An Empirical Evaluation of Stiffness Perception Using a Shoulder-Worn Haptic Interface

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***Abstract*—Many patients with an upper-limb deficiency choose not to wear their prosthetic devices due to a multitude of reasons, including physical discomfort and unintuitive, cognitively demanding control methods. A new haptic interface was developed combining the desirable control characteristics of body-powered control prostheses with the comfort of an externally powered prosthesis. A study (n = 10) was performed on the effect of the haptic feedback provided by the interface in a stiffness perception task. Participants were asked to determine the stiffness of a object with and without visual and/or haptic feedback. The haptic feedback was provided through the newly developed interface and the visual feedback through the display of a virtual slave. Results indicate that there is no significant difference in stiffness perception between the conditions with visual and/or haptic feedback.**

***Index Terms*—prosthesis, haptic interface, proprioceptive feedback, stiffness perception.**

I. Introduction

DESPITE the continuous advancements in prosthetic design, a reported 23% - 26% of patients choose not to wear their prosthetic device. [1] Users may reject their upper-limb prosthesis for a multitude of reasons, including lack of functional need, discomfort (weight, temperature, energy expense), difficulty of control and impediment to sensory feedback. [2], [3] The type of complaint is often dependent on the type of prosthesis. With the traditional body-powered prostheses users experience discomfort due to restrictive harnesses, high operation forces and compensatory movements. These issues are partly solved by modern myo-electric prostheses, which have a higher grip force potential and an increased functional work envelope. However, myo-electric prostheses require a high mental load due to a lack of proper feedback, whereas body-powered prosthesis provide secondary proprioceptive feedback and are thus simple and intuitive to control. [3]–[7]

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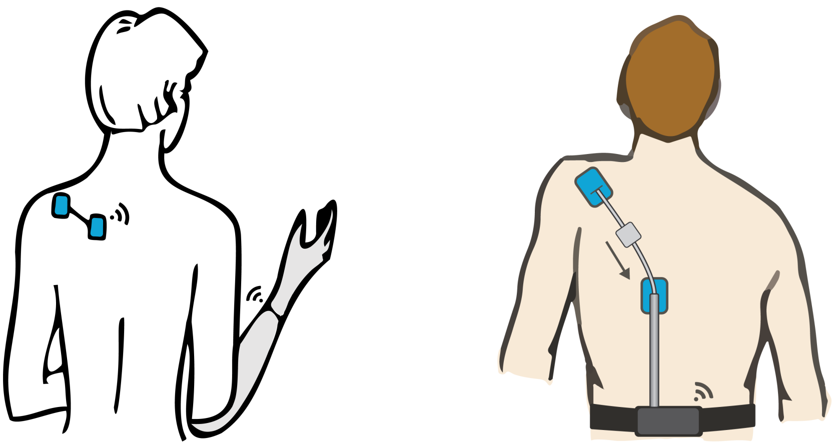
Biddiss *et al.* [2] (n = 242) found that 74% of prosthesis rejecters (i.e. used a prosthetic device once a year or less) would reconsider prosthesis use if technological improvements were made at a reasonable cost. This motivates the search for a more optimal design, combining the desirable control characteristics of body-powered prostheses with the comfort of an externally powered prosthesis. This could be implemented as a form of power assist system, similar to a power-steering system for a car [8]–[10] or even haptic x-by-wire systems. [11].

When using externally powered prostheses prosthetic users have to rely mostly on visual feedback to close the control loop, a cognitively demanding task as compared to the control of a body-powered prosthesis. [12] The strength of the feedback provided by body-powered prostheses lies in the 'Bowden cable'-design. This cable couples the dynamics of the body of the prosthetic user to the external dynamics encountered by the prosthesis. This coupling



(a) Proposal Vardy *et al.* [4] (b) Haptic Interface

Figure 1. (a) The intended solution for the prosthesis interface. Force is measured by a sensor between the skin anchors and proprioceptive feedback is provided by pulling the two skin anchors together. (b) Continuation of the proposal by Vardy *et al.*. By elevating their shoulder, the user can exert a control force on the Bowden cable. Feedback is presented to the user by shortening the Bowden cable, effectively restricting the upwards motion of the shoulder.

allows for both proprioceptive and exteroceptive feedback from the prosthesis. [13] The concept of using coupled dynamics to achieve a better control system for prosthetics was first introduced by Simpson as extended physiological proprioception (E.P.P). A control system is used such that the state of the prosthesis is (proportionally) linked to the state of one of the natural joints, for example the shoulder. [14] Because of this linkage the user can sense the state of the prosthesis through his natural joint, the proprioceptive senses of the user are thus extended to the device. A common example is that of a tennis player hitting a ball with his racquet. The tennis player does not require any visual feedback on the position of the tennis racquet to determine its position, he can derive the position of the racquet in space based on proprioceptive cues in his wrist and hand. [10] Similarly, a prosthetic user is able to derive the state from their prosthetic device from the proprioceptive cues through the Bowden cable.

