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The role of human experience when making sense of brain monitoring: an interdisciplinary case study to assess wearable, non-invasive, brain-monitoring devices for rehabilitation

Martha Risnes [a,b], Olga Korostynska [b], Peyman Mirtaheri [b] and Arild Berg [c]

[a]Faculty of Health Sciences, Oslo Metropolitan University, Oslo, Norway; [b]Department of Mechanical, Electronic and Chemical Engineering, Oslo Metropolitan University, Oslo, Norway; [c]Department of Product Design, Oslo Metropolitan University, Oslo, Norway

ABSTRACT

Wearable, non-invasive, brain-monitoring technologies could take research outside the laboratory, to make discoveries about the human brain in different, and sometimes more relevant, settings for the specific research. While this could lead to new scientific discoveries, there is a need to understand how individuals benefit from and make sense of interactions with such technology. This study considered patient experiences with wearable, non-invasive, brain-monitoring devices in a rehabilitation context. The research project Patient-Centric Engineering in Rehabilitation (PACER) provided examples from research practice to assess and discuss the potential for using such devices in patient-centric rehabilitation for lower limb amputees. Project findings suggest that concepts from technology mediation theory strengthen the discussion by describing how relations with the technology differ, depending on whether you are a health professional, researcher or patient, which is an essential understanding when assessing novel technologies for practical applications.

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Introduction

Modern medical technology is changing patient outcomes, research practice and the roles of health professionals. Consequently, designing technology for health-enhancing purposes is complex and interdisciplinary because natural and human sciences intersect, and human values play an essential role, intertwining technological and humanistic challenges and opportunities (Blandford 2019). This complexity is particularly relevant in a project's early stages when the connection between emerging technology and social need is made, as in this case study where wearable brain-monitoring technology is used for rehabilitation purposes.

CONTACT Arild Berg arildber@oslomet.no Faculty of Health Sciences, Oslo Metropolitan University, Oslo, Norway
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This case study addresses some of the reasons why it is challenging to combine biomedical engineering methods with patient-centric approaches, such as that: the technology was not mature enough; too little was known about rehabilitation challenges from a qualitative standpoint; better methods for analysing and collecting data were needed; and the understanding of what patient-centric entailed could be greater. The technology for this project could not be assessed as to whether it would be a good solution for rehabilitation based only on objective parameters, because the project was in an early phase and ways of applying it were still being discussed among project participants.

Hence, we needed to describe the ideas implicit to the project and to assess the literature on this project's opportunities and future directions. Scholars have developed frameworks for responsible innovation to engage with uncertainties on the impacts of novel technologies (Stilgoe, Owen, and Macnaghten 2013). In such frameworks one of the four dimensions of responsible innovation is anticipatory commitment, which describes the usefulness of exploring possible impacts as a constructive entry point for reflection on the purposes and promises of innovations (Stilgoe, Owen, and Macnaghten 2013). Similarly, socio-technical futures can concretise and describe the connections between technological and social changes (Urueña 2021). A socio-technical future perspective (Konrad and Böhle 2019) can help describe ideas shaped by the research project proposal in the Patient-Centred Engineering for Rehabilitation (PACER) project documants, literature, mass media, and the interaction with the specific technology. In this work, we chose to concretise the ideas implicit in the PACER project and the larger discourse the PACER project takes part in as *visions* (Grin and Grunwald 2000). The visions are often hard to concretise, but it could be beneficial to analyse them because they could add to knowledge on current embedded values. Building on the work of Grunwald (2014), Urueña (2021) describes this as the critical-hermeneutic approach to anticipation. Two visions were synthesised from the findings to assess patient-centric opportunities and challenges for applying non-invasive brain monitoring for rehabilitation purposes.

The anticipatory aspect in this work is not necessarily the technology and what is possible does not directly shape the visions for the application alone. Analysing what is technologically possible makes it feasible to describe how applications are driven by values and purposes that could be described as visions. The anticipatory aspect of this work is hence the purpose, that the application has a holistic perspective on health for the individual. It was necessary to describe how the brain monitoring experience differs depending on how the technology is interpreted as addressing that patient-centric perspective. The anticipatory action is, therefore, the goal of an application for rehabilitation.

We used a *technological mediation approach* to describe the possible interpretations of the brain-monitoring device, which breaks with traditional technology assessment (TA) by challenging its neutral position and introducing an ethical-constructive technology assessment approach (eCTA) (Kudina and Verbeek 2019; Kiran, Oudshoorn, and Verbeek 2015; de Boer, Hoek, and Kudina 2018). Kiran, Oudshoorn, and Verbeek (2015) suggest that such an approach should accompany technological development rather than merely assess it. This approach draws on the postphenomenological tradition concerned with the complexity of human–technology relations (Aagaard and Ihde 2018).

The technological mediation approach builds on the postphenomenological tradition and the analysis of human–technology–world relations (Ihde 1990). The concepts introduced in the approach are based on Don Ihde's (1990) work on technology and the lifeworld, and are further elaborated on by scholars in the field (Rosenberger and Verbeek 2015; Verbeek 2005; 2001). Postphenomenological perspectives on imaging technology have been covered in the literature (Ihde 1999; Hasse 2008; Carusi and Hoel 2014; Verbeek 2008b; Rosenberger 2011), but little attention has been given to analyses of contributions to a concrete research project.

