Understanding the Preferences for Lower-Limb Prosthesis: A Think-Aloud Study during User-Guided Auto-Tuning

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Prostheses help amputees to maintain physical health and quality of life. Prosthesis wearers' satisfaction and adherence to the prosthesis are closely related to the preferences for prosthesis tuning settings. However, the underlying factors that contribute to the preferences were under-explored. In this study, two able-bodied participants were asked to change the robotic prosthesis settings to their preferred state and the think-aloud technique with a mixed-method approach was used to reveal the contributing factors of preferences. We found that *physical perception* (e.g., positions of the prosthetic foot, balance, and stability) and *subjective feelings* (e.g., comfortableness, satisfaction, confidence, and worries) were two major factors. *Experiences with the intact leg and other profiles* were used as anchors for their preference levels. Preferences may also differ with situational *context* such as walking speed. The saturation points were reached with *no strong approach motivation*. The implications for prosthesis design and research were discussed.

INTRODUCTION

By 2005, there are more than 1 million lower-limb amputees in the United States, which may double by 2050 (Ziegler-Graham et al., 2008). To live a mentally and physically healthy life, they need lower-limb prostheses with a comfortable fit for maximized mobility (Wurdeman et al., 2018), which is achieved through tuning by a professional prosthetist. With amputees' preferences for specific prosthesis settings remain under-investigated (Yuan et al., 2021), prosthetists rely on general questions, such as "Do you like it?" or "Does this feel better?", to understand amputees' feelings about the prosthetic leg. However, these simple questions cannot provide precise information about the needs of the amputee users. Thus, prosthetists have to find the balance between gait performance and users' satisfaction through trial-and-error, a strategy that is not efficient and cannot ensure successful personalization. Considering the long appointment waiting period and limited comprehensive prosthetist service (Pettengill & Pettengill, 2020), an efficient tuning is needed to avoid a low adherence rate in prosthesis utilization and compromised quality of life in amputees (Baars et al., 2018; Roffman et al., 2016).

Recently, there have been trending efforts on user-guided prosthesis auto-tuning to improve the efficiency (e.g., Alili et al., 2021; Thatte et al., 2017). However, modern prostheses can have a lot of control parameters (e.g., nine for OttoBack). Without knowing the mechanism of preferences, the tuning procedure could be lengthy and time-consuming to exhaust all the comparison combinations. Understanding amputees' preferences in prosthesis settings could provide better assessment and guidance to ensure an efficient tuning procedure and to prevent maladaptive consequences of insufficient or lengthy prosthesis tuning experience. In this study, we employed the Think-Aloud technique with a mixed-method approach to investigate the prosthesis users' preferences for prosthesis settings during user-guided auto-tuning of a robotic lower-limb prosthesis.

Preferences for Prosthesis

Most of the previous research that investigated amputees' preferences for prosthesis focused on between-device comparisons via simple forced-choice questions (e.g., Hafner et al., 2007; Highsmith et al., 2016) or other indirect subjective measures like the Borg Scale (e.g., Brandt et al., 2017) but not the reasons behind the preferences. Although some attention has been paid to the human-in-the-loop approach by including user preferences into tuning algorithms (Thatte et al., 2017), it was still achieved through between-profile forced-choice questions with little effort being made to understand the mechanism of these preferences so that more accurate predictions could be made.

The difficulty in investigating the underlying mechanism of preferences for prosthesis tuning is that amputees are rarely allowed to have autonomy in the tuning procedure. It is understandable given that the prosthesis involves a lot of parameters to be tuned and can be complicated to manage without sufficient training. Recently, a new trending line of research made this possible by developing a prosthesis auto-tuning system and interface (i.e., User Controlled Interface) that can be operated by the users (Alili et al., 2021; Li et al., 2021). The auto-tuning system simplified the tuning process with the support of the tuning algorithm and defined only four control points of the prosthesis knee joint to be adjusted by a user. It means that amputees can be allowed to tune the prosthesis to their preferred settings in a defined and secure range until they are satisfied. It is then possible to use this system to understand the preferences of amputees on prosthesis settings and in turn to ensure a safe and efficient self-tuning process.

