User-centered Prosthetic Design: A methodological approach to transfer psychological factors to technical development
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Abstract
User-centered design is a major issue in contemporary prosthetic design. With new technologies like drive trains that are emerging in lower limb prosthetics and provide support for locomotion, new psychological issues and human factors in development arise. Beyond technical factors like biomechanical functionality, those comprise characteristics of the prosthesis as well as their experience by the user. To cope with all factors equally, this paper describes a framework for prosthetic design with focus on active lower limb prostheses. Yet, it could be generalized to other types of prostheses or other classes of human-oriented mechatronic systems. Therefore, relevant human factors are identified to be satisfaction, feeling of security and body scheme integration. Those and their influence on development based on questionnaires, interviews and the literature is described. With this, a design methodology based on quality function deployment, v-model design methodology and multi-factor optimization are proposed and their suitability to this application is shown.

1 Introduction
User-centered development represents a promising approach to determine a good tradeoff between functionality and usability of prostheses, as the loss of a leg has an enormous psychological impact [1]. By involving users and considering human factors, user requirements can be integrated into design methodology. Thus, technical devices combining functionality with intuitive usability and smart design will be achieved. For this reason, methods for assessment and transfer of human factors to development are required.

The method quality function deployment that is applied on upper limb prostheses in [2] provides the possibility to consider human factors during design. This is achieved by finding the influence of functional units on usability and determining a development focus based on this. In [3], the factors influencing prosthetic design are categorized as enabling technical factors, predisposing human factors that can only be influenced by technical development indirectly and reinforcing factors. The latter ones cannot be influenced technically as those are such as family support. Further, the importance of considering the individual requirements of the specific prosthetic user are shown in [4] based on an identification of their values and preferences. Technically, v-model development methodology and a user-centered development optimization approach as introduced in [5] are promising approaches for the implementation of basic technology concepts. Such units as electric drives or variable stiffness joints are important functional units of state-of-the-art lower limb prostheses [6]. Yet, the influence of such systems on the experience of users is not understood sufficiently and various questions as how integration of the prosthesis to the body scheme of the user can be achieved are not finally answered [7]. This question in particular remains as an open issue in the psychology of prosthetic users in general.

This paper extends the methodology from [8] and presents the identification of relevant human factors in lower limb prosthetics in Section 2. Subsequently, their influence on technical development is described in Section 3, while Section 4 proposes the design methodology and explains it on the example of active lower limb prostheses. Finally, the results are discussed and in Section 5 and conclusions are given.

2 Psychological Factors
Positive correlations between psychological factors and the characteristics of the prosthesis indicate that technical development can influence the psychological issues [1] and might thus contribute to the psychological well-being of the amputee. To achieve this, a holistic development method accounting for the psychological needs of amputees, requires an examination of psychological factors. To identify how those can be targeted by development, models as shown in Figure 1 are established to separate the influences on the specific factors. Those influences are labeled according to [3] as mentioned previously. Figure 1 shows how the psychological factor is influenced by means of prosthetic development and the limitations due to the influence of the particular user. Since only enabling factor can contribute to the psychological outcome, those are focused in design and their influence on predisposing factors is important. As those are found in perception and attitude of the individual amputee, a variability of psychological outcomes between amputees is caused. Thus, clustering users into stereotypes might help to group those with similar reactions (age, gender, activity) and hence their specific needs. Supported by the literature [9,10], results from a custom build questionnaire - $N_1=29$ transfemoral amputees [11], $N_2=29$ lower limb amputees [12] - and an interview study - $N_3=13$ - are used for an analysis of user requirements and the narrative identifica-
tion of relevant human factors. The results indicate that satisfaction, feeling of security and body scheme integration seem to be the relevant human factors in user-centered prosthetic design [8].

![Figure 1: Model of psychological factors.](image)

The satisfaction of the amputee with the prosthesis is of key relevance for the use of the device and can be interpreted as an overall user rating. Influences are found in the characteristics, the functionality, and the appearance as well as usability features [12]. In contrast to the objective safety of the amputee, feeling of security describes their perceived safety. Many amputees show both, a reduction in balance and an impairment of their physical capabilities. The increased risks of stumbling and falling as well as the resulting fear of falling have considerable influence on the feeling of security [13,14]. Beyond their technical functionality, prosthetic devices should replace the perception of lost body part [7,11,12]. The user should perceive his body as being intact, understanding the prosthesis as an integral part of his body instead of viewing it as a foreign and artificial object. A successful integration of the prosthesis into the user’s body scheme requires the feeling of control and sensory perception [7].