Other research focused on alternatives for the restrictive harness used in body-powered prosthesis. Frequent wearers of prostheses are likely to experience skin irritation and/or blisters as consequences of the prosthetic harness. [2] One of these solutions is the Ipsilateral Scapular Cutaneous Anchor System of Debra Latour, which can replace a typical harness system in cable-activated prostheses. [15] The control cable is anchored to a patch which is glued to the back of the user, anchoring the system directly to the user's skin. The system allows for unimpeded use of the unaffected side and reduces the strain on the armpit by eliminating the need for straps. The system also showed comparable metrics for force perception and control as compared to a traditional harness, which makes it an valid alternative while offering increased comfort and cosmetic value. [16]

Inspired by these 'skin anchors', Vardy *et al.* proposed the development of a new haptic interface, which makes use of two skin anchors placed on the user's back, see also fig. 1a. [4] Building further upon this concept, a prototype was developed of a haptic interface suitable for proprioceptive feedback, as shown in fig. 1b.

Ideally, the proposed haptic interface will provide more comfort, better control to the user and will have a higher cosmetic value, following all three C's of prosthetic design.

[17]. Whilst the use of skin anchors should improve the comfort and cosmetic value, better control could be achieved by providing better feedback to the prosthetic user. Currently, the prosthetic users have to rely on visual feedback to close the control loop for myo-electrically controlled prostheses. If the feedback provided by the proposed haptic interface provides an added benefit over visual feedback, this would be an indication of the viability of the haptic interface as a novel control method for externally powered prostheses. This study thus aims to quantify the added benefit of the haptic feedback provided by the interface.

This is done by asking the participants to identify the stiffness of a set of (virtual) objects. The principles underlying the ability to recognize the force/displacement relationship of an object carry over to many other manual tasks. It is also a form of grip strength regulation. Good performance in a stiffness perception task thus suggests potential utility in many areas of prosthetic use. [13] We hypothesize that haptic feedback will improve the participants' performance in the stiffness perception task.

II. Methods

A. Participants

Ten healthy, non-amputee volunteers (6 male, 4 female; mean age 25.4 + 2.2 years) participated in the study. Prior to the study each participant provided informed consent and the experiment was approved by the TU Delft Human Research and Ethics Committee.

B. Experimental Set-up

The experiments were performed using a custom-designed haptic interface (see section II-C) which mimics the actuation of a traditional cable-operated body-powered prosthesis. The experiment set-up is depicted in fig.2. The haptic interface was also connected to a laptop (HP ZBook Studio G5) via a 5m micro-USB cable. A tablet (iPad Air, via Duet) was connected to the laptop as a second monitor facing the participant. The participant was seated on a stool in front of the tablet. The tablet displayed visual feedback to the participants by means of a virtual slave. The researcher is seated across from the participants, behind the laptop. A digital experiment interface running on the laptop provided the experimenter with the controls to run and log the experiment (see section II-D).

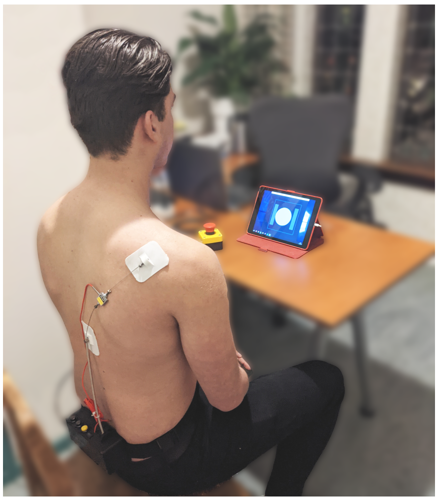


Figure 2. Experimental set-up. The haptic interface is fitted to the participant's back, with the adhesive skin anchors (white rectangles) positioned next to the vertebrae and on the dominant shoulder. The participant is seated in front of a display, providing them with visual feedback during the appropriate experiment conditions. Participants have access to an emergency button to cut power from the interface.

C. Haptic Interface

1) Hardware: All of the components of the haptic interface are depicted in fig.3. The haptic interface has two 'skin anchors', similar to the design of Debra Latour [15]. The skin anchors are 3D-printed with flexible rubber (MakerPoint FLEX 45) and are attached to the participant's skin using a double-sided, stretchy acrylic adhesive (TrueTape Supertape). The skin anchors are positioned on the shoulder of the dominant hand and next to the vertebrae, with the latter roughly aligning with the lowest point of the scapula. The neutral position of the servo can be adjusted such that there is no tension in the rest position and the participant can comfortably exert a 15N force.