Think-Aloud Method

Understanding the mechanisms behind one's preferences while performing the task can be achieved through a qualitative method called Think-Aloud. Think-aloud is an approach to understanding users' thought processes by collecting verbal data about reasoning and decision-making during a problem-solving process (Fonteyn et al., 1993). During the think-aloud procedure, participants verbalize their internal thought processes while performing a goal-directed task. Different from the retrospective data through interviews or focus groups, an advantage of think-aloud is that it captures real-time thought processes. In addition, think-aloud can generate abundant qualitative data from a few participants. Think-aloud has often been used as a usability testing method to evaluate a design (Albert & Tullis, 2013). For example, Read et al. (2009) used the think-aloud method to explore the user preferences for the design of the navigational menu. With the real-time data, it is possible to know users' reasons behind each action and the underlying components of the preferences can be revealed.

Current Study

The purpose of the current study was to understand prosthesis users' preferences for prosthesis settings during tuning. With a mixed-method approach, we used the think-aloud technique combined with some quantitative measures to reveal the factors that contributed to participants' preferences on prosthesis settings while using the User Controlled Interface (Alili et al., 2021) to tune a robotic knee prosthesis.

METHOD

Design

The current study used a mixed-method research design (Hesse-Biber, 2017) by assisting the qualitative method (i.e., think-aloud) with the quantitative method (i.e., Likert-scale rating of preferences). Specifically, after the participants finished the think-aloud on the desired changes of the prosthesis settings, Likert-scale ratings on the preferences for the current profile and last profile were followed (a profile is one whole set of prosthesis settings). One major advantage of the mixed method design in the present study is the complementarity (Greene et al., 1989). Because the goal of the task was to "change the prosthesis control points to your preferred setting as if you are an amputee and will need to use this prosthesis in your daily life", this means that there might be multiple experimental sessions with a trajectory of changes in the preference level. Quantification of the preference level could complement the qualitative information on the valence of the preference with information on differences in preference level between sessions and the specific preference level at a saturation point. In addition, using a qualitative method together with previously used quantitative methods provides opportunities for informing multidimensional questionnaires on tuning setting preferences in the future, which is another advantage (i.e., development) of using the mixed-method in the current study (Greene et al., 1989).

Participants

Two able-bodied participants were included in the current ongoing study. Both participants were undergraduate students recruited voluntarily from North Carolina State University. Participant 1 was a female aged 19 and participant 2 was a male aged 20. One inclusion criterion was that the participants had to be over 170 cm tall so that they could walk more easily with the particular active prosthesis in a five-day walking training. The female participant had some prosthesis walking experience before while the male participant did not.

Apparatus and Equipment Set-up

The experimental setup consisted of a robotic prosthesis (Liu et al., 2014) which non-disabled subjects wear via an adaptor; the set-up also included a treadmill, a remote controller, desktop monitors, a tablet, a camera, and a microphone for recording as shown in Figure 1A and 1B. The powered prosthesis was aligned and fit by a certified prosthetist for amputee users. A split-belt treadmill (Bertec Corp. Columbus, OH, USA), was used with a fixed walking speed of 0.6 m/s. An infrared remote control coupled with Arduino Mega 2560 was used for remote profile modification. Each control point can be altered up or down by pressing the buttons on the remote. The reinforcement learning algorithm (Li et al., 2021) adjusting robotic prosthesis control parameters according to the modified knee joint profile was implemented in MATLAB and was integrated to work in real-time with the prosthesis controller implemented in LabVIEW. The User Controlled Interface (Alili et al., 2021) with the knee joint profile curve (see Figure 1C) was presented on a 20-in × 11.5-in LED monitor in front of the participants. Zoom was used to record the screen actions and the participants' think-aloud sessions and to auto-transcribe the recorded audios. The video input device was a camera placed near the front monitor. The audio input was through a portable microphone. A Surface Pro tablet was used for the think-aloud practice session and to display instruction videos. Gait kinematics was also measured using the motion capture system (VICON, Oxford, UK), which was not discussed under the scope of this paper.

