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A user-specific human-machine interaction strategy for a prosthetic shank adapter

Abstract: For people with lower limb amputation, a user-specific human-machine interaction with their prostheses is required to ensure safe and comfortable assistance. Especially during dynamic turning manoeuvres, users experience high loads at the stump, which decreases comfort and may lead to long-term tissue damage. Preliminary experiments with users wearing a configurable, passive torsional adaptor indicate increased comfort and safety achieved by adaptation of torsional stiffness and foot alignment. Moreover, the results show that the individual preference regarding both parameters depend on gait situation and individual preference. Hence, measured loads in the structure of the prosthesis and subjective feedback regarding comfort and safety during different turning motions are considered in a user-specific human-machine interaction strategy for a prosthetic shank adaptor. Therefore, the interrelations of gait parameters with optimal configuration are stored in an individual preference-setting matrix. Stiffness and foot alignment are actively adjusted to the optimal parameters by a parallel elastic actuator. Two subjects reported that they experienced appropriate variation of stiffness and foot alignment, a noticeable reduction of load at the stump and that they could turn with less effort.

Keywords: human-machine interaction, shank prosthesis, customization, gait scenario

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https://doi.org/10.1515/cdbme-2017-0103

1 Introduction

People with lower limb amputation require adequate support in ambulation for mobility and participation in daily life. Recent advancements in active prosthetics indicate the potential of such devices [1]. Most available devices focus on straight walking [2], [3] or aid ascension or descension [4], [5]. However, approximately 40% of activities in daily life are turning motions [6] and the majority of common devices does not contain a degree of freedom in the transverse plane. This means that reaction forces are transmitted through the stiff prosthesis structure into the soft tissue at the stump. Studies indicate, that especially turning manoeuvres lead to high shear stresses at the residual limb, which decreases comfort and may lead to tissue damage [7], [8]. Introducing compliant elements into the prosthesis structure via passive torsional adapters results in a reduction of peak transverse plane moments at the knee, yielding an increase in comfort [7]. Further, [7] reports a reduced effort in turning activities.

While passive torsional adapters yield improvements for lower limb amputees, the stiffness and foot alignment is configured by a prosthetist. Hence, the characteristics do not adapt to gait parameters, e.g., the type of turn or the velocity, which, as indicated by [8], is required for a comfortable and safe device.

Therefore, a user-specific human-machine interaction strategy for a prosthetic shank adapter is developed.

This paper introduces a user-specific human-machine interaction strategy for a prosthetic shank adapter. To develop this strategy, a study with users wearing a configurable, passive torsional adapter performing several turning tasks at different velocities was performed [9]. The stiffness setting as well as the transverse foot alignment of the adapter is changed between experiments while measuring loads and motion in the prosthesis structure [8]. Data analysis and user feedback indicates a correlation between optimal compliance, foot alignment and gait parameters, e.g., gait velocity or type of motion. The paper describes how these correlations are considered in the controls of the prosthetic shank adapter in a customized fashion.

2 Interaction strategy

To achieve an optimal configuration of an active prosthetic shank adapter, active adaptation of characteristics is suggested. Thereby, the system is reproducing physiological dynamics to reduce stress between stump and socket and to support the users' turning manoeuvres. To achieve this, a prosthetic shank adapter introduced in [9] adapts torsional stiffness and foot alignment. Torsional stiffness is thereby defining the interaction during the stance phase, while the foot alignment is controlled in the swing phase as preparation for heel strike. Besides mechanical design and control algorithms, the characteristics of optimal human-machine interaction have to be defined as input for the active adapter. Therefore, this paper proposes the following steps based on [9]:

1. Definition of optimality criteria
2. Perform experiments with several tasks and constant settings (with passive adapter)
3. Determine dependencies and optimal configuration
4. Implementation and individual configuration (manual operation)
5. Fine-tuning (automatic operation)

The definition of optimality criteria rates the quality of the human-machine interaction and is used to select the optimal configuration. Therefore, objective parameters are defined and extended by subjective user-feedback. Subjective feedback regarding comfort, safety and ease of motion is gathered via questionnaires during experiments. As objective criteria, motion and loads in the prosthesis structure are measured and analysed. To find correlations to the optimal configuration, users wearing passive torsional adapters perform several tasks, e.g., 90°-turn or 180°-turn with different directions. In addition, each task is performed at slow, medium and fast self-selected velocities. Settings of the adapter are changed between trials by orthopaedic personnel. The transversal foot alignment was configured with a 6° deviation in either internal or external deviation to the original, neutral alignment.

Using the results, general relations between optimal stiffness and foot alignment depending on gait parameters (type, direction and velocity) are determined and stored in a general preference-setting matrix.

Moreover, individual experiments with the active prosthetic shank adapter are performed for the same tasks considering the previously found correlations. Hence, the user experiences the different states of the actual, active system. As an example, he applied stiffness settings are depicted in Fig. 1. This allows for improved feedback regarding the optimality of actual the configuration of the

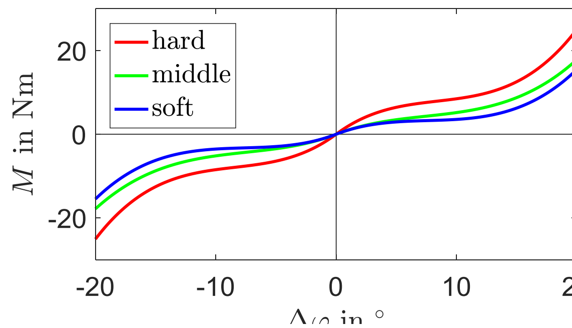

Figure 1: Hard, middle and soft stiffness setting

active adapter. If necessary, entries of the general preference-setting matrix are adjusted to create an individual preference-setting matrix (IPSM) for each user.

