Finding a Natural Fit: A Thematic Analysis of Amputees' Prosthesis Setting Preferences during User-Guided Auto-Tuning

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Amputees' preferences for prosthesis settings are critical not only for their psychological well-being but also for long-term adherence to device adoption and health. Although active lower-limb prostheses can provide enhanced functionality than passive devices, little is known about the mechanism of preferences for settings in active devices. Therefore, a think-aloud study was conducted on three amputees to unravel their preferences for a powered robotic knee prosthesis during user-guided auto-tuning. The inductive thematic analysis revealed that amputee patients were more likely to use their own passive device rather than the intact leg as the *reference for the natural walking* that they were looking for in the powered device. There were large individual differences in *factors influencing naturalness*. The *mental optimization of preference decisions* was mostly based on the noticeableness of the differences between knee profiles. The implications on future design and research in active prostheses were discussed.

INTRODUCTION

Prostheses play a vital role in the lives of lower-limb amputees, enabling them to perform daily activities and improving their quality of life (Samuelsson et al., 2012; Wurdeman et al., 2018). Amputees' preferences for prosthesis settings are critical for the successful personalization of their prosthetic devices and long-term adherence. Although several studies have made efforts to understand amputees' preferences for a single setting in passive devices (e.g., ankle stiffness; Clites et al., 2021), little is known about their preferences regarding the multi-point settings of active prostheses. To provide guidance for optimization of the tuning process in active prosthesis and ultimately improve the quality of life of amputees, this study used the think-aloud method to investigate amputees' preferences for the multi-point settings in a powered robotic-knee prosthesis during user-guided auto-tuning.

Previous Research in Preferences for Lower-Limb Prosthesis Settings

Traditionally, amputees' preferences for prostheses were measured through discrete-choice questions (Hafner et al., 2007; Kahle et al., 2008; McDonald et al., 2021), simple rating (Andrysek et al., 2021), ranking (Klodd et al., 2010), or questionnaire (Raschke et al., 2015). These measures were usually used in between-device comparisons to assess the general perception of the overall performance of the prosthesis but cannot provide information on the preferences for the specific settings.

Some studies narrowed down the settings into one factor such as ankle stiffness and assessed the preference behaviorally by allowing amputees to independently adjust the setting in a passive or quasi-passive prosthesis. (Clites et al., 2020; Clites et al., 2021; Shepherd et al., 2018). Whereas what works for these passive or even semi-active devices (Shepherd et al., 2020) may not apply to active devices.

Active or powered prostheses have enhanced functionality in various conditions such as stair climbing (Sun et al., 2021), and have been shown to provide better functional and psychological outcomes compared to passive devices (Lathouwers et al., 2023). However, the higher functionality of active prostheses also increases the complexity of the system and the number of control parameters for tuning to personalize the prosthetic legs. Investigating each control parameter individually not only is time-consuming but also does not take into account the interdependence between parameters. Therefore, to explore preferences for specific settings in active or powered prostheses, a research method that can allow investigation of the reasoning behind the preferences for multiple control parameters is needed.

The Think-Aloud Study of Preferences for Powered Prostheses

To avoid fatigue in participants while having to exhaust all the possible combinations of multiple control parameters, the most efficient and ecologically valid way is to allow the participants to make the changes to the setting on their own, as shown in the single-factor studies (Clites et al., 2020; Clites et al., 2021; Shepherd et al., 2018). But this cannot be achieved when the system to adjust is too complicated. Thanks to the recent research efforts in the auto-tuning algorithm and newly developed User Controlled Interface for powered robotic knee prosthesis (Alili et al., 2021; Alili et al., 2023; Li et al., 2021), the control parameters were integrated and narrowed down to four essential control points for the gait cycle and the interface made it more feasible to train the participants.

Based on this system, our previous study chose the think-aloud technique and successfully revealed the features of preferences for four control points in a powered robotic knee prosthesis in non-disabled participants (Yuan et al., 2022a). The success of this study not only suggests the potential of allowing users to lead the tuning with the assistance of the system of auto-tuning and the User Controlled Interface but also demonstrates the feasibility of using think aloud technique to unravel the reasoning behind the prosthesis users' preferences.

