In contrast, Di Pino et al. examined the embodiment of neurally-interfaced robotic hand prostheses. By utilizing stimulation using intraneural invasive electrodes, Di Pino et al. demonstrated the potential to extract motor intention signals from the users' brains and translate them into robotic arm movements. Non-invasive stimulation using mechanical tappers was used to establish comparability with a control group of healthy participants. Using two different robotic hand devices, an amputee participant conducted this active prosthesis experiment that included a TOJ and a visuotactile integration task. An overview of the experimental protocol is included in the Appendix, see Figure 6.4. This approach resulted in a sense of embodiment and allowed users to operate the prosthesis with a natural sense of control. However, limited availability of amputee subjects and their subjective reports remain a challenge in prosthetic studies.

paper	**sensor**	**stimulation**	**prosthesis**	**measurements**
[40]	targeted reinnervation	robotic touch interface (G10 tactor)	rubber hand	questionnaires, TOJ, residual limb temperature
[62]	intraneural and perineural multichannel electrodes	non-incasive mechanical, tappers invasive intraneural electrodes	robotic hand (research and commercial device)	visuotactile integration, TOJ

Table 4.1: Comparison between prosthetic embodiment studies

These studies collectively emphasize the need for continued research and development in the field of prosthetic embodiment. Addressing the challenges identified in these studies will be crucial for achieving a more seamless integration of prosthetic devices. Furthermore, the challenges of comparing prosthetic embodiment studies arise from the differences in parameters and methodologies used across the studies, see Table 4.1. Future studies should use standard embodiment measurements, such as those described in Chapter 3, to improve comparability. Additionally, an increased number of participants, multiple prosthetic devices and different sensor technologies would enhance the representativeness of the study results, but implementing these aspects is complex. Overcoming these challenges will ultimately contribute to improving the functionality and embodiment of prosthetic limbs, thereby improving the quality of life for individuals with limb loss.

4.6 Chances of Virtual Reality in embodiment research

VR (Virtual Reality) is a computer-generated, three-dimensional simulation which allows for physical or seemingly physical interaction. It is a technology that is becoming increasingly accessible, featuring electronic equipment such as goggles with an integrated screen and controllers equipped with sensors.

A recent study [63] provides evidence that embodiment through VR intensifies emotional responses to virtual stimuli. The ability to enhance emotional response through virtual embodiment is crucial for human-computer interaction in embodiment research. As a result, the use of VR can contribute to the standardization of experiments and measurements. By conducting experiments digitally, they can be reproduced and thus become more comparable than previous illusion methods.

VR offers an intuitive and immersive user experience. In VR, the simulated fake body part is directly overlapped on its real counterpart [35], whereas in RHI studies, participants must view the rubber hand via a mirror in order to perceive its coincidence with their real hand [64]. The Simulation of prosthetic limbs in a virtual environment is advantageous because it allows modifications to the experiment. Digital prosthesis creation allows visual and functional parameter adjustment and measurement of embodiment influence. As a result, VR may become a key tool for measuring embodiment, which could be used for both prosthetic design and prosthetic adaptation.

5 References

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6 Appendix

Genetic and epigenetic level	DNA sequence (genetic polymorphisms), RNA expression levels, gene × environment interactions, DNA methylation patterns, histone modifications, quantification of microRNA	DNA, mRNA, ncRNA (incl. different types of microRNA), DNA methylation, chromatin structure
Level of cell metabolism	Protein level quantification, single unit-recordings, cell anatomy measures (size, form, type, count)	Cell specific proteome, synaptic sensitivity, firing rates, cell anatomy
Level of neural connectivity patterns and physiological feedback mechanisms	EEG, fMRI, resting state MRI, hormone levels, diverse measurements of basic metabolic functions (e.g., heart rate, breathing, blood glucose levels)	Neural network activity, hormone levels, physiological feedback cycles
Sensory and motor activity level	EEG, fMRI, behavioral observation of movement patterns, reaction time to sensory stimuli	Motor action, sensory function, neural activity in sensory and motor systems
Level of integrative sensations, (intero)perception, and discrimination	EEG, fMRI, experimental tests of perception and basic cognitive functions (e.g., via reaction time, stimulus intensity, conflicting stimuli)	Sensory integration, basic cognitive functions, basic levels of self-awareness, pain perception
Level of complex psychological functions, psychiatric symptoms, and behavior	Behavioral data (field observation, experimental induction), psychological and psychiatric diagnostics (test, interview), self-reports, introspection, intersubjective communication, health records	Psychosocial and physical health, first-person experiences, behavioral patterns (habits), complex cognitive functions
Level of social and cultural interactions	Qualitative interview data, discourse analysis, behavioral data (field observation), socio-economic data, epidemiological data (e.g., prevalence rates, survival rates)	Socio-cultural interactions, complex behavior, intersubjective coordination and communication