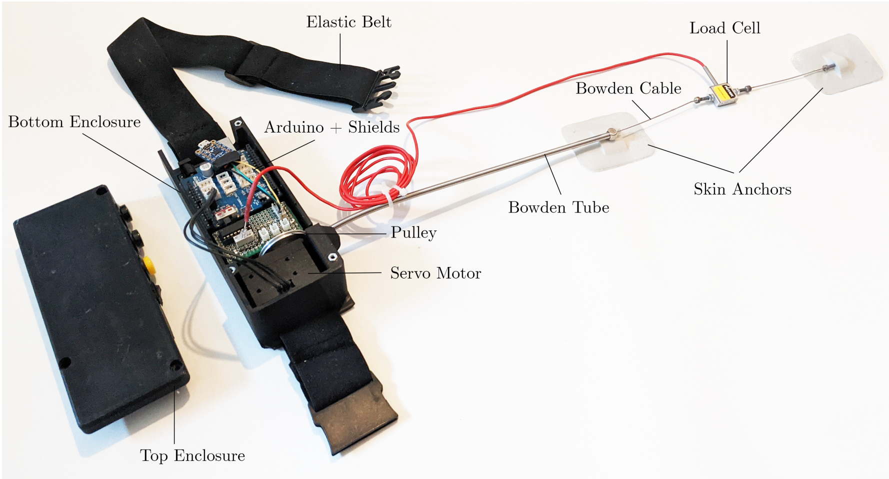


Figure 3. Overview of the components of the Haptic interface. An interrupted Bowden cable runs from the upper skin anchor to the pulley attached to the horn of the servo motor. The second skin anchor is connected to the Bowden tube. A load cell measures the force on the cable. The Arduino handles the processing of the sensor signal and control of the servo motor. All electronics are secured in a 3D-printed enclosure which can be worn at hip hight with an elastic belt. Haptic feedback is provided to the participant by controlling the distance between the two skin anchors, which can be shortened by winding up the Bowden cable on the pulley.

An interrupted Bowden cable runs from the upper skin anchor to a pulley attached to a servo motor (Robotis Dynamixel XM430-W210-T). The pulley can wind up the Bowden cable, thus pulling down the participant's shoulder via the upper skin anchor.

Forces on the Bowden cable are recorded by a load cell (Futek LSB200, 10 lb) amplified by an instrumentation amplifier (Burr-Brown INA125) and sampled by a micro-controller (Arduino Mega 2560) at 50 Hz. The micro-controller and the servo motor are attached to a 3D-printed PLA enclosure. The enclosure has an elastic belt with a break-away buckle and is worn at hip height. A Bowden tube (l = 240 mm) with an inner Teflon lining connects the enclosure with the lower skin anchor. The haptic interface can easily accommodate participants from different heights by changing the neutral position (θ_0) of the servo motor.

Finally, a second serial port of the micro-controller is attached to a USB to Serial converter (Adafruit CP2104), which can communicate with the digital experiment interface. The same system can be used for a wireless solution by swapping out the serial converter by a standard UART Bluetooth adapter.

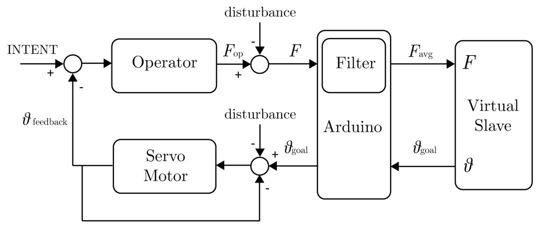


Figure 4. System Architecture of the haptic interface. The human operator forms a input force F_{op} based on their intent and the positional feedback provided by the haptic interface. The measured force F is filtered and the resulting F_{avg} is used as an input for the virtual slave. The virtual slave then translates the input force to a goal position for the servo motor. The servo motor has a separate feedback loop for its position.

2) Control System: A schematic representation of the system architecture can be seen in fig.4. The human operator acts as a controller in the system. The human operator translates the combination of their intent and the positional feedback provided by the servo motor into an input force F_{op}.

The force F measured by the load cell was filtered using a moving average filter with a window size of 10 samples. This reduces high-frequency jitter by significantly diminishing signals > 5Hz. This does not interfere with the input signals from the shoulder, as the estimated bandwidth for motion commands to the limbs is 2-5 Hz and the shoulder has 99% of it's power spectrum below 5 Hz. [18]–[20]

The resulting averaged force F_{avg} at time i can be written as:

$$F_{\text{avg},i} = \sum_{k=0}^{n-1} \frac{1}{n} F_{(i-k)}, \quad n = 10 \tag{1}$$

The averaged force serves as a control input for a force-controlled prosthetic hand, from which the position u_{slave} can be measured. This position is of course dependent on the impedance of the environment that the prosthetic hand is interacting with. The positional feedback is provided to the prosthetic user by the Dynamixel servo motor, which is also controlled by the micro-controller via a Robotis Arduino Shield. The goal position (θ_{goal}) of the servo is determined by the position of the prosthetic device.

For the experiment the prosthetic device is replaced by a virtual slave. The force/position-relationship is then not determined by the impedance of the environment but instead modelled as a perfect linear spring with a given virtual stiffness k. In this case, the goal position of the servo can be rewritten as a function of the force and virtual stiffness. With the haptic feedback 'on' ($H = 1$) and haptic feedback off ($H = 0$), the goal position can be written as:

$$\theta_{\text{goal}} = \theta_0 - H\frac{F_{\text{avg}}}{kr} \tag{2}$$

With r as the radius of the pulley (r = 15 mm) connected to the servo horn. The position control loop of the servo is handled by the Robotis software, with $K_p = 800$, $K_i = 0$ and $K_d = 0$. This loop is executed at 50 Hz, which should be sufficient for the feedback loop. Research has shown that whilst low-frequency haptic feedback (7-9Hz) substantially improves task performance, further increasing the bandwidth only yields marginal improvements. [21], [22]

D. Experiment Design

The experiment design is largely based on the research of Brown *et al.* [13], where the effect of force feedback was evaluated by conditionally removing force feedback in a body-powered prosthesis.

