PERCEPTUAL AND CONTROL PROPERTIES OF A HAPTIC UPPER-LIMB PROSTHETIC INTERFACE

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ABSTRACT

Current upper-limb prostheses fail to meet user expectation. Common complaints are the large control forces for body-powered prostheses (BPP) and the lack of proprioceptive feedback in myo-electric prostheses (MEP). This study investigates sensitivity and control accuracy and feedback sensitivity of a haptic (master-slave) interface that combines BPP-like control for a MEP utilizing low control forces in the presence of proprioceptive feedback. This first step focuses on static forces. One experiment focused on the just noticeable differences (JND) and the Weber fraction (WF) of the shoulder, and a second on force control. JND and WF were determined by a two-alternative-forced-choice-method at 4 forces levels (2, 4, 6, and 8 N). Force control was evaluated by a visual matching task and blind reproduction task at the same force levels, and force error (FE) and force variability (FV) were obtained. WF results (7% for 2 N, 3% for 4 N, 3% for 6 N and 2% for 8 N) indicated a level of sensitivity comparable to human weight perception. FE and FV values were small enough as not to affect usability when grasping objects. We conclude that forces of 2-10 N are sufficient to operate an externally powered prosthesis while maintaining a sufficient level of proprioceptive feedback.

INTRODUCTION

Despite advancement in prosthesis design, many users remain dissatisfied [1], where the main complaints concern discomfort of wearing the prosthesis, the difficulty to don and doff, and the difficulty of controlling the prosthesis which demands a high mental and physical load [1]. When considering the two main types of upper-limb prostheses, body powered prostheses (BPP) and Myo-electric prostheses (MEP), BPP suffer from high control forces resulting in discomfort and compensatory movements, and MEP are accompanied by a high mental load due to the lack of proper feedback [2]. A good prosthesis should provide the user with enough information to perform daily tasks that require fine motor adjustments. This can only be achieved if there is sufficient (proprioceptive) feedback [2, 3].

This paper takes a first step in investigating a new method for controlling an upper limb prosthesis combining the strengths of both BPP (proprioceptive feedback) and MEP (low control forces). More specifically, we aim to develop a haptic interface that provides proprioceptive feedback and allows the user to set a comfortable control force range and feedback for optimal gripping experience. The system consists of two parts, a master and a slave system. The master system is worn on and controlled by the shoulder. The slave side is an externally powered prosthesis.

Improvements in cosmesis were obtained by using skin anchors instead of a shoulder harness [4]. The use of skin anchors also removes the discomfort of the harness digging into the skin. Compared to BPP, control forces are markedly lower. Pilot studies revealed that static forces up to 10 N were most comfortable, and forces below 2 N were deemed too low for useful control.

To improve feedback, the master device provides proprioceptive feedback to the user. As the control system is implemented electronically, the control and feedback level can adjusted to suit the user. By using two skin anchors [4], the device can easily fit underneath clothing. Note that, the shoulder-worn master system can be placed on the affected and healthy side of the body. See also Figure 1. Control is improved by using control forces up to 10 N. Together, the proposed solution provides the necessary level of comfort, control and cosmesis to the user [3].

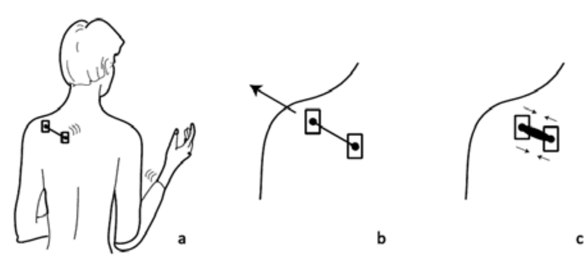

Figure 1. The intended solution for the new prosthesis interface. The control forces are exerted by the same movement as a body-powered prosthesis (a). Force is measured by a sensor between the skin anchors (b) and proprioceptive feedback is provided by pulling the two skin anchors closer together (c).