Therefore, the research question is: What are the implicit goals when applying non-invasive brain monitoring in patient-centric rehabilitation?

Background

Challenges in non-invasive brain-monitoring development for health

Non-invasive brain-monitoring devices are important because they can recognise functional changes in the brain due to changes in cognition. Cognition can be defined as any form of information processing, mental operation or intellectual activity such as thinking, reasoning, remembering, imagining or learning (Wessinger and Clapham 2009). Functional brain imaging technologies, in comparison to structural brain imaging technologies, measure the functional changes of brain activity associated with cognition. Functional changes can be measured directly as neural activation and indirectly by neurovascular coupling (Petzold and Murthy 2011) due to oxygen transportation to the active regions of the brain. Modern non-invasive wearable devices are based on functional near-infrared spectroscopy (fNIRS) (Ferrari and Quaresima 2012) and electroencephalography (EEG) (Teplan 2002). EEG measures the brain's electrical activity through electrodes placed over the scalp, while fNIRS, on the other hand, measure hemodynamic changes in the brain, i.e. oxygenated (HbO) concentration and deoxygenated (HbR) haemoglobin in the brain, as shown in Figure 1.

Wearable, non-invasive, brain-monitoring devices are evolving from high-cost stationary equipment into low-cost wearable devices. The combination of smaller and more reliable sensors (Petzold and Murthy 2011), machine learning and improved internet connections (Silva et al. 2015) has increased the possibilities of using self-tracking (Lupton 2014) and personalised medicine (Swan 2009; Kumari, Mathew, and Syal 2017). Such improvements to non-invasive wearable devices for brain-monitoring can also lead to a variety of new research approaches. For instance, devices can be used by participants while in motion, either in natural environments outside the laboratory or in clinical settings (Pinti et al. 2018). This technology could enable rehabilitation practice to accommodate the considerable differences between individuals (Gray 2017). In precision medicine (Kumari, Mathew, and Syal 2017; Swan 2009) and precision rehabilitation, machine-learning techniques have been used to account for the large variability between participants. This perspective on rehabilitation has been successful in simplifying predictions and estimates of clinical scores (Adans-Dester et al. 2020). However, there are ethical concerns about applying this technology to assistive devices (Sample et al. 2020; Thorstensen 2019). Involving patients when designing new technology could be an essential step to avoiding unwanted consequences, but there are significant challenges and pitfalls related to such involvement which should be investigated.

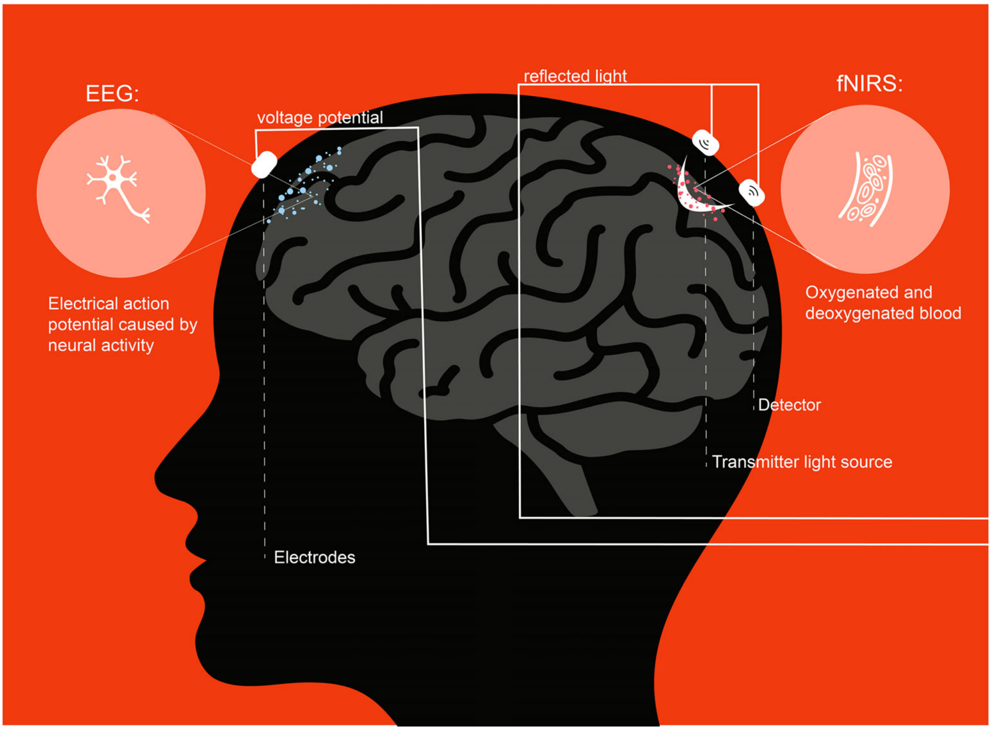

Figure 1. Non-invasive brain-monitoring technology, EEG and FNIRS. Illustration by Author 1.