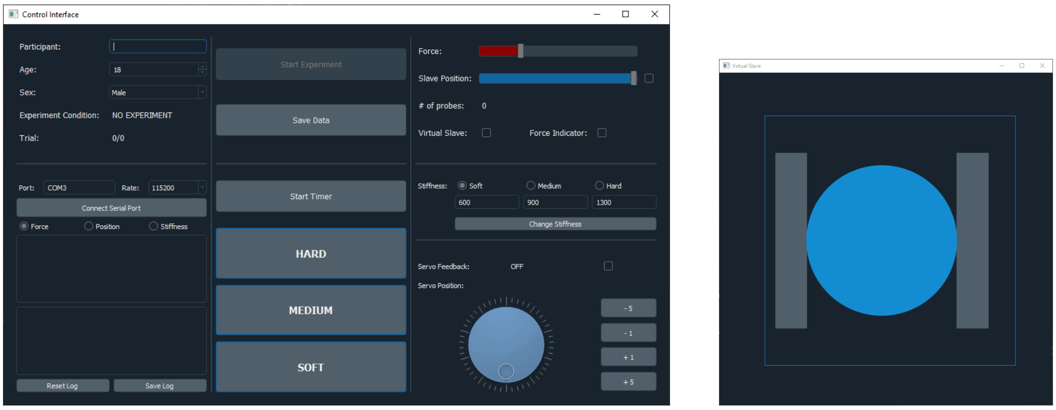
The experiment mimics a voluntary-closing force-controlled prosthetic hand by controlling a virtual slave, as depicted in fig.5b The virtual slave consists of two bars that compress a 'ball' which is modelled as a perfect linear spring with initial length l_0 = 60 mm. The virtual stiffness of the spring can be changed to different levels. The bar on the left-hand side is fixed, and the position of the right bar can be written as:

$$u_{\text{slave}} = l_0 - \frac{F_{\text{avg}}}{k} \tag{3}$$

The stiffness levels for this experiment are based on three gel balls (TheraBand Handtrainer) in three resistance levels: light, medium heavy and extra heavy. The approximate linearised stiffnesses of these balls were measured to be k = 600 N/m, 900 N/m and 1300 N/m respectively. These levels are referred to in the experiment as 'soft', 'medium' and 'hard'.

To evaluate the effect of haptic and visual feedback in stiffness perception, the haptic feedback can be turned on and off. Without the haptic feedback, there is uni-lateral force control of the virtual slave. With the haptic feedback turned on, the position of the virtual slave is fed back to the participant. In total there were four conditions: "No Feedback", "Visual Feedback", "Haptic Feedback" and "Visual + Haptic Feedback".

Before the experiment the skin anchors are placed on the participants' back. The participants were presented with a slider showing visual feedback of their force level such that they would get accustomed with the range of forces used in the experiment. The participants were allowed to experience each of the four experiment condition with a stiffness value of k = 750 N/m. They were not allowed to feel the stiffness values used in the experiment.



(a) Experiment Interface (b) Virtual Slave

Figure 5. Main windows of the digital experiment interface. **(a)** The experiment interface for the researcher. This window provides an interface to log the participant details (top left), establish a connection with the hardware (bottom left), log experiment metrics (middle section) as well as some debugging features, manual control and the option to change experiment parameters (right section). **(b)** Virtual slave as displayed to the participant. The left bar is fixed, the right bar moves to the left as a function of the force F_{avg} and stiffness k, compressing the ball into an ellipse. The amount of compression indicates the 'stiffness' of the ball.

Based on the received input, the researcher would adjust the neutral position of the servo motor and/or the placement of the upper skin anchor to ensure that the participants could comfortably reach an input force of 15N within their range of motion.

Participants were told that the goal of the experiment was to accurately identify the stiffness level of each trial as quickly as possible. Before starting a trial the condition was indicated to the participant.

The participants started from a rest position ($F_{\text{avg}} < 1.5$N) and were instructed to wait for a verbal cue from the experimenter. When the experimenter announced 'start', participants were instructed to 'squeeze' the virtual ball and verbalize their choice on the stiffness level: hard, medium or soft. After choosing a stiffness level the participants were not allowed to change their choice. The experimenter can time each trial via the digital experiment interface (see fig.5a). This program also logs all other metrics as well as the raw data of the experiment.

When the participant's choice has been logged the digital experiment interface waits for the participant to return to a rest position before updating the stiffness to the value of the next trial. For each of the four conditions there was a random selection of 8 stiffness values from an array of 12 values (4 soft, 4 medium and 4 hard). After completing the eight trials for a condition, the experimenter would provide the participant with some correct answer feedback before continuing to the next condition. For example, if the participant categorised three trials as 'Soft', the verbal feedback could be: 'Within the three balls you categorised as soft, there were two soft balls and one medium ball.'

