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Prosthesis-User-in-the-Loop: User-Centered Design Parameters and Visual Simulation

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Abstract— **After an amputation, processes of change in the body image as well as a change in body scheme have direct influences on the quality of living in every patient. Within this paper, a paradigm of experimental induced body illusion (the Rubber Hand Illusion, RHI) is integrated in a prosthetic hardware simulator concept. This concept combines biodynamical and visual feedback to enhance the quality of rehabilitation and to integrate patients' needs into the development of prostheses aiming on user-centered solutions. Therefore, user-centered design parameters are deducted. Furthermore, the basic concept of the visual simulation is presented and a possibility for its implementation is given. Finally, issues and conclusions for future work are described.**

I. Introduction

An amputation marks a distinct intervention in the life of patients. It directly influences wellbeing, quality of life and autonomy [1]. Additionally, patients have to cope with challenges in their family and social environment [14]. The main processes of change after the amputation are a change in the body image as well as a change in body scheme [1]. In contrast to the body image, which comprises the psychological experience (the subject's perceptual experience, conceptual understanding and emotional attitude of the own body) the body scheme describes the representation of the characteristics of the own body in a subconscious, neurophysiological and multisensory way [13], [4]. As described in [1], these changes of the amputees' identity emerge in multiple phases. The first phase represents the first contact with the own amputation and the experience to be a disabled person in the future. Secondly, the actual change of identity, body image and body scheme occur, before a new identity is formed integrating the amputation. Certainly, several negative emotions arise throughout all these phases and support from the social background seems to be necessary for a positive rehabilitation process of amputees, an integration of the prosthesis to their body scheme and a positive self-appearance through the new body image [15], [13], [12], [1]. Another important factor for the integration of the prosthesis to the amputee's body scheme seems to be the time after the amputation [15], [13]. Regarding the wellbeing and quality of life of individuals with amputation, functional limitations seem to have major influence [15], [13], [1]. These body functioning is closely related not only to the appearance in elderly people [5]. A functional adaptation to the prosthesis is successful if both, the artificial and the unharmed extremity are equally integrated and represented in the body scheme and body image [13]. The integration of artificial objects in the human body scheme as a neuro-scientific paradigm and the holistic visual simulation of a healthy body may offer new perspectives for this integration process and a positive update of one's body image.

This paper presents those new perspectives in association to the Prosthesis-user-in-the-Loop simulator concept (see below) and gives a basic structure for a possible implementation of the visual simulation in this concept. In section II the basic process of integrating artificial objects in the human body scheme is explained. Ideas about this basic process should be focused and validated with experimental data when the user requirements are clear. These user requirements, experimental data and their consequences for visual simulation are presented in section III. A concept for visual simulation and its realization in the Prosthesis-user-in-the-Loop simulator follows in section IV. Finally, a conclusion and an outlook are given in section V.

II. Body Scheme Integration

Feelings of unrealistic body parts are related to deficits in human information processing and can occur as a part of phantom sensations after amputation [8]. Coping with phantom sensations and body scheme integration of the new prosthesis can take up to four years [13], [12]. The observed symptoms prior to a successful body scheme integration of the prostheses suggest disturbances in the experience of the body scheme and image (for discussion of these concepts see [4]). This includes the sense of knowing in the real world which are parts of one's body and which are not. Additionally, the integration process is directly linked to the sense that one has control over one's body.

Botvinick and Cohen showed that the body scheme can experimentally be manipulated in healthy volunteers [2]. This simple paradigm (synchronously brushing the hidden real hand and the visible rubber hand) induces the rubber hand illusion (RHI), i.e. the feeling that the rubber hand belongs to me; the position of the real (hidden) hand is subsequently indicated closer to the rubber hand. The latter

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is a proprioceptive re-calibration towards the rubber hand. The cause of these effects is attributed to multisensory integration between visual, tactile and proprioceptive information. For now there is no systematic overview regarding the evoked RHI during movement, its maintaining factors and transfer to lower limbs. Moreover, requirements of the user might narrow the scope down to the necessary user centered design parameters.

III. Design parameters

In this section the work of our group and empirical findings that can be deduced from and will lead to design parameters will be presented.

A. Survey of user requirements

Christ et al. [8] obtained with a newly developed questionnaire data from patients regarding their needs using lower limb prostheses. Five main items (satisfaction with/during the prosthesis fit to the shaft, appearance, standing, walking and sitting) were rated. Possible answers on a numeric rating scale were 1 (not satisfied) to 4 (very satisfied). Irrespective of the prosthesis technology, the results indicated a lack of satisfaction with the prosthesis shaft, a lack of satisfaction in walking and a lack of satisfaction in sitting. Furthermore, satisfaction with appearance as a descriptor for subjective body scheme integration and body image was measured and showed low values. The satisfaction with the prosthesis shaft was significantly ($p<.0001$) correlated with the satisfaction in voluntary ($r=.82$) and postural ($r=.70$) movements. Also the appearance was significantly ($p<.001$) correlated with the satisfaction with the prosthesis shaft ($r=.61$), the voluntary ($r=.63$) and the postural ($r=.58$) movements. Although all lower limb amputees made experiences with different prosthesis technologies, no technology was reported to fulfill all user demands. The appearance as a descriptor for subjective body scheme integration seemed to be an important factor that is associated to the conditions that deal with perception (prosthesis shaft) and action (postural and volitional movements). This indicates a need of further knowledge about factors that are directly correlated to the unsatisfying and interfering experiences in body scheme integration during movement. Experimental data regarding the RHI and maintaining factors may help to prevent unsatisfying and interfering experiences. Furthermore, this data should help to deduce criteria for visual stimulation.