Although the ultimate goal of prosthesis design is to help amputees to regain the locomotion functionality as non-disabled people (Prost et al., 2022; Schlafly & Reed 2020), amputees' gait is different from the non-disabled individuals due to the technical limitations of existing prostheses. To regain daily functioning, amputees developed different compensation strategies, for example, in gait termination (Vrieling et al., 2008) and obstacle crossing (Vrieling et al., 2007). These walking patterns and preferences (e.g., Howard et al. 2012) shaped by the passive devices are qualitatively different from non-disabled participants and may perpetuate while adapting from passive to active devices. For example, from an anecdotal perspective, one amputee stakeholder was surprised that the non-disabled participants used the intact leg as the reference for their preferences for prosthetic settings. Therefore, it is necessary to understand which aspects and to what extent the amputee may have similar or different preferences compared to the non-disabled.

The Current Study

In all, to provide insights into the mechanism of preferences in amputees and to contribute to the development of powered prosthesis, the current study investigated the preferences for multiple prosthesis settings in a powered robotic knee prosthesis using think aloud technique during user-guided auto-tuning and explored the differences of preferences between amputee vs non-disabled users while comparing with results in Yuan et al. (2022a).

METHOD

Design

Similar to Yuan et al. (2022a), we employed a mixed method approach, with the qualitative method (i.e., the think-aloud technique) as the main focus, supplemented with quantitative ratings on preference levels and other experiences. The main goal was to follow the amputees' natural preferences and reveal the underlying reasons as they make changes to the prosthesis pretending that this is the device they would use in daily life. Self-tuning has shown both repeatability and reliability in the exoskeleton domain (Ingraham et al., 2022) and also in amputees using lower-limb prostheses (Shepherd et al., 2018). With allowing prosthesis users to tune the powered device at home the inevitable trend in the future, the user-led approach in preference research not only is ecologically valid but also can take the holistic view of device control parameters tuning and users' characteristics into account.

Participants

Three amputee participants were recruited from the community. The age range was 24–67 years old and all of them were male. The height range was 165–173 cm, and the weight range was 66–77 kg. Years of amputation ranged from 4–21 years. The reason for amputation was either congenital or trauma. Regarding the knowledge level on gait and prosthesis, participant 1 had moderate knowledge, participant 2 had professional-level knowledge, and participant 3 had limited knowledge. Participants' own devices were microprocessor-controlled passive prostheses (i.e., Ottobock C-leg or Blatchford Linx).

Experiment Setup

We utilized a robotic prosthesis that was specifically designed for transfemoral amputees (Liu et al., 2014). To ensure that the prosthesis was aligned and fitted correctly for amputees, a certified prosthetist oversaw the process. The gait kinematics and kinetics of the participants were recorded using a motion capture system (VICON, Oxford, UK) as they walked on a split-belt instrumented treadmill (Bertec Corp. Columbus, OH, USA) with 0.6 m/s. The interface (Alili et al., 2021; Alili et al., 2023) developed for changing the target knee joint profile is controlled by infrared remote control coupled with Arduino Mega 2560. Participants were able to modify the target knee profile by changing the four control points in the interface corresponding to the peaks of four gait phases: stance flexion, stance extension, swing flexion, and swing extension. One-degree increase in each control point corresponded to one degree higher in knee bent and vice versa. Up to 4 degrees can be adjusted both above and below the baseline for the control point in stance flexion, and it was 8 degrees for the control point in stance extension and both swing phases. As shown in Figure 1, participants could see the gait curve and changes they made through a monitor in front of them. We used Zoom to record and transcribe the think-aloud sessions.

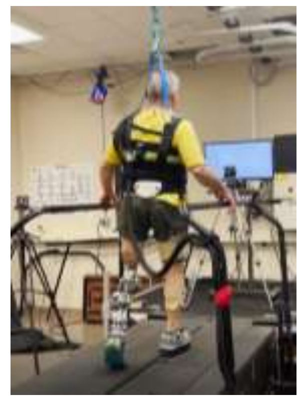

Figure 1. Experiment Setup.