After completing a set of all four conditions a short break of 1 minute was taken. This process was repeated five times, giving a grand total of 160 trials per participant. The order of the conditions was randomized within each of the five repetitions. After the experiment a post-test survey was conducted via a digital form.

E. Metrics

All raw experiment variables from the micro-controller (F_{avg}, u_{slave}, k, H, θ, t) were logged by the experiment interface at a rate of 50 Hz. Additionally the performance metrics for the experiment were recorded for each individual trial. The performance metrics were the stiffness identification accuracy (%), the stiffness identification completion time (s) and the number of probes by the participant.

1) *Identification Accuracy*
For each trial, the actual stiffness k and the chosen stiffness k_{choice} were recorded. The identification accuracy can then be calculated for any condition when post-processing the data.

2) *Completion Time*
The completion time was measured as the time between the 'start' announcement of the experimenter and the verbal choice affirmation of the participant. Both events were recorded with button presses in the digital experiment interface.

3) *Number of Probes*
Two threshold values were set at $u_{\text{slave}} = 55\text{mm}$ and $u_{\text{slave}} = 50\text{mm}$. A full probe of 10 mm would consist of the moving bar of the slave passing both thresholds in both directions. Passing one threshold in either direction will add 0.25 to the total number of probes. A smaller probe of 6 mm would thus accumulate to 0.5 probe. The number of probes was logged at the time of the participant's choice.

For the survey, participants were asked to rank the difficulty of each condition on a 3-point Likert scale, as well as ranking them in order of preference and distinguish-ability of the stiffness values. The participants were also asked what strategy (if any) they employed during each of the conditions to a get a more qualitative assessment.

F. Statistical Analyses

The statistical analyses were performed using SPSS (v.26). A general linear mixed model (GLMM) was used to analyse the data, with the feedback condition as the fixed effect. To account for inter-personal differences, the participant was added as a random effect. A potential learning effect was suspected between each of the five sets (`trial_set`), the order in which each condition was presented (`condition_order`) as well as within the eight trials of each condition (`trial_order`). To test and adjust for this learning effect, these variables were all added as a covariate in the model.

The confidence level was set at 95%, resulting in a significance level of 0.05. As multiple analyses are applied to the same data, a Bonferroni adjustment was applied to the significance levels during the pairwise comparisons.

III. Results

A. Stiffness Identification Accuracy

The results of the linear mixed model indicated a significant effect for the intercept (F(1,306.9) = 127.22, MSE = 28.89, p < 0.001) and experiment condition (F(3, 26.77) = 40.19, MSE = 13.26, p < 0.001).

A significant effect was also found for the trial order (F(1, 1557) = 17.07, MSE = 3.48, p < 0.001), but not for the condition order (F(1,1557) = 0.43, MSE = 0.09, p = 0.513) or the trial sets (F(1, 1557) = 0.44, MSE = 0.09, p = 0.506). Whilst the effect is significant, trial order has an effect size (partial η^2) of 0.010, meaning that it accounts for approximately 1% of the variance after excluding the variance explained by other factors. When excluding the 'no feedback' condition from the data, the partial η^2 for trial order increases to 1.8%.

There was no significant effect found for the participant (F(9, 26.17) = 1.73, MSE = 0.572, p = 0.130), but a small significant effect was found for the interaction component `condition * participant` (F(27, 1557) = 1.61, MSE = 0.33, p = 0.024,) with a partial η^2 of 2.7%.

A bar plot of the estimated marginal is shown in fig. 6. The highest identification accuracy was found for the visual feedback condition (M = 74.0%, SE = 2.3%), followed by 'visual and haptic' feedback (M = 72.0%,

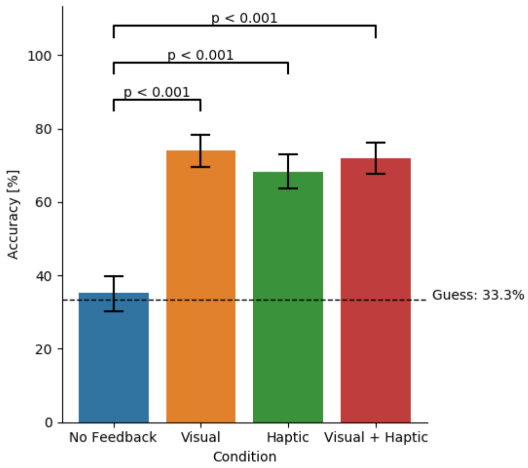


Figure 6. Estimated marginal means for the identification accuracy per condition after correcting for the covariate effects. The error bars represent the standard deviation. A significant effect was found for three pairwise comparisons.