B. Experimental data

As pointed out earlier the multisensory integration between visual, tactile and proprioceptive information is necessary to evoke the RHI. Christ et al. [6] showed that the temporal and spatial relation during the integration process is important. In a systematic literature review we tried to find data which were related to experimentally induced RHI and maintaining factors during movement. We searched in the following www.dimdi.de data bases (CCTR93, CDAR94, CDSR93, DAHTA, EA08, ED93, EM00, EM47, HG05, KP05, KR03, ME00, ME60, PI67, PY81, TV01, TVPP) with various search terms to get a maximum of search results. A total of 160 articles were found. After duplicates were removed, the remaining list was filtered with the objective to explore the influence of active or passive movement during experimentally induced RHI. Six articles were identified which experimentally examined persistence of RHI during active or passive movements. The findings showed that the tactile stimulation can be completely replaced by movements. However, in movements a distinction must be made between active and passive ones. Active movement is a self-generated [17] and voluntary action [19] whereas passive movement is externally generated for example by an experimenter. The important difference is the presence of agency (AY), i.e. the subject's self-induced movements, during the active condition. While the sense of agency involves a strong efferent component [17], the passive or tactile stimulation only involves afferent sensory signals [19], [3]. One might assume that this makes a difference, but sense of ownership (SO) is present through all induction types. All studies consistently produced these results. Over all conditions the persistence of the illusion seems highly dependent on spatiotemporal congruency (synchrony) between the different information (e.g. no or low visual delay). During all asynchronous conditions the illusion was greatly reduced (e.g. high visual delay). Apart from that there were different effects especially in the active movement condition. Longo [18] examined effects in reaction time of ownership and agency during RHI. Only in the synchronous active movement condition a significant speed-up in reaction time was measured. Longo assumed this effect as specific for agency. Another effect which was attributed to agency is a more global illusion [16]. In the corresponding study during synchronous active movement, the proprioceptive drift could be measured not only in the stimulating finger, but also over the whole hand.

C. Deduction of criteria for visual stimulation

Within the reported data, no study was focused on a rubber "leg" illusion (RLI) or on other parts of the lower extremities. Furthermore, one maintaining and enhancing factor could be the spatiotemporal congruency. If a subject is recognizing a visual delay between his moving limb and the visual feedback, the effect of the illusion is assumed to decrease or disappear. The literature describes different threshold values for the perception of visual delay. As mentioned before, there is only data for upper extremities available (see table 1).

TABLE I.

Author	Delay threshold detection times
Blakemore et al. [9]	150ms
Christ et al. [7]	70ms
Frank et al. [10]	100-150ms
Shimada et al. [11]	up to 230ms

Besides a "natural look" of what has to be simulated, the reaction time of the visual simulation has to be high or the individual threshold of a user has to be measured to prevent an interfering process. Although the importance of active or passive movements during the illusion process seems to also have an impact of the haptic feedback information (and therefore on the biodynamical simulation unit of the Prosthesis-user-in-the-Loop simulator concept in the next section), we will focus subsequently on some basic ideas transforming the results into a visual simulation unit.

IV. VISUAL SIMULATION

The Prosthesis-User-in-the-Loop hardware simulator concept enables the design and optimization of lower limb prosthetic devices based on the user-centered design parameters described before. By providing a holistic simulation of gait with prosthesis to the participating users, the experiences and assessments during gait with the prosthesis can be determined and translated into technical design criteria supported by psychological methods. Besides the mechanical simulation of the biodynamic behavior, the visual stimulations to the user are simulated to complete the illusion of the usage of the investigated prosthetic technology. While the mechanical interactions between the stump of the participant and the simulated prosthesis are simulated by a robotic device, this visual simulation creates a virtual room using screens and projectors. Due to the induced illusion, the participant can experience gait with the investigated prosthesis while seeing an intact leg. Thus, the assessment of the functionality of the prosthesis by the participant can be isolated from its integration to the body scheme and vice versa.

A. Simulation concept

Different computations are necessary to put the visual feedback on screens or projectors into practice. A video or virtual three-dimensional simulation of an intact leg, for example, can be mapped to the movements of the disabled leg using the acquired sensor data from both sides as shown in figure 1.