Further fine-tuning is performed after a training period with the system in automatic operation with adaptation of torsional stiffness and foot alignment according to the specified, optimal configuration.

3 Individual preference setting matrix

The IPSM contains the individual, optimal torsional stiffness and foot alignment for different gait parameters. Hence, it characterizes the human-machine interaction and is essential in defining the quality of the support as well as improvements over passive adapters.

The IPSM consists of an attribution of optimal torsional stiffness and foot alignment to different gait parameters as determined before. An exemplary extract from an IPSM is depicted in Tab. 1 and shows the configuration for a 90°-turn. Hence, when an ipsilateral 90°-turn at fast velocity is detected, the stiffness is configured to the soft setting and the foot is aligned in the external direction. Optimal configuration at differing gait parameters, e.g., for a velocity between slow and medium is determined via cubic interpolation.

Situation	Velocity	Stiffness	Foot alignment
90°-turn, ipsilateral	Slow	Middle	External
	Medium	Soft	External
	Fast	Soft	External
90°-turn, contralateral	Slow	Middle	Neutral
	Medium	Middle	Neutral
	Fast	Middle	Neutral

Table 1: Exemplary extract from an IPSM [9]

4 Realization and preliminary results

An active prosthesis shank adapter is developed to realize adaptation of stiffness and foot alignment [9]. From the required function, several components of the actuation system can be derived, which are presented the following.

The high-level control strategy contains a sensor-minimal approach to determine the gait parameters [9]. A fuzzy-based evaluation of the shank velocity signals of an inertial measurement unit in the sagittal and frontal plane is developed to detect type and direction of motion as well as velocity [10]. The high-level control scheme detects the gait parameters and transfers the corresponding optimal torsional stiffness and foot alignment to the low-level control algorithm.

The low-level control is based on an impedance control law, which models the dynamic response of a system to external loads according to a desired response. It is designed to set toe optimal torsional stiffness in the stance phase and the desired foot alignment is controlled in the swing phase.

The mechanical design features a parallel elastic actuator (PEA), selected according to optimizations regarding minimization of required energy and peak power. Compared to a directly driven system, the peak power is thereby reduced by 78% and the energy consumption by 57% [9]. This allows to reduce weight as well as dimensions of the adapter and battery. As depicted in Fig. 2, two rotational springs in opposite directions are aligned with an electric motor and gearbox to realize the PEA. The housing of the adaptor is designed to interface to standard pyramid adapters of prostheses.

Before utilizing the adapter in experiments with subjects, the mechanical system and control algorithms are extensively tested at a custom test bench. Nonlinear effects and friction are identified and compensated via control algorithms. Further, the adapter did undergo a structural testing according to ISO 10328.

Experiments with two persons with lower limb amputation are performed with the developed prosthetic shank adapter to evaluate the presented human-machine interaction strategy. Both subjects underwent the set-up of the IPSM based on the general correlations. After implementation of the adapter by certified personnel, the shank adapter was operated in manual mode to consider the individual preferences. Afterwards, the automatic adaptation was enabled and parameters were fine-tuned. After a short training period, both subjects reported that they experienced appropriate variation of stiffness and foot alignment, a noticeable reduction of load at the stump and that they could turn with less effort.

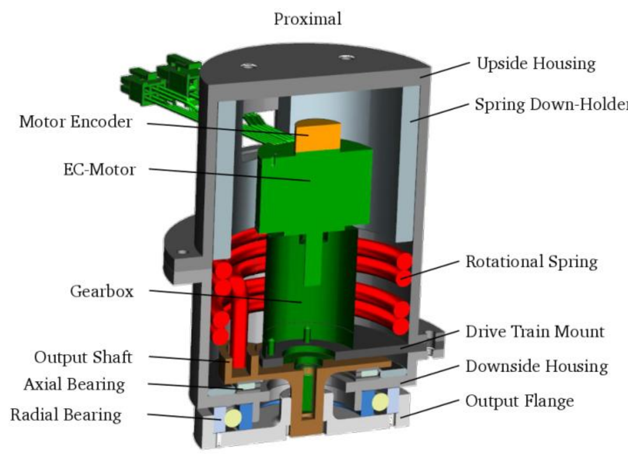

Figure 2: Schematic of the prosthetic shank adapter with PEA [4]

5 Discussion

The determination of user-specific, optimal torsional stiffness and foot alignment depending on the gait situation with the proposed procedure combines objective measurements with subjective feedback to achieve a high-quality human-machine interaction. However, this procedure is influenced by the human ability to quickly adapt motion. A subject could for example subconsciously alter balance, resulting in an unsymmetrical gait. Such an effect may show reduced loads in the prosthesis structure but are not considered in the proposed strategy and could be avoided by additional gait analysis, either by motion capturing or by certified personnel. Furthermore, the specification of the optimal configuration is constant after the fine-tuning process. The incorporation of machine-learning algorithms could yield improved results by considering additional effects, e.g., changing surface quality.

6 Conclusion

Based on a preliminary study, the need to adapt torsional stiffness and foot alignment to gait situation and velocity in order to achieve a high-quality human-machine interaction is shown. A strategy to determine user-specific optimal configuration parameters for the IPSM based on objective data and subjective feedback is presented. The realization of the adaptation via an active prosthetic shank adapter with PEA is implemented and evaluated by two subjects, confirming the functionality of the system. Subjective feedback yielded a noticeable reduction of load at the stump and improved ease of turning. Thus, adaptation of optimal stiffness and foot alignment to the actual gait situation indicates an improved human-machine interaction.

Author's Statement

Research funding: This work was funded by Deutsche Forschungsgemeinschaft (DFG, no. RI 2086/7-2). Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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