Procedure

Informed consent was obtained from the participants and the procedure was explained. They then filled in a pre-test survey including questions about demographics and knowledge of gait and prosthesis. The powered prosthesis was then set up for each participant and a baseline knee profile was tuned.

To ensure that the participants can provide enough data with quality, they were shown an example video of think-aloud and given opportunities to practice think-aloud with a similar-structure task (i.e., picture editing with four parameters to adjust) while receiving feedback from the experimenter.

In order to guarantee the efficiency of the user-led tuning process so that the participants can find their preferred profile before fatigue, they were first educated with an instructional video to learn about the association between the interface, gait cycle, and the prosthesis leg position. Then, a physical demonstration was performed by the experimenter, followed by exercises of the skills they can use to locate which control point was associated with the potential uncomfortableness. At the end, a quiz was completed to ensure comprehension.

The formal think-aloud sessions started with walking the baseline profile (See Alili et al., 2021 for profile details). After experiencing the profile for 45s, they provided verbal feedback on the changes they would like to make to the profile and the reasons. After they rated the preference for this profile from 1-10, a new knee profile was tuned based on the participant's feedback. Then another new session started with another 45s walking until the participants found the preferred profile that they would like to wear on a daily basis. Lastly, a post-test survey was conducted to assess participants' satisfaction and additional comments.

Data Analysis

An inductive thematic analysis method was used following the six phases by Braun and Clarke (2006). The audio recordings were first transcribed through Zoom and cleaned manually by the experimenter. Two researchers got familiarized with the script together with the recording and independently coded the data using a thematic analysis approach. Then the researchers checked each other's codes, and the inconsistencies were resolved through further discussion or consultation with a third researcher. Following this, the initial codes were grouped into themes, which were discussed between three researchers to ensure that they were accurately capturing the data. After the initial themes were determined, the themes were revisited and revised to ensure that they reflected the experiences of the participants in a larger group with different stakeholders. Finally, the themes were finalized and defined.

RESULTS

Three participants achieved the preferred profile respectively in three, four, and six times of changes. The final preference level reached 7, 9, and 8.5 for participants 1, 2, and 3 (Due to technical reasons, the tuning procedure was prolonged for participant 1, which resulted in tiredness before he reached the true preference). In total, three themes emerged around the mechanism of amputees' preferences for settings of a robotic knee prosthesis (see Table 1).

Table 1. Thematic Analysis Codes, Themes, and Excerpt Count

Themes	**Sub-themes**	**Codes**	**#1**	**#2**	**#3**	**Total**
Theme 1: Reference for natural walking		Prosthetic knee	3	1	2	**6**
		Intact knee	0	1	0	**1**
Theme 2: Factors related to naturalness	Physical perceptions	Movement sensations	12	19	11	**42**
		Balance	1	3	3	**7**
		Stability	0	2	31	**33**
	Workload	Attention	0	0	7	**7**
		Physical efforts	0	0	11	**11**
	Feelings	Subjective feelings	0	2	15	**17**
Theme 3: Mental optimization in decisions		Degree of differences	2	6	9	**17**
		Tuning goals trade-off	0	0	4	**4**
		Total	**18**	**34**	**93**	**145**

Reference for Natural Walking

Finding a natural fit in the prosthesis seemed to be the main tuning purpose for all the participants. The references that the amputees used when they described natural walking were either their own passive prosthesis or the intact leg.

All participants mentioned using their passive devices as the references for the movement or the overall walking that they defined as natural. Participant 1 with moderate knowledge of gait and prosthesis tended to use his knowledge about the gait trajectory of previous passive device as a reference. For example, *"…and just based on my knowledge of … I know, roughly what the knee profile for a passive device that I'm used to walking on looks like."* Participant 3 with limited knowledge used the overall functional experience of his own passive device as a baseline and he knew that these two prostheses were different, such as, *"I'm also kind of comparing it to how it feels walking with my prosthetic, and I know it's a whole different piece but I'm trying to use that as a baseline. Like with my prosthetic, I walk, and I don't think about it. I don't feel that wobble. I don't feel instability. I just walk in. You know I can be on my phone. I can be caring something. I can be talking."*

Only participant 2, who had extensive experience in observational gait analysis, used the intact leg as an additional reference in terms of transition between gait phases: *"When I think about knee flexion here, maybe because it's anatomical or physiological smoother. I don't know. But it feels to me that, as we have it now, it's closer to what I sense on the natural knee, on the sound side."*

Factors Related to Naturalness

There were various factors or manifestations of the preferences for natural walking. Three sub-themes were summarized: physical perceptions, workload, and feelings.