Brain-monitoring devices have been used in research for a long time, but devices are now available to the consumer which claim to be health-enhancing. Coates McCall et al.'s (2019) review of EEG devices marketed for consumers identified four claims made by the producer in the categories of health, wellness, enhancement and practical applications. A similar identification of claims was made by Wexler and Thibault (2019) on the topics of concentration, relaxation, meditation and sleep. Concerns regarding misleading claims are related to a device's reliability and validity (Coates McCall and Wexler 2020).

The literature contains several perspectives on non-invasive brain-monitoring technology and opportunities in rehabilitation. Raisamo et al. (2019) describe the augmented human approach as aiming to enhance human abilities through medicine or technology. This aim is relevant to the development of wearable, non-invasive, brain-monitoring devices given the potential for using brain activity as an input for physical enhancements such as prostheses. This field overlaps with brain–computer interface research and the interaction between human and machine, enabling the human to control machines through new interfaces such as vision, brain activity and voice (Brunner et al. 2015).

The idea of ubiquitous control of an enhanced body is also seen in science fiction and the media. For example, the World Cup football tournament starts with somebody kicking off the game, but in 2014 that person had paraplegia and kicked with the help of an exoskeleton controlled by a non-invasive EEG cap. That work was part of the Walk Again project (Nicolelis 2014), and the exoskeleton's haptic feedback gives the patient the sensation of feeling. The possibilities that can be imagined are very promising for assistive technology. However, highlighting the possibilities often overshadows identifying development issues.

Methods

The PACER case study

This work used Yin's (2017) explanatory case study to analyse how to assess a particular technology development based on the PACER project's socio-technical aim. We used an explanation-building strategy (Yin 2017, 179) and a pattern-matching approach on the empirical data collected from the lens of socio-technical futures and visions. A technological mediation approach was chosen to structure and analyse the data regarding the relations made with the technology. The findings were also thematically represented as visions of the projects, as described by Grin and Grunwald (2000), to assess and discuss the project's human-centred issues (Steen 2011; Spinuzzi 2005; Bate and Robert 2006).

The technological mediation approach has been described as an approach from within (de Boer, Hoek, and Kudina 2018; Kudina and Verbeek 2019). In the context of this study, this inside perspective is understood in two ways: first, the authors are project insiders and the interpretation from within cannot be separated from the commitment to the project aim; and second, through a relational ontology (Ihde 2008) in which technology and people are fundamentally linked. As a result, a method was chosen that includes perspectives from within the case to clarify how this relational ontology affects the project's development.

Research introspection

The empirical turn in postphenomenological literature is the field's response to methodological discussion in relation to the more analytic direction of postphenomenology (Adams and Turville 2018). As of the time of writing, there are no clearly established methods regarded as postphenomenological. The use of auto-ethnography has been both critiqued and pointed to as a valuable method of inquiry (Adams and Turville 2018). A critique is that it restricts postphenomenology to studying only what it knows (Adams and Turville 2018). In this work, we believe that an auto-ethnographic approach could contribute valuable knowledge as it enables a description of the technology in use.

Access to technology, such as for brain-monitoring, can be difficult because of its cost and availability, so an advantage of the auto-ethnographic method is that it makes access easier, although becoming familiar with the technology and the specialised environment takes time. By using a case study methodology, it is possible to triangulate data to decrease biases related to the choice of the auto-ethnographic method.

In the human–computer interaction (HCI) literature, research introspection has been suggested as an overarching term, with auto-ethnography as one alternative. In relation to Yin's (2017, 114) account of data evidence, we see the use of research introspection as an extension to the use of a physical artefact combined with a version of participant observation. Xue and Desmet (2019) describe imaginary introspection as a tool for envisioning future design possibilities, and it has been connected directly to the use of design fiction. In this work, we want to use imaginary introspection to construct visions in the work. Xue and Desmet (2019) describe how imaginary introspection has been used to engage in thought experiences to expose conflicts or dilemmas. In this work, we want to use the visions to expose conflicts and dilemmas in terms of a human-centred design direction. There is a similarity in imaginary introspection to what Verbeek (2006) describes as technological imagination, or as the ability to imagine technology as a socio-technical phenomenon as mediators (Verbeek 2008a).

If we look at the opportunities for a certain technology, in this case non-invasive brain monitoring, there are endless possibilities for design variations. Innovation can be seen as imagining those possibilities and assessing the most fruitful direction. To a greater extent than is common today, technological mediation can be a tool for understanding the assumptions of visions created by collective and personal imaginations. In this case study, we use research introspection to create visions of opportunities for the use of non-invasive brain monitoring. These identified visions are based on analyses of research introspection in the laboratory and of the document review of the PACER project description. The assumptions or propositions identified are then discussed within the broader field of non-invasive brain monitoring to assess any human-centred issues.

Data collection procedures

To strengthen the case study approach methodologically, a protocol was used in accordance with recommendations from Yin (2017, 95). Data triangulation improved the construct validity by a convergence of evidence (2017, 129). The data was collected over one year from three sources. The first source was a document describing the overall objective of the PACER project and the individual PhD tasks presented as part of the accepted funding application.

The two other sources for data collection were part of the researcher introspection method in the context of the PACER project. The first fieldwork in the motion analysis laboratory consisted of preparing and conducting an experiment with co-researchers on the effect of a walking aid on brain activity using an fNIRS device. The researcher role in the laboratory experiment was to contribute as a subject in the experiment and to help with planning, technical facilitation and setup. The second fieldwork consisted of planning an event on how best to showcase EEG in an AI laboratory for two groups of 13–16-year old pupils. A commercially available device was demonstrated together with a simple relaxing/concentration game. The researcher role was to participate in planning and facilitating demonstrations.