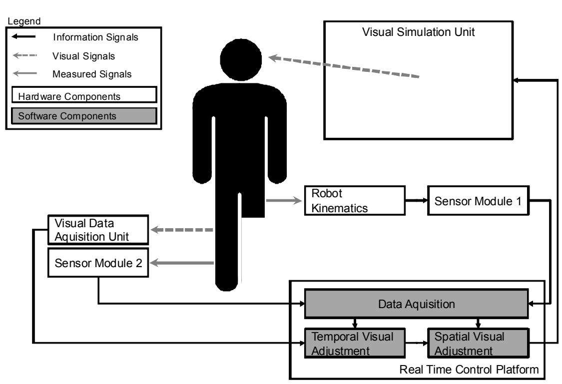

Figure 1. Visual simulation concept

This mapping is conducted in two steps, which are the temporal and spatial adjustments. For the temporal adjustment, a recorded video stream of the intact human leg as well as a virtual three-dimensional simulation of the same can be synchronized to the gait movements of the intact side, which are simulated with a human model on a real time control platform. The spatial adjustment of the video or simulation of the body and movements of the participant can be implemented by using a model adapted to the subject and the measurements and predictions of the recent and following joint trajectories during locomotion.

B. Three-dimensional animation and multi-body-dynamics

One possibility to implement the temporal as well as the spatial adjustment of the visual feedback is to utilize a 3D-animation controlled by a dynamics simulation of a multi-body system. The latter will be achieved by biomechanical multi-body simulations using the object-oriented class library MBSLIB presented in [20]. By obtaining joint trajectories from a biomechanical forward kinematic simulation, the motion of the virtual character and the participant can be adjusted and synchronized. It is assumed that such a representation already exists in order to control the biodynamical simulation unit of the concept that is described in [21]. Figure 2 shows a possible three-dimensional visualization of a virtual character that can be actuated by simulated joint trajectories. This character can be created using the software MAKEHUMAN [21] that is designed to produce three-dimensional characters. Beyond this basic three-dimensional model, extensions as hair and clothes and the adaptation of those to the ones of the particular participant are feasible.

Figure 2. Implementation of a 3D-model

The path of the visual data from generating the animation of the human model to the final visual data stream that is given to the visual simulation units of the Prosthesis-User-in-the-Loop simulator is depicted in figure 3. Starting with the generation of the three-dimensional virtual character and the gait simulation, the information from those is transferred to the temporal visual adjustment. In this software component, the temporal delay between the data acquired at the intact leg and the side of amputation is determined and synchronized. Based on this, the stream is forwarded to the spatial video adjustment, where the trajectories for the movement of the disabled side are predicted and the animation is adapted to the movements of this side. The adaptation also uses data from the simulation environment, which is resulting from a simulation of the participant's gait with the prosthesis.

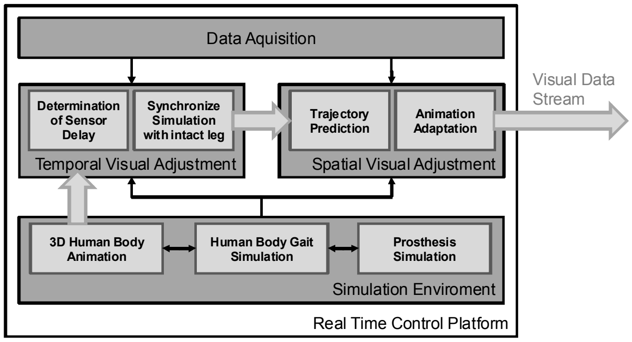

Figure 3. Generation and modification of a three-dimensional simulation

V. CONCLUSION

This paper showed new ideas to facilitate the integration of prosthesis technology in the human body scheme. The holistic visualization may offer new possibilities for this integration process and a positive development of the amputee's body scheme and image. The results show that the RHI paradigm in combination with movements could give a more global and maybe also a more resistant illusion. Thus, the Prosthesis-User-in-the-Loop concept might use such resistant illusions in the rehabilitation and gait training. The sensory information, that is needed in return, can be generated in simulations, especially active routine movements. The aim of a Prosthesis-user-in-the-Loop simulator concept must be to coach and facilitate daily movements. Another advantage of using illusions with active movements can be to accelerate reaction time [18]. In certain everyday situations there is an enhanced capacity of reactions needed, especially in lower limb amputees, where safely walking is important and the natural reaction, stumbling, is impaired. The apparent domination of visual input in RHI plays (beside self-generated actions) a key role in inducing a sense of agency. Given that sense of agency is induced by active movement, we begin to correct visual feedback through passive movements. After this or in periods of normal mobility, the sense of agency could be strengthened by various active movement exercises.
Alternative solutions for the visual simulation are video modification or augmented reality. On the one hand, video modification might deliver worse quality of the illusion due to spatial adjustment problems, but provide easier implementation of a realistic presentation. On the other hand, augmented reality approaches provide the possibility to combine different advantages of the two aforementioned kinds of visualizations.

Finally, a direct comparison between the studies is difficult because different methods were used. The most common method is the questionnaire. This method lacks comparability, because items were especially designed for the detection of SO and AY in only two studies. In the resulting studies, SO and AY were simply assumed or not further elaborated. To utilize specific effects of passive or active movement due to RHI it is necessary to use standardized methods to better replicate and compare such findings in the future.

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