It's not surprising that most of the excerpts were about physical perceptions, especially the movement sensations. The unnatural behaviors of the prosthetic leg can involve foot clearance (mentioned by participants #1, #2, #3), range of motion (#1, #2), speed of motion (#1, #2), foot placement (#1, #3), the transition between gait phases (#2). Balance was more like an outcome caused by specific unnatural movements. Stability was mostly reported by participant 3 who had a higher need for stability in the knee. Participant 3 also described the mechanism of the instability manifested in his behaviors physically and psychologically: "*There's just a wobble. Basically, it feels like the leg is not supporting me. It just doesn't feel as planted which makes me pull my weight off the leg, which it's kind of like a domino effect. So I trust it less. I put less weight on it …Basically, it throws me just a little bit off balance. It just feels like I need to use my real leg, my right leg to over-compensate for the left leg. And I don't spend as much time. At that point, I'm going to hurry up and try to get off the prosthetic faster. [I was] supposed to spend more time on that step."*

The workload was mentioned by participant 3 in both cognitive and physical aspects. He pointed out the additional attention workload that the walking instability posed: *"As soon as I take my focus off the walk, and I start looking on the room. It starts to feel like, not as stable, and I have to return my focus to walking. So I'd like to be able to get to the point where I don't have to think about it. I can just walk."* He also mentioned the physical efforts of kicking out forward during the swing phase: *"The only thing I want to try to then change is I started walking a little more casually. Since I felt so much more confident about the way I was walking, I tried to walk a little more casually, not trying to kick my leg forward as much."*

The subjective feelings co-occurred with the previous two sub-themes, serving as mediators for the later decisions. Examples of the adjective words were secure, confident, trust, comfortable, reliable, fear, worried, and uncertainty.

Mental Optimization in Decisions

The two main factors that determined the decisions towards the preferred profile were the degrees of differences and the trade-off between tuning goals. Participants usually kept the decision that they could feel the significant differences and gave up on exploring the control points that the changes did not make noticeable differences. There were individual differences regarding the minimal difference participants could tell regarding the changes they made to each control point.

The trade-off between tuning goals only happened to participant 3. This was because he fixed the main issues already in two changes. When he still had the energy and time, he decided to strive for a more advanced tuning goal of walking casually (i.e., with less physical effort). After he tried different other options, although he could walk a little bit more casually with less effort in dragging the leg during the swing phase, it would compromise either the stability of the foot or the foot placement. Then he weighed the different options and still prioritized the profile that was more stable and predictable foot placement but needs slightly more effort in the swing phase.

DISCUSSION

In this study, we explored amputees' preferences for settings of a powered prosthesis using the think-aloud technique. We found that finding a natural fit similar to what they knew or felt in their own passive devices or human knee was the primary goal in their self-tuning of the powered prosthesis. The manifestations of the naturalness they were looking for could be summarized into three aspects: physical perceptions, workload, and subjective feelings. Whether they kept one preference decision in tuning was mainly determined by the degree of the differences that were noticeable. Trade-offs happened when tuning-goal conflicts existed.