Theoretical framework for analysis and interpretation of data

The analysis used an explanation-building principle according to Yin (2017, 179). Thus, two visions were constructed, based on the findings, and were discussed from a human-centred perspective.

The authors used the mediation approach, as defined by Kiran, Oudshoorn, and Verbeek (2015), to map three different types of human–technology–world relations: *hermeneutic relation, embodied relations,* and *alterity relations* (Verbeek 2011; Ihde 1990).

These were used as a starting point for describing a non-invasive brain-monitoring device as part of a socio-technical interaction in the PACER project. The possible *reduction/amplification structures* describe how some aspects of a phenomenon become amplified or reduced due to human–technology–world relations (Ihde 1990 as cited in Verbeek 2011, 8).

Ihde refers to the concept of a hermeneutic relation as a translation of a phenomenon to something perceivable (Ihde 1990 as cited in Verbeek 2003). One example used by Ihde to explain this relation is a thermometer (Ihde 1990 as cited in Verbeek 2011, 8), which translates the temperature into a number that is helpful for an objective perception of temperature. In research, this objective measurement makes it possible to understand and compare a physical phenomenon.

Ihde uses the cash machine, or ATM, to describe an alterity relation where the technology interacts with the 'quasi other' (Ihde 1990 as cited in Verbeek 2003). An interaction that is perhaps even more intricate than Ihde's representation. Through a 'technology of the self' Bergen and Verbeek (2021) elaborate on varieties of the alterity relation in a self-tracking app. The technology enables a confrontation with the self, where the goal is often a change in behaviour. This intentionality could be mediated by technology through confrontation, gamification or social networks.

Ihde uses the example of how glasses can be viewed as an embedded relation (Ihde 1990 as cited in Verbeek 2011, 8), as we engage in seeing without paying attention to the glasses themselves, unless something is wrong with them, like fingerprints on the glass.

Discussion of findings

The three main findings from the research introspection and the document review were: first, the different relations between expert and novice interpreters, based on literature representing the expert researcher and on the research introspection method for novice interpretations; the second finding describes the context as an essential mediator of purpose; and the third, the phenomena in focus through non-invasive brain monitoring, includes how the findings from the PACER data can be seen in the context of the larger research field. The findings were then synthesised into two possible visions from a human-centred perspective.

Possible limitations of using the technological mediation approach to analyse this data are the generalisability of the relations and the technology. Several types of devices have different specifications and uses, and part of the description might not be applicable in another context. Hence, such methods do not substitute for objective measures to assess an intervention. The purpose is to describe the early process that often happens outside the research format. Innovation is an iterative process in which it is challenging to leave biases outside the work. Engaging with what does not yet exist makes it possible to be transparent about what values are embedded in the process, especially if the technology is part of defining healthy behaviour and characteristics.

There is an ongoing discussion on the role and relevance of using socio-technical futures (Nordmann 2014; Urueña 2021). We wanted to avoid using the word future because it could be misleading as we do not discuss the future. Even though we talk about what does not yet exist, the use of future implies that it might happen, and it is not our purpose to speculate on that. However, by engaging with this activity, we are assessing a technology whose development will have future consequences.

There is a methodological issue as to whether it would strengthen the external validity if participants from outside the project had taken part. The main reason for not including outside participants was that we were interested in the project's internal reflective process. But we also we did not recruit participants from outside the project because of the uncomfortable fitting of the device.

Expert and novice interpreters

Two different relations can be described through two different devices used in the research introspection. The EEG device, Figure 2, was marketed to consumers where no prerequisite was necessary, whereas the fNIRS device was for research use in the lab. The fNIRS device has no apparent applications for the novice user as, without knowing how the technology works, you do not know what you are looking for or how to interpret it. Preparing the fNIRS device to obtain accurate results requires practice, as the complete setup can be uncomfortable to wear over extended periods. EEG might be more suited to commercial purposes since the setup is easier and can be compared to using a headset. The mental states are 'easily available' through the frequency measurements (Newson and Thiagarajan 2019) and can be viewed through an app user interface.

Figure 3 shows testing in a laboratory using fNIRS as part of the PACER project. From the participant's perspective, the raw data makes little or no sense without the researcher's interpretation. Noise from the environment must be filtered out, and the data needs to be evaluated in the context of the stimuli. In particular, when using the fNIRS continuous-wave technique, only relative changes are measured and there are no absolute values, it is therefore not possible to make a direct comparison between participants.

Figure 2. Introspective fieldwork: illustration of laboratory activities to test experiences of an EEG device.