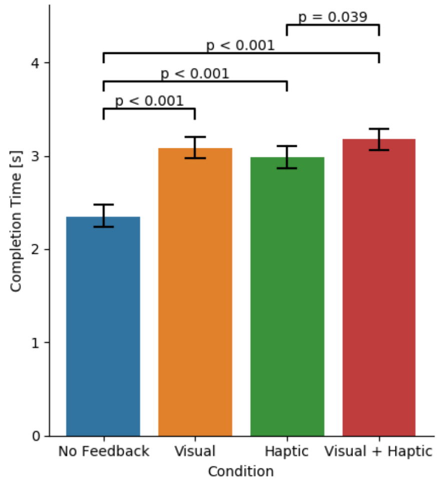


Figure 7. Estimated marginal means for the task completion time per condition after correcting for the covariate effects. The error bars represent the standard deviation. A significant effect was found for four pairwise comparisons.

SE = 2.3%), haptic feedback (M = 68.2%, SE = 2.3%) and finally 'no feedback' (M = 35.3%, SE = 2.3%).

Pairwise comparisons of these means showed that a higher identification accuracy can be obtained for the 'visual and haptic' condition than for the 'no feedback' condition (β = 36.7%, SE = 3.2%, p < 0.001). Similarly, when compared to the 'no feedback' condition, higher identification accuracies were obtained with visual feedback (β = 38.6%, SE = 3.2%, p < 0.001) as well as haptic feedback (β = 32.7%, SE = 3.2%, p < 0.001).

No significant differences were found between the results of the three conditions with haptic and/or visual feedback.

B. *Completion Time*

A significant effect was found for the intercept (F(1, 13.94) = 283.82, MSE = 1250.14, p < 0.001), the condition (F(3, 26.96) = 7.23, MSE = 56.10, p < 0.001), the participant (F(9, 26.94) = 7.23, MSE = 56.10, p < 0.001) as well as the interaction component (F(27, 1557) = 8.33, MSE = 7.70, p < 0.001). All three covariates were found to be significant as well, but only the trial set had a partial $\eta^2 > 5\%$, with (F(1,1557) = 114.23, MSE = 105.63, p < 0.001).

The largest η^2 was found for the intercept, at 95.3%, followed by the participant (70.7%), the condition (44.6%) and the interaction component between condition and participant (12.6%).

A bar plot of the estimated marginal means in shown in fig.7. Participants completed the 'no feedback' condition the fastest (M = 2.35 s, SE = 0.048 s). Haptic feedback was the second fastest condition (M = 2.99 s, SE = 0.048 s), closely followed by visual feedback (M = 3.09 s, SE = 0.048 s) and finally 'visual and haptic' feedback (M = 3.17 s, SE = 0.048 s).

Pairwise comparisons of the means showed a faster completion time for the 'no feedback' condition as compared to haptic feedback (β = 0.64s, SE = 0.07s, p < 0.001), visual feedback (β = 0.74s, SE = 0.07s, p < 0.001) and the combination 'visual + haptic' feedback (β = 0.82s, SE = 0.07s, p < 0.001).

A significant difference could also be found between haptic feedback and 'visual + haptic' feedback (β = 0.19s, SE = 0.07s, p = 0.039). No other significant differences were found.

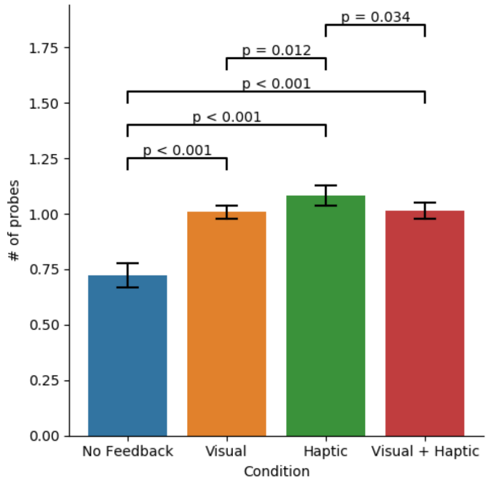


Figure 8. Estimated marginal means for the number of probes per condition after correcting for the covariate effects. The error bars represent the standard deviation. A significant effect was found for five pairwise comparisons.

C. # of probes

A significant effect was found for the intercept ($F(1, 18.45) = 422.83$, $MSE = 152.40$, $p < 0.001$), the condition ($F(3, 26.98) = 4.54$, $MSE = 10.14$, $p = 0.011$) and the interaction component ($F(27, 1557) = 19.10$, $MSE = 2.22$, $p < 0.001$). All three covariates were found to be significant as well, but only the trial set had a partial $\eta^2 > 5\%$, with $F(1,1557) = 87.19$, $MSE = 10.13$, $p < 0.001$. No significant effect was found for the participant ($F(9, 26.98) = 1.78$, $MSE = 3.99$, $p = 0.118$).

The largest η^2 was found for the intercept, at 95.8%, followed by the participant (37.3%), the condition (33.6%) and the interaction component between condition and participant (24.9%).

A bar plot of the estimated marginal means in shown in fig.8. Participants executed the the 'no feedback' condition with the least amount of probes ($M = 0.723$, $SE = 0.017$ s). This was followed by visual feedback ($M = 1.007$, $SE = 0.017$), then the combination 'visual + haptic' feedback ($M = 1.015$, $SE = 0.017$) and finally haptic feedback ($M = 1.018$, $SE = 0.017$).