As shown in the results, amputees with different levels of knowledge on gait and prosthesis all referred to their own passive devices to some extent while tuning the powered device. Only participant 2 who had professional knowledge in gait and prosthesis tried to align the powered device to the intact leg, which suggests the consideration of gait symmetry. In contrast, the non-disabled participants all reported using the other non-prosthetic leg as a reference (Yuan et al., 2022a). Additionally, the non-disabled participants explicitly mentioned symmetry in their physical perception and tuning criteria, but none of the amputees did. This indicates that most amputees' preferences are highly biased towards their existing prostheses. However, due to technical limitations, it is still not possible to achieve a symmetrical gait using existing passive or semi-active prostheses (Lathouwers et al., 2023). The long-term asymmetrical gait of using passive devices would not only change the biomechanics of the body but also lead to various complications such as back pain or osteoporosis (Gailey et al., 2008). If the future goal is to achieve self-tuning of the powered device at home, it might be necessary to educate the participants on the tuning mindset that is not only for their own comfort but also for long-term health. If future studies are going to use amputees' preferences to directly generate knee joint profiles, it is also important to weigh between what the amputees feel comfortable with – highly likely from their experience with previous passive devices – and what is healthy in the long run.

Consistent with previous studies that found large inter-individual differences in preferences for degrees of ankle stiffness (e.g., Shepherd et al., 2020), we also found high variability in their preferences for not only the magnitude, direction, and pattern of the changes but also the underlying reasoning or factors related to naturalness (Schaffalitzky et al., 2009). Among the factors, the workload sub-theme was not mentioned in the non-disabled participants (Yuan et al., 2022a), surprisingly, nor in two amputee participants. Although it was only mentioned by one amputee participant, it doesn't mean that the other participants did not have the experience or the need. It could be that they were not as elaborative as participant 3 or they did not have time to explore these advanced needs. The factor worth highlighting is the attentional workload. The amputee mentioned it as a need to attend to the environment. Other research also showed that a better ability to multitask was related to higher satisfaction with the prosthesis (Hafner et al., 2007). Attention to the environment is also critical for walking safety (Yuan et al., 2022b). Future studies should consider adding not only a divided attention measure but also a measure for visuospatial attention during walking into clinical outcomes.

Our results in the determinants for the preference decisions stressed the importance of knowing the noticeable differences of each control point. The psychophysical method can be a good option and has been used to identify ankle stiffness in passive prostheses (Shepherd et al., 2018). This information can be used to give clearer instructions to the participant in self-tuning. Although the trade-off in tuning goals only happened to one amputee in our study, it may become more common if the participants will be allowed to tune the prosthesis as needed in the home setting. For example, according to the simulation, one study suggested that symmetry and energy expenditure might be two conflicting goals in a powered prosthesis (Handford & Srinivasan 2016). Future studies could further investigate participants' decision-making when a trade-off is needed.

As the first study that investigated the amputees' preferences for multi-point settings in an active prosthesis, we found the interdependence of control points. More specifically, there were situations when the change of the control point in one gait phase influenced the feelings of another gait phase. 2 also highlighted the importance of the transition between gait phases in his experience. It suggests that future studies should not only consider the control point itself but also the transition and association between the control points.

Although this study provided valuable insights into mechanisms of preferences for active prosthesis settings in amputees, there are some limitations to be considered. First, our sample was relatively small and all male, which may not capture the diversity in the preferences and the underlying reasons. We are currently trying to recruit more participants. Second, our study only lasted for one day which may not have lower ecological validity in the preferences. In the post-test interview, all the participants mentioned that they would still explore and play around with the interface if they were given chance to use it in daily life. So the preferred profile was only the best one among the options they were able to explore on that day and may not be the best profile. Last, we were not able to give the participants enough time to acclimate to the powered device beforehand. The preferences may be slightly different after walking with the device for a while. For example, one participant walked the baseline profile again towards the end of the sessions and found that the baseline profile was not as uncomfortable as he remembered, which led him to change the rating of it from 6 to 6.5. Although the influence might be minimal, future studies can consider longer acclimation time.

In all, as the first effort to reveal the underlying mechanisms behind amputees' preferences for multi-point settings in a powered robotic knee prosthesis, our findings indicate that past experience with passive prostheses might bias the preferences of amputees for active devices from the non-disabled. The results again highlighted the importance of preferences in the design and fitting process given the distinct preferences of each amputee but professional guidance for long-term health would be recommended. Researchers working on developing active prostheses might benefit from exploring the noticeable differences of each setting and also the interdependence of the settings in a more holistic view.

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