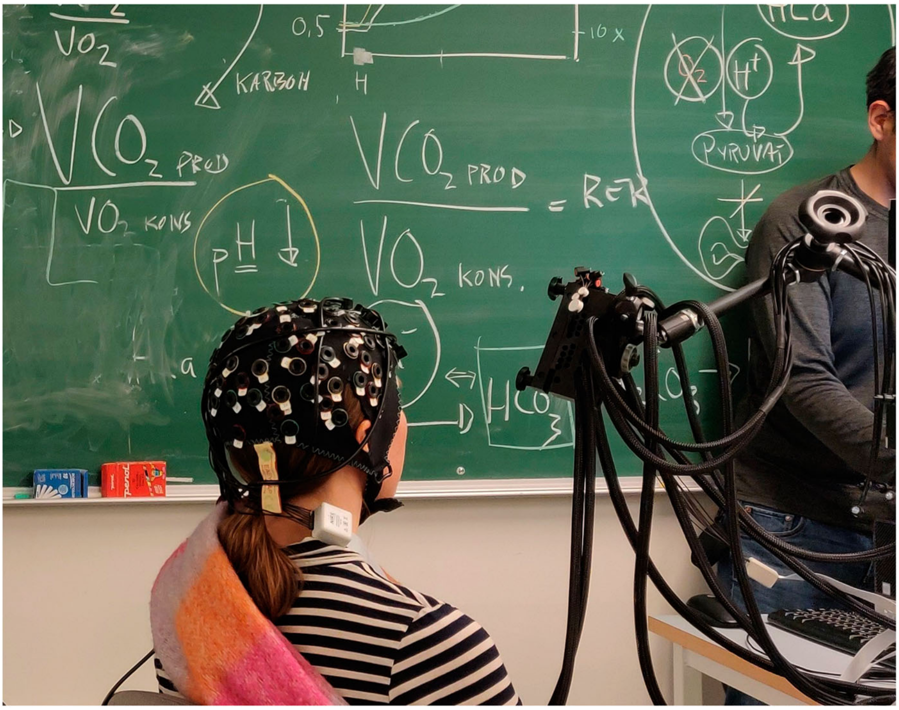

Figure 3. Introspective fieldwork: laboratory activities to test experiences of a fNIRS device.

A hermeneutic relation occurs as the neurons' electrical potential and the hemodynamic responses are identified and interpreted as brain activity by the technology. This interpretation takes place 'inside' the technology and the software. Several mathematical and physical assumptions are needed to transform the unperceivable into the perceivable. The interpretation also takes place between the researcher and the technology when making sense of the data – what it implies and how it could be made understandable to others. From this perspective, the technology is being interpreted and is also the interpreter itself. We would argue that both interpretations are essential for design and development as they shape the context of the technology in use. The context in this setting could be understood as the physical environment and interactions of the device in use.

A challenge when interpreting this data is that we only see the brain's response to a certain stimulus. Limitations of the technology mean it is only possible to see parts of the brain's response to the stimuli. The novice interpreter may try to understand the data by connecting it to human experience in a causal relation, which is not a good strategy. The first impression from the research introspection of the device as a tool for the individual to learn about themselves can be far from reality. The technology is not usually there for participants to understand themselves, but rather as a tool for the researcher to understand the relation between the physiology and the brain. This is important because, whether it is a tool for the physician or for the patient, it is essential to the experience.

Unlike the fNIRS design, the EEG design gives immediate feedback. The EEG research introspection used one of many available games built on a similar logic, where the level of concentration or relaxation was the input. The aim of the game was to get the car to the goal as fast as possible, with brain activity working as the accelerator pedal. The brain activity could be controlled through concentration and relaxation. The user had an immediate hermeneutic relation with the device without understanding the technology. The interpretation in the device becomes secondary to the game of control and ability experienced by the user. Through the limitations of the game one could argue that the relation has aspects of embeddedness as the user understands how to achieve a high speed. These two examples do not necessarily describe the differences between fNIRS and EEG devices, but rather how technology can be designed for research purposes and for consumer markets and how it influences interpretations.

Context as a mediator of purpose

The context, such as a service, a programme or a game, is part of the interpretation of the technology and, therefore, part of defining its purpose. The research introspection found that the fNIRS device had a different objective to that of the EEG device used in a game context. The technology cannot be separated from the context of use and be assessed on a general basis. The document review for the research application described the design as having the following characteristics:

> There is a need to develop hybrid models where sensor information combined with artificial intelligence tools provide patients and clinicians with simple information to adapt and make decisions, so that new and healthy behaviours are encouraged … Alternative representations of the data with regard to user experience; focusing on the relation between patient motivation and health professional practice where participatory design is explored for alternative ways to communicate with patients and rehabilitation professionals

The characteristics describe a purpose of providing ‘patients and clinicians with simple information to adapt and make decisions so that new and healthy behaviours are encouraged’. Furthermore, it describes a need to make the current interpretation of data more relevant for patients and rehabilitation professionals. From this the question arises: How can non-invasive brain monitoring support such design?

Figure 4 was produced to summarise the activities and findings of the document review. It allows for different interpretations and can work as a starting point for discussion. Our methodological choice was to describe document content without publishing confidential material and as a feedback opportunity on the authors’ interpretations. Using this abstraction of topics and activities, we reviewed the literature to understand how relations between expert and technology shape the parameters of rehabilitation through the phenomena in focus.