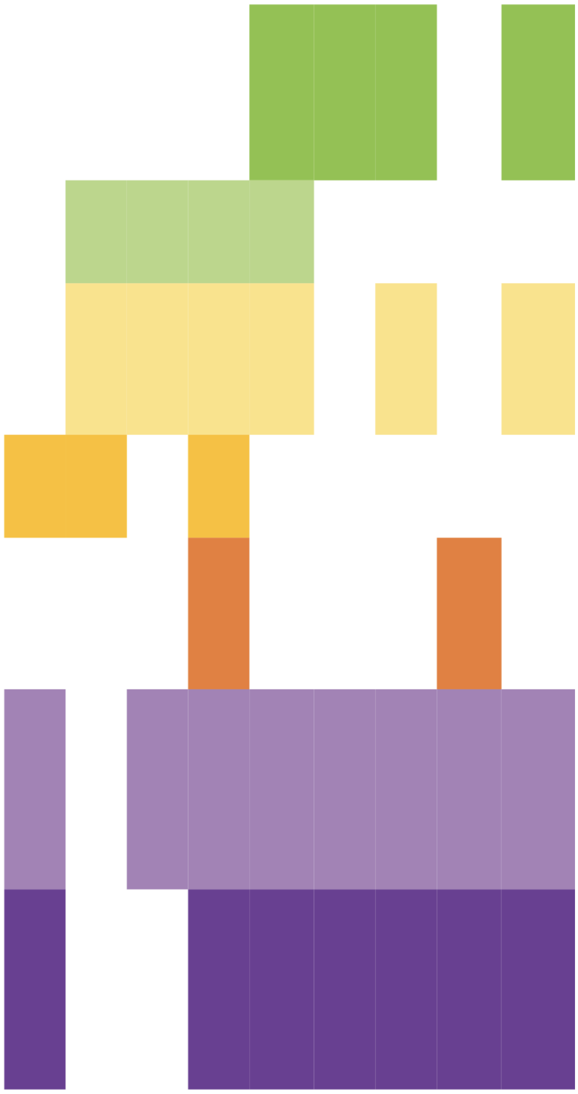

Figure 6.1: Table: different levels of embodiment and their approached concepts [58]

Prosthesis Embodiment Scale for Lower Limb Amputees (PEmbS-LLA)

□ I have put on my prosthesis.

Instruction: Please make sure that you can look directly at your prosthesis (for instance, by wearing shorts). For each of the following statements, please indicate how much you agree or disagree with it. If you agree with the statement, mark one of the positive numbers (1, 2, 3): the more positive the number, the more you agree with the statement. If you disagree with the statement, mark one of the negative numbers (-1, -2, -3): the more negative the number, the more you disagree with the statement. You should select the zero (0) only if you neither agree nor disagree with the statement. Please reply spontaneously, without thinking twice, and do not skip any statement. There are no right or wrong answers.

Please look at your prosthesis for about 60 seconds.

□ I have looked at my prosthesis for about 60 seconds and I am ready to continue.

	strongly disagree						**strongly agree**
1. I feel as if I was looking directly at my own leg, rather than at a prosthesis.	-3	-2	-1	0	1	2	3
2. The prosthesis belongs to me.	-3	-2	-1	0	1	2	3
3. It feels as if I had two legs.	-3	-2	-1	0	1	2	3
4. The prosthesis is my leg.	-3	-2	-1	0	1	2	3
5. The prosthesis is a part of my body.	-3	-2	-1	0	1	2	3
6. The posture of the prosthesis corresponds to that of a real leg.	-3	-2	-1	0	1	2	3
7. My body feels complete.	-3	-2	-1	0	1	2	3
8. The prosthesis is in the location where I would expect my leg to be, if it was not amputated.	-3	-2	-1	0	1	2	3

Please stand up and walk around the room for about 30 seconds.

□ If you are not able to walk around the room, mark here and skip the following items.