Five significant differences were found in the pairwise comparisons of the means. In the 'no feedback'-condition, the participants probed the virtual object less as compared to when they had visual feedback ($\beta = 0.28$, $SE = 0.024$, $p < 0.001$), haptic feedback ($\beta = 0.36$, $SE = 0.024$, $p < 0.001$) or both ($\beta = 0.29$, $SE = 0.024$, $p < 0.001$). When receiving only haptic feedback, participants required more probes as compared to the combination of 'visual + haptic' feedback ($\beta = 0.067$, $SE = 0.024$, $p = 0.034$) or visual feedback alone ($\beta = 0.074$, $SE = 0.024$, $p = 0.012$). No significant difference in the number of probes was found between the visual feedback condition and the 'visual + haptic' feedback condition.

D. Post-Experiment Survey

The results of the closed-ended questions of the post-experiment survey are presented in table I.

1) Ratings: The participants consistently rated the 'no feedback' as difficult, least distinguishable and least preferred.

Generally, a slight majority shows preference for the visual feedback condition, with half of the participants citing it as the most distinguishable and a majority of the participants having it as their first or second preferred condition.

The opposite is true for haptic feedback, with the least number of participants scoring it at the most distinguishable or the most preferred. Furthermore, half of the participants felt 'neutral' about the haptic feedback difficulty and a few found it 'difficult'.

A slight majority of the participants evaluated the difficulty of the 'visual and haptic' feedback condition as 'easy'. For the other two questions the responses were divided.

2) Strategies: For the 'no feedback' condition, most participants mentioned using either a '(pseudo)-random' strategy or consistently answering with the same stiffness.

For the visual feedback condition, all of the participants indicated the (end) position of the slave being an indicator for their choice. Additionally, two participant mentioned utilizing the velocity/acceleration.

Six participants mentioned using the 'force', 'tension' or 'resistance' in their decision strat-

Table I
POST-EXPERIMENT SURVEY RESULTS (# OF RESPONSES)

		Easy	Neutral	Difficult	
How easy/difficult was the given condition?	No Feedback	0	1	9	
	Visual Feedback	5	5	0	
	Haptic Feedback	3	5	2	
	Visual + Haptic Feedback	6	4	0	
		1 (most)	2	3	4 (least)
How distinguishable were the stiffnesses in the given condition?	No Feedback	0	0	0	10
	Visual Feedback	5	4	1	0
	Haptic Feedback	1	3	5	0
	Visual + Haptic Feedback	3	3	4	0
		1	2	3	4
Rank the four conditions in order of preference:	No Feedback	0	0	0	10
	Visual Feedback	4	4	2	0
	Haptic Feedback	2	4	4	0
	Visual + Haptic Feedback	4	2	4	0

egy for the haptic feedback. Three out of the ten participants indicated utilizing the position of their shoulder, mentioning for example 'feeling how far the shoulder moves with similar force' and two participants stated using the velocity/acceleration. Four participants mentioned listening to the sound of the haptic interface when describing their strategy for the haptic feedback condition. Three participants mentioned being able to feel 'a light click when the device changed settings'. This gave them an indication whether the stiffness had changed as compared to the previous trial. Two participants specifically brought up mostly comparing the current trial to the previous trial.

Finally, for the combination of 'visual and haptic feedback', half of participants mentioned (equally) combining their previously mentioned strategies. Four participants stated to mostly focus on the visual aspect, while the last participant said to focus mostly on the haptic feedback, using the visual strategy 'only to check the difference between medium and hard if I could not distinguish.'

IV. DISCUSSION

The goal of this study was to determine the added benefit of haptic feedback provided by the new interface, specifically for the participant's ability to discriminate between different stiffness levels. To assess the task performance, three metrics were used: identification accuracy, completion time and number of probes. These were tested across four feedback conditions: no feedback, visual feedback, haptic feedback, visual + haptic feedback. The hypothesis was that haptic feedback would improve the participants' stiffness perception, which would be indicated by a higher identification accuracy, faster completion times and fewer number of probes for the trials with haptic feedback. Additionally, a survey provided a qualitative assessment of the participants' experiences with the different feedback conditions.

The results indicate that with respect to the identification accuracy, there was no significant different between haptic feedback, visual feedback or the combination of the two. Whilst the effect size (partial η^2) was small, a learning effect was observed within the eight trials of each condition. This could be explained by the participants basing their reference on the first stiffness presented. With each additional trial there is a higher chance of the participant experiencing all three stiffness levels and readjusting their baseline accordingly, leading to more accurate choices.

Participants completed the identification task slightly faster with haptic feedback as compared to the combination 'visual + haptic' feedback. Furthermore, a slightly higher number of probes was used to identify the stiffness with haptic feedback as compared to 'visual +

haptic' feedback or visual feedback alone. Aside from the 'no feedback' condition, the absolute differences between the means of the different conditions are marginal (0.18s, 0.01 probe), which is supported by the very high effect sizes (partial η^2) of the intercepts, which were 95.3% and 95.8% respectively. The larger differences with the 'no feedback' condition can be explained by a couple of participants realizing that probing had no effect on their scores and thus answering as quickly as possible with zero probes. Generally, the participants were very consistent in both their timing and their number of probes.