Phenomena in focus through non-invasive brain monitoring

Two relevant research phenomena investigated through the non-invasive wearable brain-monitoring devices are balance and automaticity when walking. Most people consider both to be necessary aspects of walking. Not surprisingly, Wittenberg et al. (2017) show evidence of increased brain activity in balance control tasks. Most people would agree that the environment is essential, for instance, many people have experienced

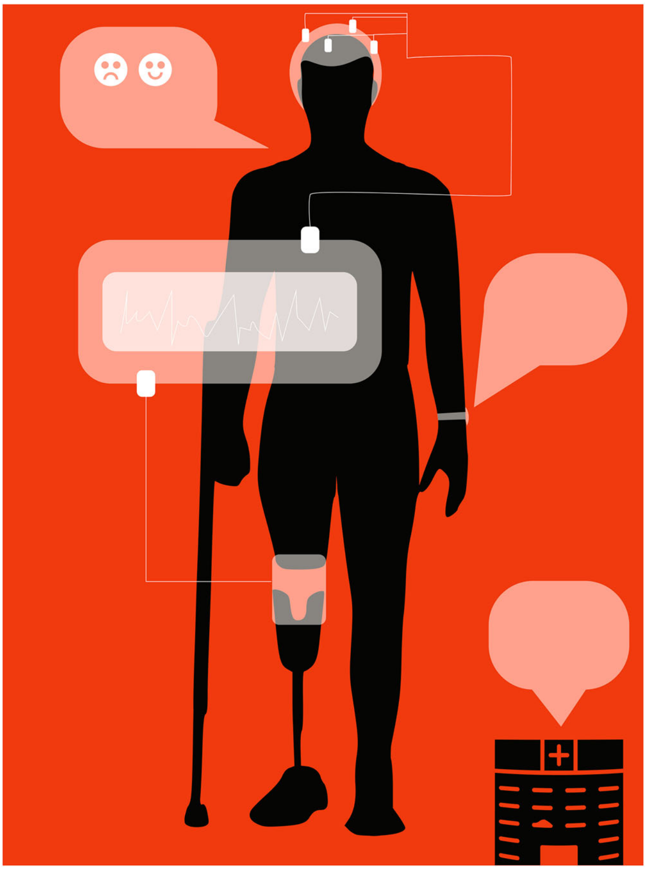

Figure 4. An illustration of two visions: 'the digital physiotherapist' and 'brain-controlled prosthetics'. Design by author 1.

how a fear of heights changes their perception of balance. Research shows (Schaffalitzky et al. 2011) that fear of falling is an important factor when walking with a lower limb prosthetic and could be central to the experience of balance. The fNIRS research community is interested in the negative relation between the activation of the prefrontal cortex and the degree of automaticity in motor control (Pelicioni et al. 2019; Herold et al. 2017).

A limitation of the devices is that they make some phenomena more relevant as objects of research than others. In EEG, the signal's spatial origin is a limitation. The mental state is related to the signal frequencies accessible for interpretation. Historically, frequencies were identified as delta, theta, alpha, beta and gamma, with the alpha and beta bands being perhaps the most used. Alpha frequencies (8–12 Hz) are found in awake but relaxed states (Wang 2010) and are strengthened by internal tasks and modulated by attention (Klimesch 2012; Palva and Palva 2007). Beta frequencies (12–30 Hz) are associated with preparation and control of motor activities (Nicolas-Alonso and Gomez-Gil 2012). In fNIRS, temporal resolution is a limitation, while the spatial origin is more accurate than in EEG. When using fNIRS for experiments, the available spatial areas dictate what is relevant as an object of research. When fNIRS and EEG are combined they can complement each other (Khan et al. 2021). De Boer, te Molder, and Verbeek describe how the technology in their study does not comprise neutral instruments, but instruments that 'actively mediate the reality that scientists investigate' (2020, 1).

EEG can interpret patterns or frequencies of phenomena such as attention, relaxation and automation without understanding the concepts from the perspective of experience as these are frequencies found under such stimuli. There is a gap between the traces of cognition that we can read from the technology and the experience of that phenomena. This might not be an issue in research, where the goal is to understand the brain, but it might become an issue when using the technology to understand individual experience in rehabilitation.

Non-invasive brain monitoring offers an opportunity to contribute to evidence-based rehabilitation by using essential quantitative measures to assess the interventions' effects. For instance, by using brain activity as an indicator of the automaticity of motor control and to measure successful rehabilitation using robot-assisted gait training (Berger et al. 2019). Another area of interest is the cortical area related to motor functions (Stuart et al. 2018). Several studies have investigated the effect on cortical compensation strategies in gait for people with gait diseases and impairments (Gramigna et al. 2017). Activity in the prefrontal cortex, or the cognitive load, is relevant to understanding balance and automaticity in walking. The challenge when interpreting these results is that they show correlation rather than causal effects.

We have argued that non-invasive brain-monitoring technology mediates a specialised view on rehabilitation through the object of research, such as balance and automaticity in walking. The hermeneutic relations revealed in the analysis of non-invasive brain monitoring, as presented above, suggest it is common practice to use technological instrumentation to create quantitative measurements. Developing instruments for quantitative measurements are essential in research but using the same measurements in service innovation calls for a certain precaution, as we will discuss through the introduction of visions.

Visions

Two visions – *the digitalised physiotherapist* and *the brain-controlled prosthetic* – were synthesised as two options for using non-invasive brain monitoring in rehabilitation in PACER, based on the findings, Figure 4. These visions are only two of many possibilities, but by concretising them it becomes possible to discuss patient-centred issues and opportunities.