3 Impact of Dimensions on Development

Knowledge about psychological dimensions that are directly linked to the satisfaction and well-being of a prosthesis user will help to modulate satisfaction and well-being with changes in the relevant psychological dimension. The latter ones can be influenced by technical innovations from user-centered design. Knowledge from interviews, questionnaires and experiments will give ideas about relevant dimensions.

3.1 Questionnaires and Interviews

Regarding satisfaction, literature shows consistent and inconsistent results [11,12]. Regarding inconsistent results, satisfaction with the prosthesis showed significantly positive relationship to the experiences of problems due to a swollen stump (r = .394, N1) and satisfaction with the transition from standing to walking was positively associated with swollen stumps (r = .556, N1) [11]. These inconsistent results indicate that users accept a certain amount of dissatisfaction and hence show the relevance of satisfaction as a human factor [12]. Feeling of security seems to be directly correlated to the flexibility of prostheses. Problems in changing gait velocity were negatively related to feeling of security during spontaneous movements (r = -.426, N1) [11]. As flexibility is a part of functionality, this marks a connection between predisposing human factors and enabling technical factors [12]. Regarding further consistent results, an impact of balance and confidence on the fear and incident of falling is shown in the literature and a correlation between appearance and functionality during walking (r = .634, N2) and sitting (r = .580, N2) can be observed in the results from the questionnaire [11]. Interpreting appearance as a descriptor for body scheme integration due to this significant correlation with voluntary movements, the consideration of this human factor is expected to be most useful to optimize biomechanical functionality.

3.2 Experimental Investigations

Regarding the human factor body scheme integration, the occurrence of a Rubber Feet/Leg Illusion was experimentally evaluated. First results indicate small effects regarding the transfer from the hand to the feet [15,16]. A psychometric approach regarding the identification of ideal illusion paths on the skin disproved the importance of haptic differences. Further studies should explore possible reasons for the differences between survey data and proprioceptive data for further technical development [17]. Finally, the simulator Prosthesis-User-in-the-Loop is proposed to integrate users in the whole design process [12].

4 Transfer Methodology

To integrate of human factors, quality function deployment is presented as a method to rate, reduce and cluster such based on expert knowledge. Since enabling factors are perceived different than predisposing factors, a two-dimensional assessment and optimization of basic technologies as the drives of active prostheses is proposed. In combination with this and system integration by the v-model development methodology, quality function deployment enables to focus design by considering human experience.

4.1 Quality Function Deployment

With quality function deployment, a technical development focus regarding human factors can be determined by means of expert knowledge. Therefore, the viewpoints of users and developers are assessed by based on the correlations between those. The resulting QFD-values represent scales for influence of functional units on the factors and hence allow for a targeted development. As a basic example, this is performed for the factor satisfaction regarding an active lower limb prosthetic system determining the QFD-values in a discussion of experts and calculating user weightings based on data from [10]. As no clustering of users is performed there, this results in an overall focus that does not distinguish the particular demands of specific groups. Further, those are not validated, since the number of experts in is not sufficient.
Anyhow, it is appropriate to indicate the possible results, if the number of experts and the basis of user data are sufficient. The results depicted left in Figure 2 show that actuators and variable stiffness show strong influence on satisfaction. The socket is only ranked at the fifth position, although experts know that this is of key importance in lower limb prosthetics generally. This is due to the selected criteria, as the socket does not influence sounds or operating time of the prosthesis. Hence, this does not indicate that the socket is unimportant in active prostheses, but provides the information that new psychological issues occur due to such technologies. For a validation of the specific QFD-values, more data from experts and users should be acquired and stereotypes should be distinguished.