□ I have walked around the room for about 30 seconds and I am ready to continue.

	strongly disagree						**strongly agree**
9. The prosthesis is moving the way I want it to move.	-3	-2	-1	0	1	2	3
10. I am in control of the prosthesis.	-3	-2	-1	0	1	2	3

PEmbS-LLA total score (recommended) **Mean of items #1-10** __________

Sub-scales, 3-factor solution

Ownership/Integrity Mean of items #1-5,7 __________

Agency Mean of items #9,10 __________

Anatomical Plausibility Mean of items #6,8 __________

Sub-scales, 2-factor solution

Ownership/Integrity + Anatomical Plausibility Mean of items #1-8 __________

Agency Mean of items #9,10 __________

Figure 6.2: PEmbS-LLA [49]

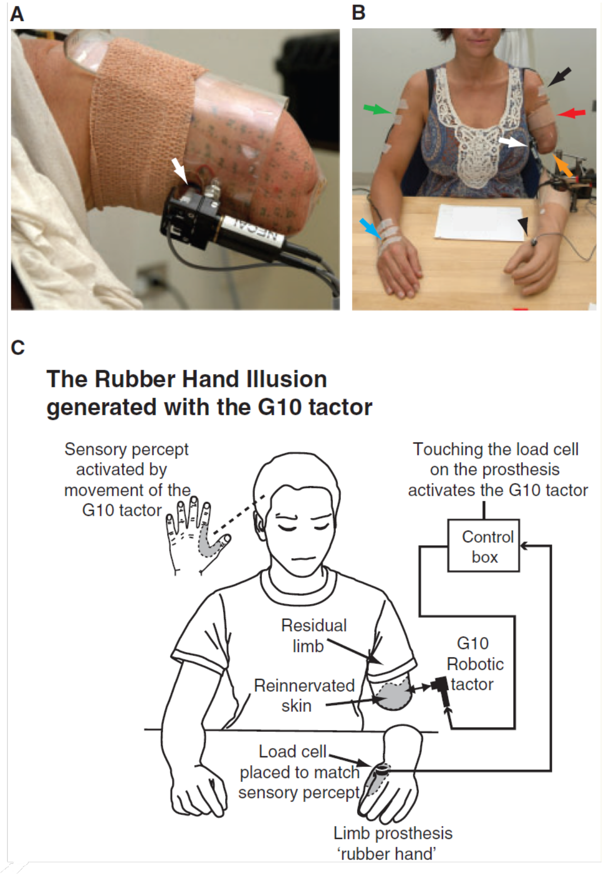

Figure 6.3: Experimental setup of the G10 tactor [40]

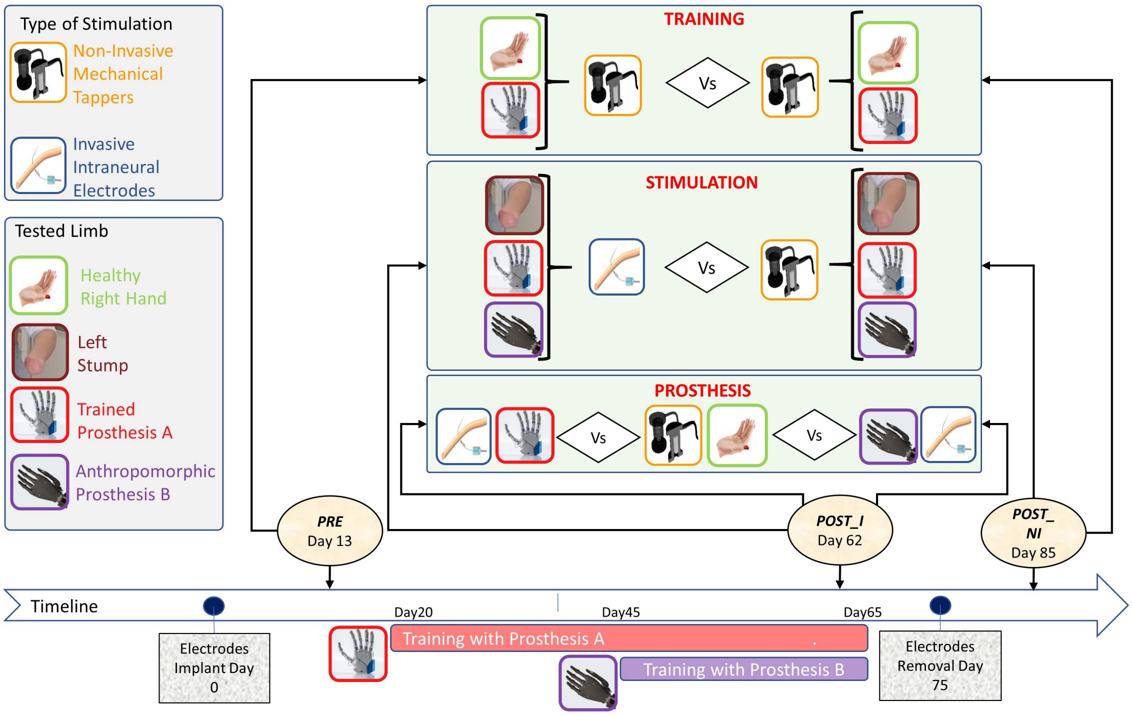

Figure 6.4: Experiment overview with timeline and protocol of limbs and stimulation types [62]