Vision 1: the digitalised physiotherapist

This vision offers one notable opportunity and a possible driver that is essential from a welfare perspective, which is to deliver services to more people at a lower cost. A cost-effective perspective will sustain welfare going forward, as an increasing proportion of the population will need such services. One solution to this is apparent in the alterity relation, where there is a potential to digitalise and automate some of the physiotherapist's work. There are many examples of how this can be done, such as non-invasive, brain-monitoring devices as a clinician's tool to assess rehabilitation progress and to tailor programmes through trial and error to maximise progress to fit individual preferences. The connection between the patient's potential for rehabilitation and brain activity levels could show whether the user would benefit from a more advanced prosthetic. It could also help to deliver services at home, as many prosthetic users live some distance from a rehabilitation centre.

Depending on the device's transparency, and ease of in interpretation of data, using a brain-monitoring device could affect how users interpret their cognition, even though the device does not necessarily measure higher levels of cognition.

As discussed through the PACER project, a principal difference is whether the patient is a tool in the research, or whether the technology is a tool for the patient. From a value perspective there are differences when the focus is rehabilitation for the individual from when rehabilitation is the research topic. Non-invasive brain-monitoring technology used as a tool for the health professional could mediate paternal control rather than offer an opportunity for better treatment. For a patient this might be a step in the wrong direction, away from an ideal patient-centric rehabilitation, in which patients can express and understand what is best for them.

To reduce risks in a design used for control we assume that knowledge about brain and mobility in relation to rehabilitation should make it possible to give more direct feedback to the patient. The goal of such design is often to change user behaviour and there are many approaches to achieving this through motivation, identifying mistakes and practice, to name a few. It could be argued that a non-invasive brain-monitoring device used in an alterity relation has the power to delegate responsibility for rehabilitation. Depending on the design, delegating responsibility is critical, whether you are monitoring yourself or interacting with a physiotherapist or other people, such as relatives. From a patient-centric perspective the critical questions are how does the prosthetic user want to be faced with their rehabilitation, and on what aspects? For example, is walking the goal of rehabilitation? This is a critical assumption as walking is an essential part of rehabilitation. However, non-invasive brain monitoring only investigates a specific perspective on walking described through the phenomenon focus.

The underlying assumption common to health apps that 'knowing what is good for you leads to change in behaviour' needs to be challenged. We would argue that this is especially difficult with brain-monitoring technology because it is challenging to understand what the information means and requires the users to have meta-perspectives on themselves.

Kiran (2017) exemplifies how good patienthood could be approached by posing the ethical question, 'How can I take an active part in shaping my daily life so that the technology supports my conception of a good life?' (25). In the PACER project context, a good patienthood could be addressed by giving the prosthetic user an opportunity to actively engage in what they identify as good rehabilitation (Murray 2013). A responsibility issue when designing a solution that fits into a vision such as the digital physiotherapist, is that it needs to be understood as not fitting all situations. Therefore, the personalised rehabilitation term should acknowledge that some people will need a physical meeting with the physiotherapist, as emphasised in several studies on rehabilitation's psychosocial aspects for lower limb amputees (Horgan and MacLachlan 2004; Senra et al. 2012). Using only brain activity as a performance measurement will not take into account the prosthetic user's motivation or social situation. An example from the PACER application document is that the meaning of patient-centric from a human-centred perspective can be interpreted differently from the personalised technology perspective. Although both focus on the patient as an individual, the framing of the individual is different. On the one hand the patient could be viewed as the sum of physical interactions taking place in the brain, based on the medical or physiological model. On the other hand, a human-centred approach is often more complex as it focuses on more than the physical interactions in the brain and body by including the patient's whole life.

Vision 2: the brain-controlled prosthetic

The feasibility of brain-controlled prosthetics is possibly entertained more in mass media than the PACER project application suggests. The literature and the research introspection describe two different functions of the technology, as a tool for information and as a tool for control. The former vision of the digitalised physiotherapist is a tool for information. In this part about the vision of the brain-controlled prosthetic we discuss non-invasive brain monitoring as a tool for control.

In research on the augmented human and on the brain–computer interface, embedded relations between body and technology are often an ambition. The brain-controlled prosthetic reveals a difference between the actual experience and the idea of embedded relations. In a patient-centric approach it is possible to use an experience perspective to evaluate the success of embedded relations based on aspects other than accuracy.

The direction of physical enhancement is often linked to the idea of embodied technology. The differentiation between an embodied and a hermeneutic relation can be understood through Heidegger's notion of technology as 'ready at hand' as opposed to 'present at hand' (Heidegger 1962; Verbeek 2011, 8). This process is not necessarily related to a technology's ability to adapt to the environment, but rather to a human's ability to adapt to the technology.

The idea of non-invasive, wearable, brain-computers as a mind-reading technology, is in contrast with the actual interaction that is limited to the different control paradigms, as covered in a comprehensive review by Abiri et al. (2019) of the possibilities and challenges of using EEG devices as an interface. The challenges relate to training time, fatigue and that a low signal-to-noise ratio is needed to control three degrees of freedom. Challenges when using fNIRS are related to the delay in the physiological response caused by the hemodynamic neuro-vascular coupling. What would seem at first glance to be an embodied relation could, arguably, more often be an alterity relation similar to a voice control interaction, since it is more 'present at hand' than embodied.