Figure 2: Left - QFD regarding satisfaction based on [10], Right - Example for optimization results

4.2 Two-Dimensional Assessment and Optimization

The Aim of two-dimensional assessment and optimization is to identify technical solutions that suit technical requirements and human factors equally. Based on a weighted sum of technical ratings and user-feedback, a cross-component of the prosthetic system can be achieved. For active lower limb prostheses, the optimization of the drive train is one of the most important issues. Especially, investigating actuators with variable compliance characteristics seems to be promising, as present designs mostly rely on such solutions [6]. Anyhow, the selection of the drive train topology as well as components and control strategies has to be performed specifically due to the different types of prostheses and user stereotypes. While serial, parallel and hybrid topologies can be chosen for the physical event chain, different combinations of gears and drives can be applied. Besides the global control strategy, one important sub-issue is the selection of a power-optimized stiffness value [18]. As the configuration and dimensioning of all functional units cannot be optimized independently, the high number their permutations shows the advantage provided by a global optimization. Hence, an approach based on [5] is proposed: Starting with the definition user stereotypes, the population of users is clustered into subgroups with compatible requirements for user-centered design. Those stereotypes might be dynamic young people with increased need for functionality and elder and less secure people who show a strong demand of security [1,10]. For the development of an evaluation matrix, objective parameters as those given in [5] are acquired, clustered in groups and assessed. In this evaluation matrix, the results from quality function deployment are considered by adjusting the weightings specifically to the stereotypes based on the determined development focus. To identify the assessment of the various combinations, simulations of system dynamic drive train models are performed that might be optimized by design of experiments as in [19]. After determining the configuration that is optimized for the specific stereotype and thus the particular objective parameters, a sensitivity analysis is performed to ensure a robust result.

The right part of Figure 2 shows exemplary results from an optimization of a prosthetic knee that only considers technical requirements. In this, three real DC motors from different manufacturers are combined with three transmissions with different ratios. For the assessment an inverse dynamics simulation with real gait data from [20] stretched to a gait cycle length of 1.3s is performed at a fixed joint stiffness of 100 Nm/rad. The assessments represent the result of the evaluation function, where the highest value is the best result. Hence, the combination of motor B and a transmission of 160:1 achieve the best result in this scenario. As this basic study only considers technical parameters, the result is dominated by the reflected inertia of the drive train. Anyhow it shows the capability of the method to reject invalid combinations, to assess and rank the remaining ones and integrate human factors in the evaluation function.

4.3 V-Model Design Methodology

For the identification of an integrated implementation of the optimized functional unit, v-model design methodology as used in [21] can be applied. This allows for fitting the identified concept to the available installation space by geometric integration and may provide improvements due to functional integration. For this, a requirement analysis and design of the global system are performed. Therefore, results from psychological assessment and biomechanical investigations can be considered directly as well as weightings from quality function deployment. After this global definition on system level, the components of the prosthesis are designed, integrated and tested. Based on simulations from two-dimensional assessment and optimization, aspects of biomechanical functionality as well hand factors can be considered in these steps. In these steps, the Prosthesis-User-in-the-Loop simulator would provide the possibility to integrate users during the component design, as it allows for varying single components of a prototype during development and acquiring user-feedback immediately. The results from component design are used for the
synthesis of an integrated system, which is finally evaluated regarding the requirements determined in the first step on global system level. Regarding human factors, feeling of security has different impact in the v-model design methodology than satisfaction or body scheme integration, as it mainly influences the development on system level. This becomes distinct, as feeling of security is directly associated to the fear of falling [13] and the balance confidence of the amputee [14]. Both issues cannot be tackled by a single component, since they are influenced by the overall functionality of the prosthesis and thus by all hard and software components as well as their interaction. Hence, treating feeling of security as a global issue in the v-model is appropriate, although every single component is required to be reliable. Satisfaction and body scheme integration have to be focused in component and system design.

As an example, an active prosthetic knee can be considered: In this case, the system requirement analysis and design aim at the knee functionality, while component design might focus on the implementation of a specific kinematic concept in combination with an elastic drive train concept. After the design of those, their integration in the knee system would be performed and tested.

5 Conclusion

The authors results and literature indicate a strong potential for user-centered development in prosthetics. Satisfaction, feeling of security and body scheme integration seem to be key factors. As quality function deployment and v-model methodology are well established, they should facilitate a good transfer of user assessment. In combination with the authors’ approach for two-dimensional assessment and optimization of prosthetic technologies, that is already applied for user-centered development of automotive drive trains, this leads to a framework for user-centered design. Examples show the suitability of these three methods for integrating user experience to prosthetic development. As the three key human factors are identified already, those are not validated. To substantiate those, two-dimensional assessment and optimization, determination of the development focus and finally the proposed user-centered development framework, extended data from users and experts is required. For quality function deployment, the authors cooperate with developers, clinicians and users, while for two-dimensional assessment and optimization an improved questionnaire based on an expert study is in preparation. Finally, a factor analysis and the investigation of objectivity, reliability and validity of the results are necessary.

References


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