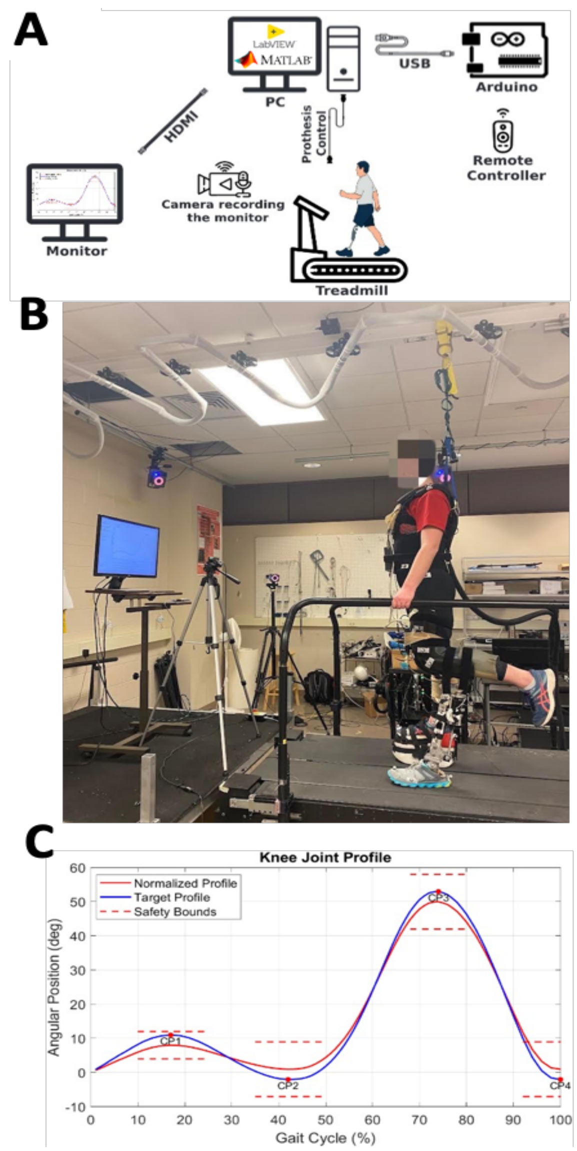

Figure 1. Equipment Set-up and User Control Interface layout.

Procedure

Each participant was first directed to sign the informed consent and fill out the pre-test survey on sex, age, height, weight, and knowledge of prosthesis and gait. Then, the experimenters helped the participant to set up the prosthesis and biomechanical markers. To prepare participants for the think-aloud, an introductory video and practice sessions were given. During the practice sessions, participants were asked to think aloud while changing four parameters using a photo editing tool to improve the quality of the pictures to their preferred state (a similar task as the experiment task).

To get participants familiarized with the User Control Interface, they were asked to watch an instructional video, go through walking exercises, and take a quiz to ensure sufficient understanding of the associations between the control points and the prosthesis.

The formal think-aloud sessions started with settings of the standard knee joint profile. After tuning, the participant walked on the treadmill for 45 seconds followed by the decisions on the changes to be made to the control points. The participant was asked to verbalize decisions, feelings, and reasoning for the changes. The experimenter then asked participants to report their preferences on the current profile on a scale from 1 to 10. Memorability questions on each profile were also asked. The session was repeated until the participant became satisfied with the results. In the end, the participant filled out questionnaires and was asked to provide comments about the study.

Data Analysis

Given the space limit, this paper focused on the thematic analysis of the think-aloud data.

First, the auto-transcripts from Zoom were cleaned and verified by two researchers who were involved in the experiments and had a good knowledge of the topic terms. Meaningless filler words (e.g., umm, like), irrelevant conversations, and identifiable information were deleted from the transcripts (Fonteyn et al., 1993). In addition, incomplete sentences, abbreviations, and acronyms were completed or explained by adding brackets (e.g., [I] don't like it) to increase the readability and clarity of the sentences. Contextual information for some answers to the questions was also added to the transcript using parenthesis (e.g., what questions the experimenter was asking or prompting at that time).

Dedoose, a computer-based qualitative data analysis software, was used to manage, organize, and code the data (Dedoose, 2022). The Thematic Analysis method and the proposed six phases described by Braun and Clarke (2006) guided the data analysis. The data were analyzed inductively, meaning that themes emerged from the data only (Braun & Clarke, 2006). Two researchers first became familiarized with the data. Initial codes and themes were generated based on observations and discussions. Then, each researcher independently coded transcripts in Dedoose based on the initial codes, which were then checked by the other researcher. During coding, emerging new codes and themes were added and discussed. Memos and concept maps were used alongside the coding process. Interrater agreement was 0.73, which suggested good agreement (Cicchetti, 1994; Fleiss, 1971). Disagreed excerpts were further discussed and resolved with the involvement of a third researcher.

After the first-round coding, the grouped themes were discussed in a meeting with three experts in biomedical engineering (one of them had experience with daily use in lower-limb prosthesis) for insights from various stakeholders to ensure the validity of the themes and interpretations.