In the post-experiment survey, visual feedback and the combination 'visual + haptic' feedback scored better than haptic feedback on the perceived difficulty of the task as well as the distinguish-ability of the different stiffness levels. These conditions also ranked higher in the order of preference as compared to haptic feedback alone.

The analysis of the data indicates that the hypothesis is not correct, as (the addition of) haptic feedback did not lead to better results. Instead, when compared to visual feedback, participants performed on par with haptic feedback and rated the haptic feedback slightly worse. The results do not fit with the theory on extended physiological proprioception or the results from Brown *et al.* [13], [14] The disparity with the theory could be due to several reasons.

A. Limitations

1) Feedback Modality: Firstly, the haptic feedback provided by the new interface design may be perceived by the user as tactile feedback rather than proprioceptive feedback. The benefit of proprioceptive feedback is that it is modality-matched, meaning that the user senses the feedback signal in the same way it would sense the original signals. In the case of this haptic interface that would mean that by coupling the state of the shoulder to the state of the prosthetic joint, the user can sense the joint state through the proprioceptive senses of their shoulder. It is unclear if the haptic interface does in fact provide this kind of feedback. The participants could for example also rely on the tactile feedback of the skin anchors 'pulling' on their skin. The information from the prosthesis is then communicated through a different sensory channel, and the user has to be able interpret the signal and associate it with the correct information from the prosthesis, a technique known as sensory substitution. The need to process the perceived feedback signal applies an extra cognitive demand on the user. When the haptic feedback is not in the right modality, there is still a need to process the signal and the feedback would thus not show an improvement over the visual and auditory systems already in place. [12], [23]

2) Virtual Slave: Another possibility could be the design of the virtual slave. For the purpose of the experiment, the prosthetic hand was simplified to a two-bar virtual slave with one degree of freedom perpendicular to the participant. One could argue that this simplified representation is easier to process than the compression of a actual, three-dimensional ball by a prosthetic hand. Especially given the experiment task, it may have been easier for the participants to remember certain 'reference levels'. This is supported by the responses in the survey on the strategies for the conditions regarding visual feedback. The simplified visual feedback may have skewed the difficulty between the different conditions, resulting in higher scores than expected for the visual feedback.

3) Combination of Strategies: The strategy of using visual 'reference levels' with the virtual slave may also explain why there is no improvement between visual feedback alone and the combination of visual and haptic feedback. Most participants described their strategy of the visual feedback as mentally coupling a specific shoulder position (and thus a certain strain on the shoulder) to a specific displacement of the virtual slave. When the haptic feedback was added, the shoulder must be displaced higher to achieve the same 'strain' or force level input. Some participants mentioned this discrepancy throwing them off, finding the combined feedback condition more confusing than helpful.

4) Experiment Design: Finally, there are also some limitations to the design of the experiment. The haptic interface was only tested on a small number of able-bodied participants, which is not a fair representation of the target demography. While the statistical analysis still found some significant differences between the means, most of these differences are with respect the 'no feedback' condition. One can question the validity of the model, as the remainder of the error is not normally distributed, but it is hard to draw conclusions with so little data.

As for the execution of the experiment, the participants mentioned being able to feel a 'click' when the device changed between different stiffness levels. This guided them in deciding whether the stiffness had changed with respect to the previous trial. Pre-cautions were made in the design of the experiment interface to avoid this effect, by waiting until the participant has reached a rest position (F_{avg} < 1.5N) before executing the command to change the virtual stiffness. However, this does not account for the cases where the participant quickly moves in and out of the rest position, and could thus be improved. Furthermore, as discussed earlier, the simplified visual slave may not be an accurate representation of the operation of an actual prosthetic hand. Additionally, the experiment currently has no way to assess the cognitive load between the different feedback conditions.

B. Recommendations

Future research into this subject could be improved by concretizing the experiment task. This could be done by replacing the one-dimensional virtual slave with a functional prosthetic device, the addition of a cognitive task and changing the task from stiffness perception to activities of daily living. Alignment of the experiment with day-to-day use of prostheses could provide further insight on the benefit of different feedback conditions. The research should also be performed on a larger group of participants to provide more definite results.

V. Conclusion

This study aimed to identify the added benefit haptic feedback provided by a new interface on the results in a stiffness perception task. Based on a analysis of the identification accuracy, completion time and the number of probes it can be concluded that there was no significant improvement in stiffness perception when using haptic feedback as compared to visual feedback. Qualitatively, participants expressed a slight preference for visual feedback or the combination 'visual + haptic' feedback. Further research, should indicate whether the haptic feedback provides added benefit over visual feedback in more elaborate tasks.

Finally, a novel haptic interface was developed as a part of this study. For those who currently prefer body-powered operation, this system shows a promising alternative that allows for a wireless connection to the prosthesis and lower operation forces. Besides providing haptic feedback, this system also implemented a new way to combine traditional cable-operated input with modern externally powered prosthetic devices. Further research could be also done on the control of prosthetic devices through this haptic interface as compared to control through electromyographic (EMG) signals.

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