Specifically, this study investigates the sensitivity of a dual skin anchor solution for static forces by determining the Weber Fraction (WF) and the Just Noticeable Difference (JND) for forces and comparing the results to known perceptual results for weight sensitivity. Weber's Law predicts a subject's difference threshold of any intensity value, and the WF equivalent is defined as $\Delta\Phi/\Phi=c$, where

$\Delta\Phi$ is the difference threshold or JND, Φ the initial stimulus intensity and c is a constant; the WF [5, 6]. The same law also states that the JND is proportional to the original stimulus. The WF is a ratio comparing the stimulus intensity with the change in the stimulus magnitude [5]. The WF shows the minimum decrease or increase an object has to make in order to be noticeable. A WF of 0.05 or 5% means that a subject can reliably detect a change of 5% in stimulus intensity. In addition we will investigate the relationship between applied and perceived force by performing a force reproduction experiment.

These two experiments will be performed and the following question will be answered in experiment 1: 'what is the Weber fraction equivalent for the threshold of force feedback for the skin anchors used for prosthetic control?'. Experiment 2 will answer the question 'what is the accuracy of force control, in terms of force perception and force reproduction, for shoulder muscles used in this type of prosthetic control?'

METHODS

Two experiments were performed. The first experiment focused on the WF for static force feedback and the second focused on the accuracy of control where subjects followed a force profile. Both experiments used the right shoulder to produce force by elevations and protraction. Forces were sufficiently low as not to induce fatigue. Both experiments were performed in a single session separated by a break and lasted 1.5 hours. The same group of subjects participated in both experiments. Both experiments used the same setup.

Participants

Ten healthy, right-handed males aged 18 to 37 performed in both experiments. Subjects provided informed consent and both experiments were approved by the local ethics committee.

Setup

Forces were recorded by a load cell (Futek LSB200, 50 lbs) amplified (Scaime, CPJ), discretized (NI, MyDAQ) and stored using custom Matlab (R2014b) software. A load cell interrupted a cable connecting two skin anchors positioned on the right shoulder and to the right of vertebrae T7, see Figure 2.

Methods experiment 1 – The Weber fraction equivalent

The 2AFC discrimination task is a psychophysical method and is commonly used to measure performance as a proportion of correct responses when comparing two stimuli. We determine if the subject judged test force to be larger than a reference force [5]. Perception is determined during active force production by the subject to simulate normal prosthetic use.

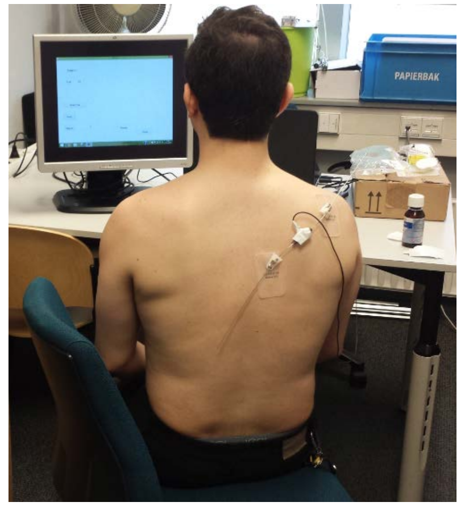

Figure 2. The experimental setup for both experiments

Each session started with several familiarization trials. Four reference forces were used: 2, 4, 6, and 8 N. Trials for the different reference forces were blocked and the order of the reference forces was counterbalanced.

A trial consisted of the subjects exerting force and matching a reference force level and a test force level (the order was randomized). Each force was produced for 5 seconds with a 3 second delay between the two force levels. In between forces, the subject was asked to relax and prepare by cues on the screen. Target height was kept constant to eliminate any visual cues relating to the magnitude of the target force. The target ensured that force level was not simply discernible from the magnitude of the movement. The test force levels comprised 10 stimulus intensities deviating from the reference force at ±3.5%, ±7%, ±10.5, ±14%, and ±17.5%. Each of the 10 test force levels was presented 4 times for each of the 4 reference forces yielding a total of 160 trials. The 160 trials took about 1 hour to complete.