From a patient-centric perspective, we argue that there is a potential to improve rehabilitation through embedded relations (Murray 2008). Whether this is most effectively achieved through non-invasive brain monitoring is a topic for future research. It is crucial in a patient-centric perspective not only to view walking as a physical phenomenon, but also to include aspects such as trust and identity as part of the wider walking experience.

We also argue it is crucial that embedded relations are explored in other rehabilitation technologies, particularly how they are influenced by psychosocial aspects, which are often left out if the aim is to replicate able-bodied walking. In the vision of a brain-controlled prosthetic, the challenges of using non-invasive brain-monitoring devices to create meaningful embedded relations can also be seen as an opportunity for considering other control paradigms in further work.

Concluding remarks

This work has focused on an especially important and sometimes neglected topic connected with the introduction of a technological mediation approach. By focusing on patient experience, the work adds new knowledge to the current framing of the development and assessment of technology use for rehabilitation. The technological mediation approach has been used to analyse human–technology–world relations in the PACER case study, which has found different relations between *expert, novice and technology, context as a mediator of purpose and phenomena in focus through non-invasive brain monitoring*. These findings were used to construct two visions (Grin and Grunwald 2000) that facilitated a discussion on patient-centric approaches in the case study.

The technological mediation approach exemplified how non-invasive brain-monitoring devices mediate a specific aspect of human motion. In contrast to other studies that emphasised rehabilitation's psychosocial aspects for lower limb amputees (Horgan and MacLachlan 2004; Senra et al. 2012). Using brain activity to measure and individual's performance may not take into account the prosthetic user's motivation or social situation.

The findings suggest that further work should consider a prosthetic user's rehabilitation experience, in particular, if the technology is used in alterity relations where the goal could be to provide digital physiotherapy services. Such designs will impact perceived health, and a potential consequence is that the softer aspects of rehabilitation normally picked up by a physiotherapist are overlooked. The patient experience perspective could be addressed if the prosthetic user has the opportunity to actively identify what they see as good rehabilitation and how they want to be faced with this. From a PACER project perspective, these findings showed the relevance of considering other technological solutions for rehabilitation, and not limiting such a project to fNIRS and EEG.

A more nuanced and experienced-based view of these phenomena could contribute to a more responsible development of non-invasive brain-monitoring technology. This case study has shown how technology can be both interpreter and interpreted, and that the intentionality of the researcher plays a part in shaping that technology.

As a practical consequence of these findings, we argue that a more complementary and holistic framing is sometimes necessary – from development to intended use of a device – since the mediations will be affected by the technology in use. It is also essential to be more aware of the user's perspective, to clarify whether the interpreter is the scientist, the physiotherapist or the prosthetic user.

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Notes on contributors

Martha Risnes is a PhD candidate in the Health Science program at Oslo Metropolitan University. She has an educational background in engineering and design. Martha's research interests include design perspectives on emerging technologies for health purposes.

Olga Korostynska is current a Prof. In BioMedical Engineering in Oslo Metropolitan University in Oslo, Norway. She has a BEng and MSc in Biomedical Engineering and PhD in Electronics and Computer Engineering from the University of Limerick, Limerick, Ireland for developing a personal gamma-radiation sensor using thin/thick film technologies. Previously she was a Senior Lecturer in Advanced Sensor Technologies at the Faculty of Engineering and Technology, Liverpool John Moores University, Liverpool, UK. Before that she was a postdoctoral researcher working on a number of projects, including funded by IRCSET, EI, EU FP7 and H2020. She has published a book, several book chapters, 4 patents and over 200 papers in both peer-reviewed journals and conferences.

Peyman Mirtaheri received Cand. Scient. and Dr.Scient. degrees in physics and electronic engineering from the University of Oslo, Oslo, Norway in 2006, and the Dr. Scient. Degree with the thesis on a novel biomedical sensor for early detection of organ ischemia from the same the institution in 2005. He is currently a Professor of Biomedical Engineering at the Faculty of Technology, Art and Design, Electrical and Electronic Engineering, OsloMetropolitan University, Oslo. His current research interests include functional Near-Infrared Spectroscopy (fNIRS), Optical Sensors, Diagnostic Instrumentation and Monitoring Devices applied in medicine.

Arild Berg is Associate Professor with Doctor of Art in Artistic research in Public Space, and he has a MA in Ceramic Art. He is a member of the research groups Design, Culture and Sustainability, Art in Society and the Collaborative Action Research Network (CARN). His principal work focuses on research collaboration between professional practitioners to contribute to studies of cross disciplinary innovation. He has been Head of studies for the Bachelor Program in Product Design. He has been Vice Dean of Research at the Faculty for Technology, Art and Design and was project leader in establishing the interdisciplinary PhD Program 'Engineering Science'.

ORCID

Martha Risnes http://orcid.org/0000-0001-9972-0347
Olga Korostynska http://orcid.org/0000-0003-0387-6609
Peyman Mirtaheri http://orcid.org/0000-0002-7664-5513
Arild Berg http://orcid.org/0000-0001-8876-7641

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