RESULTS

Participant 1 made changes five times and Participant 2 made changes three times to reach the preferred setting. In total, 125 excerpts were coded, and five themes emerged regarding the overarching question: what contributed to the participants' preferences on prosthesis settings during self-tuning? *Physical perception*, *subjective feelings*, and *experience and knowledge* were the initial three themes with *context* and *saturation point* added during coding.

Physical Perception

Physical perception was defined as the awareness or comprehension of one's physical movements, sensations, and states. There were 61 excerpts falling under this theme. The most mentioned reasons in both participants were perception of the *position or movement of the knee or foot*. For example, "It was nice that the prosthetic leg also didn't bend quite as far back in the swing phase." "...because sometimes it gets a little too close to my thigh." Each specific reason was associated with the feature of a walking phase and the person's preferences. One worth-noting reason related to the perception of position was the perception of *tripping* mentioned by participant 2: "I don't have as much confidence that the foot won't hit the treadmill and cause me to trip." Due to this reason, the participant made the prosthetic knee bent more during the swing phase. Participant 1 also mentioned *speed perception* as a reason: "It feels like it [the prosthesis leg] moves too fast." Descriptions of the holistic physical status such as *balance, symmetry, and stability* were brought up frequently by both participants: "I just feel like that it's a little like it throws me off balance a little more." "It just felt more symmetrical." "I was pretty stable on that position when the leg was straight". *Physical control* was also mentioned a few times by participant 1: "It feels a little like, not out of control, but it's harder to control when it swings up higher and then comes down."

Subjective Feelings

Subjective feelings were defined as one's momentary subjective or emotional judgments on the physical experience. There were 67 excerpts related to this theme, ⅓ of which co-occurred with physical perception. The subjective feelings were usually conveyed using adjectives such as, "normal" "nice" "favorite" "comfortable" "satisfied" "happy" "confident" "worried" or verbs such as "like", providing valence information of the preferences (i.e., positive, neutral, or negative attitudes). The adjectives were either used in the general statements (e.g., "That was really comfortable.") or together with physical perception (e.g., "I would like it to bend more as to feel more confident [so] that it will avoid that and then I can properly move my leg forward and I'm not worried about possibly hitting the ground of the treadmill as I go forward.").

Experience and Knowledge

Experience and knowledge were defined as using current or previous walking experiences and knowledge on prosthesis and gait. There were 24 excerpts categorized into this theme. Interestingly, both participants reported using *the intact leg* as a reference for how the prosthetic leg should perform. For example, "It just felt more similar to my leg without the prosthetic on in terms of balance." Unsurprisingly, the experience of walking with *other profiles* was also used as a reference for comparisons: "The improvements from profile 0 to profile 1 with the more bend in the peak 2 felt more comfortable." With prior experience with prosthesis studies, Participant 1 also referred to prosthesis preferences from previous experience with *prosthesis and the control interface.* For example, "I am not a big fan of when my knee bent in the stance phase."

Context

Context was defined as the environmental and situational context when the preference exploration happened. This theme was only mentioned in one participant with three excerpts, but we deemed it an important factor that determined the preferences. For example, participant 1 specifically mentioned that the pre-set walking speed of the treadmill may have determined the prosthesis setting changes she made: "I think it's because I'm also walking slower on a treadmill than they would like in normal life. So I feel like it doesn't need to swing quite as far back." This suggests that if the context changes, the preferences may also change accordingly.

Saturation Point

Saturation point, as when a participant stopped making further adjustments to settings, was added as a separate theme to discuss when the preferred setting was achieved. Both participants stopped making changes when *no strong approach motivators* existed. Participant 2 mentioned that "I couldn't imagine any adjustments that I would need to make" and "I don't know whether it needs to bend or be more straight." Participant 1 made a similar statement: "Honestly, I don't really know what else to change." It did not mean that no approach motivators remained, but they were not strong enough to drive further action. Participant 1 mentioned that "I mean I could try like three degrees difference rather than two degrees, but I'm not really sure how much of a difference that's gonna make." When the experimenter confirmed whether the profile would be the one that the participant would wear in daily life, the logic-based motivators still existed: "If it was really that I was going to wear this every day, I would try every single option and compare them all. I would try things like a bunch of different combinations and see all the different combinations." However, it was not strong enough to offset other avoidance motivations like tiredness: "I mean definitely a little tired. [If] I had more energy, I will be more willing to try all of the other options."