Data analysis – experiment 1

During the experiment the number of trials where the test force was identified as larger than the reference force were counted and divided by the number of repetitions (4). Data for all subjects were pooled and a logistic psychophysical curve was fitted for each of the references forces (Psignifit 3.0, bootstrap method http://psignifit.sourceforge.net/). The JND was determined by determining the differences in force (ΔF) corresponding to 25% and 75% success probability using the following formula [7]:

$$JND = (\Delta F(75\%) - \Delta F(25\%))/2 \quad (1)$$

The calculated JNDs were used to determine the WF by dividing the JNDs by the different reference forces. A low

WF indicates a high level of precision. The WF was determined using the following formula:

$$WF = JND/F\_ref \times 100\% \quad (2)$$

Methods experiment 2 – accuracy of force control

The second experiment consisted of 4 blocks of 10 trials each corresponding to the four reference forces (2, 4, 6, and 8 N). The order of the 4 blocks of the 4 reference forces was counterbalanced. Each trial consisted of producing a constant force level with visual feedback, where a line on a screen indicated the target force. This force was exerted for 5 seconds. After completion, the subject was asked to reproduce the force level without visual feedback, also for 5 seconds. The two stimuli were separated by 3 seconds and relax/starting cues were displayed on the screen. Data was recorded with a sampling rate of 1 kHz. The 40 trials of experiment 2 took about 20 minutes to complete.

Data analysis – experiment 2

From each trial, the first 2.5 seconds and the last 0.5 seconds were discarded to remove transition effects. The remaining samples were analysed to obtain two measures: 1) the force error (FE), which was defined as the absolute difference between mean of the data and the target, 2) the force variability (FV), which was defined as the standard deviation of the produced force.

RESULTS

The pooled results revealed JND values of 0.14, 0.11, 0.16 and 0.17, and WF of 7%, 3%, 3%, and 2% for 2, 4, 6, and 8 N respectively. Figure 3 shows the psychometric functions indicating the probability of a correct response as a function of the difference between the forces of the reference and the test stimuli. Higher differences between force levels were detected correctly more frequently than lower differences.

The FE (Figure 4) and FV (Figure 5) results for the force reproduction task are presented below. Error bars represent the standard error of the mean. FE is markedly lower in the presence of visual feedback compared to the blind reproductions trials. Both conditions, however, illustrate the know property where the error scales with force level, as also seen in the FV. Surprisingly, the FV was comparable for both conditions. The FV shows the biggest variation for 8 N, with a mean variability of about 0.2 N.

DISCUSSION

The first experiment investigated sensitivity for static force production using shoulder movements. In summary, we found good force discrimination using shoulder movements with WFs: 7% for 2 N, 3% for 4 N, 3% for 6 N and 2% for 8 N, which are in the range of weight perception [5]. However, for 2 N, the sensitivity was markedly lower.

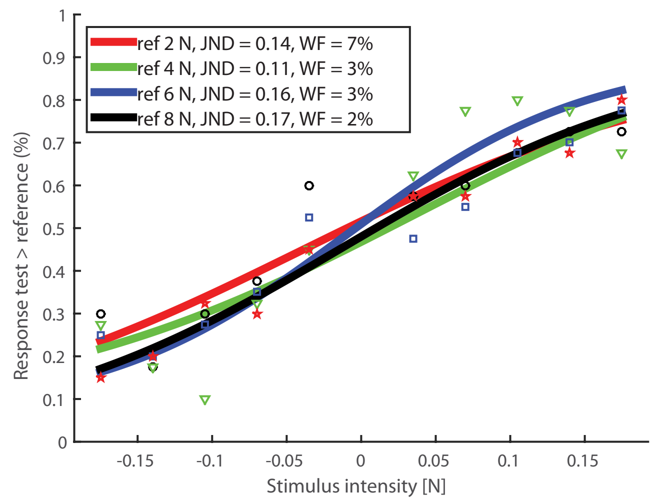

Figure 3. The psychometric functions for the four reference forces.