DISCUSSION

Through thematic analysis of the think-aloud sessions, the current study revealed that physical perceptions, subjective feelings, previous experience and knowledge, and context contributed to the final preferred prosthesis profile. The saturation point was usually reached when no approach motivator was strong enough considering the time and effort to continue the setting adjustment.

Defined as the liking towards one over the other option, preferences could be considered an affective aspect of attitudes (Yuan, 2021) towards prostheses. Similar to the acknowledged components of emotions (Shiota & Kalat, 2018, pp.5-6), we also found the cognitive aspect (i.e., experience and knowledge), the physical aspect, and the subjective aspect of preferences. The behavioral aspect such as adopting the changes made or expressed intention of using the prosthesis in daily life may reflect the preferences as well. Future research could investigate whether the preferences may lead to actual behaviors in daily life (e.g., more time using the prosthesis).

One finding that is unique and worth highlighting is that the experience from the intact leg and other profiles were used as anchors in participants' preference exploration. Anchoring effects have been robust in preferential judgment (Yoon et al., 2019), which seemed to be applicable to prosthetic setting preferences as well. Although the current trend in technology is to develop algorithms to generate one's preferred knee profile directly without active inputs from a wearer, the liking of such a profile may be compromised if it does not allow anchoring or autonomy. According to the self-determination theory (Ryan & Deci, 2017), with autonomy as a basic psychological need, the resulting self-determined behaviors are critical for one's health and well-being. Future studies could further investigate the necessity and impact of providing suitable anchors or freedom to make changes when developing algorithms.

What surprised our stakeholders is that both participants used the intact leg as a reference for the prosthetic leg. This may imply that, for able-bodied participants at least, the biomechanical data from the intact leg could be potentially used to predict the preferences for the prosthetic leg. This may be applicable to wearable assistive technology such as exoskeletons. However, the case may be different for amputees. One amputee stakeholder mentioned that he usually focused on the functioning of the prosthetic leg itself but did not use the intact leg as a reference. Based on the biomedical researchers' observations of prosthesis use, wearers usually made efforts to use the intact leg to accommodate the movement of the prosthetic leg. One possible reason is the qualitative differences between the amputee and able-bodied participants' experiences and embodiment of the prosthetic leg. One study found that when asked to stand on one leg, compared to able-bodied participants whom always chose the dominant leg, 65% of the amputee participants – and more likely those with longer prosthetic experience – chose the prosthetic leg to stand on (Howard et al., 2012). Another possible reason is the changed mindset when given the autonomy in making changes to the prosthesis. Usually, prosthesis wearers are not allowed to change the prosthetic settings freely. Given that this study allowed participants to make decisions, their mindset might have changed from "using the intact leg to accommodate the prosthetic leg" to "making the prosthetic leg in harmony with the intact leg". Future data collection with more able-bodied participants and amputee participants may help us to confirm the between-group differences.

Another innovative finding is that the preferences may differ based on the context. A previous focus-group study also found situational context to be part of the mobility experience (Hafner et al., 2016). This implies that allowing prostheses to be flexible and self-adjustable regarding environmental and situational contexts such as walking speed, terrain conditions, or weather could be a promising and critical future direction. Another aspect is the psychological context. For example, feeling bored, running out of patience, or even being in a negative mood could also potentially impact the preferences in the self-tuning process, which future studies on the self-tuning interface may want to take into account.

As the first study investigating preferences of prosthetic settings while allowing the participant to control the tuning process, the results from our think-aloud protocol were informative and valid due to several reasons: 1) to mimic the approach-avoidance conflicts (Förster et al., 1998) of amputee population in participants without disabilities, we promoted the approach motivation by instructing the participants to imagine that they were amputees and they would wear this prosthesis in their daily life; 2) structured practice sessions in a similar preference-exploring task were designed to get participants familiarized with talking aloud while changing parameters; 3) standard operating procedure was written to standardize the prompting questions and feedback during and after thinking aloud; 4) instruction videos and exercises were developed to ensure the equivalent and sufficient understanding on the tuning system. The results could not only inform future theories of preferences, questionnaire development, and think-aloud protocol standardization but also inspire the next steps in prosthesis design and practices. Despite the advantages, we acknowledge that due to the small sample size with able-bodied participants, the results may not capture the entire picture. In the future, we are going to get a larger sample size and recruit amputee participants for comparisons.

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