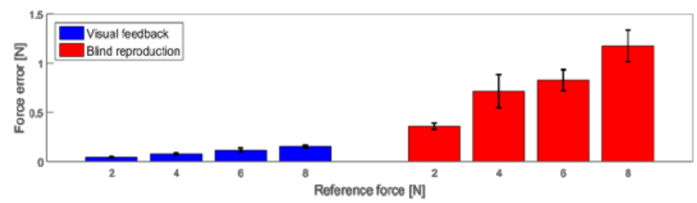

Figure 4. The FE averaged over subject and repetitions for the visual matching and blind reproduction tasks.

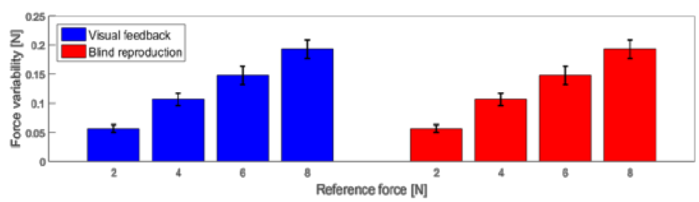

Figure 5. The FV averaged over subject and repetitions for the visual matching and blind reproduction tasks.

The resulting WFs ranged from 2% for 8 N to 7% for 2 N. The WF of 2% for 8 N shows that the subjects have a high level of sensitivity for differences in force levels. Previous studies on WF for force detection in healthy shoulders found fairly similar outcomes. Feyzabadi et al. [6] used also a 2AFC paradigm where the subjects had to perform a rotating shoulder movement in the upper arm for 3 different force intensities of 0.5, 1 and 1.5 N, and found a WF for the shoulder of 8% [6]. Hurmuzlu et al. [8] used shoulder-elbow motions to determine the JND for masses of 1, 2, 3 and 4 lb, and found WFs of 5%, 1.25%, 17% and 6%

respectively. Our results suggest that control using two skin anchors has a more than adequate level of sensitivity.

The focus of the overall project is to decrease the forces required to operate a prosthesis while still having a good level of proprioceptive feedback. The WF for different forces levels indicate that this has been achieved. Prosthetic users tend to prefer body-powered prostheses over externally powered prostheses because of the possibility to receive proprioceptive feedback, which is not available with externally-powered prostheses [3]. The results from Experiment 1 indicate that skin anchors may be intuitively used to control an externally powered prosthesis with shoulder movements.

The second experiment was designed to separate the influences of force perception and force reproduction on the judgment of the different force levels. Force reproduction gives insight in force production and force perception. Both force production and force perception are of interest for the control mechanism of the newly developed prosthesis. When it is able for a future user to produce an intended, or previously perceived force, the control over the artificial hand will increase. In summary we found that during the reproduction test the FE was increased compared to visual matching, this is in agreement with previously found data [9, 10]. This increase in FE is largest for the reference force 8 N, with a FE of approximately 1.2 N.

The results of the second experiment show that the force level affects FE and FV, where both measures increase when force levels increase; a known property of muscular control [9]. The FV seems independent of feedback as both the visual matching test and the blind reproduction test provide us with similar values. The FV was measured to give information about the force control and seems to be comparable, for inexperienced subjects using, in both visual and blind tests. Force errors did not exceed about 1 N and variability was less than 0.2 N. These results indicate that a user would not drop or crush an object.

One of the main advantages of this system is the presence of mode-specific proprioception, i.e., proprioception is provided for the muscles that provide force. This type of control is natural to the human body and is the fastest and most intuitive form of feedback and affords a reduced mental workload for the user [2].

The control source was chosen to be the shoulder as degree of freedom that could be manipulated without changing the position of the prosthesis. For example, elbow-powered prostheses require elbow flexion and extension to open and close the prosthesis resulting in displacement of the object that is gripped. With shoulder control, however, an object can be held at any position within the range of motions while still being able to change grip force.

The main motivation for using skin anchors was to provide an unobtrusive solution which could be hidden beneath clothing. We believe that the final design of the complete system, (anchors, actuator, power source) will remain small enough to achieve this goal.

CONCLUSION

The results presented in this paper indicate that a haptic interface using two skin anchors may provide a solution that allows low control force in the presence of meaningful force feedback. This study was a first step and efforts are underway investigating dynamic grasping. Pilot results indicate that this system performs as well as BPP for the Box and Blocks test [11].

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