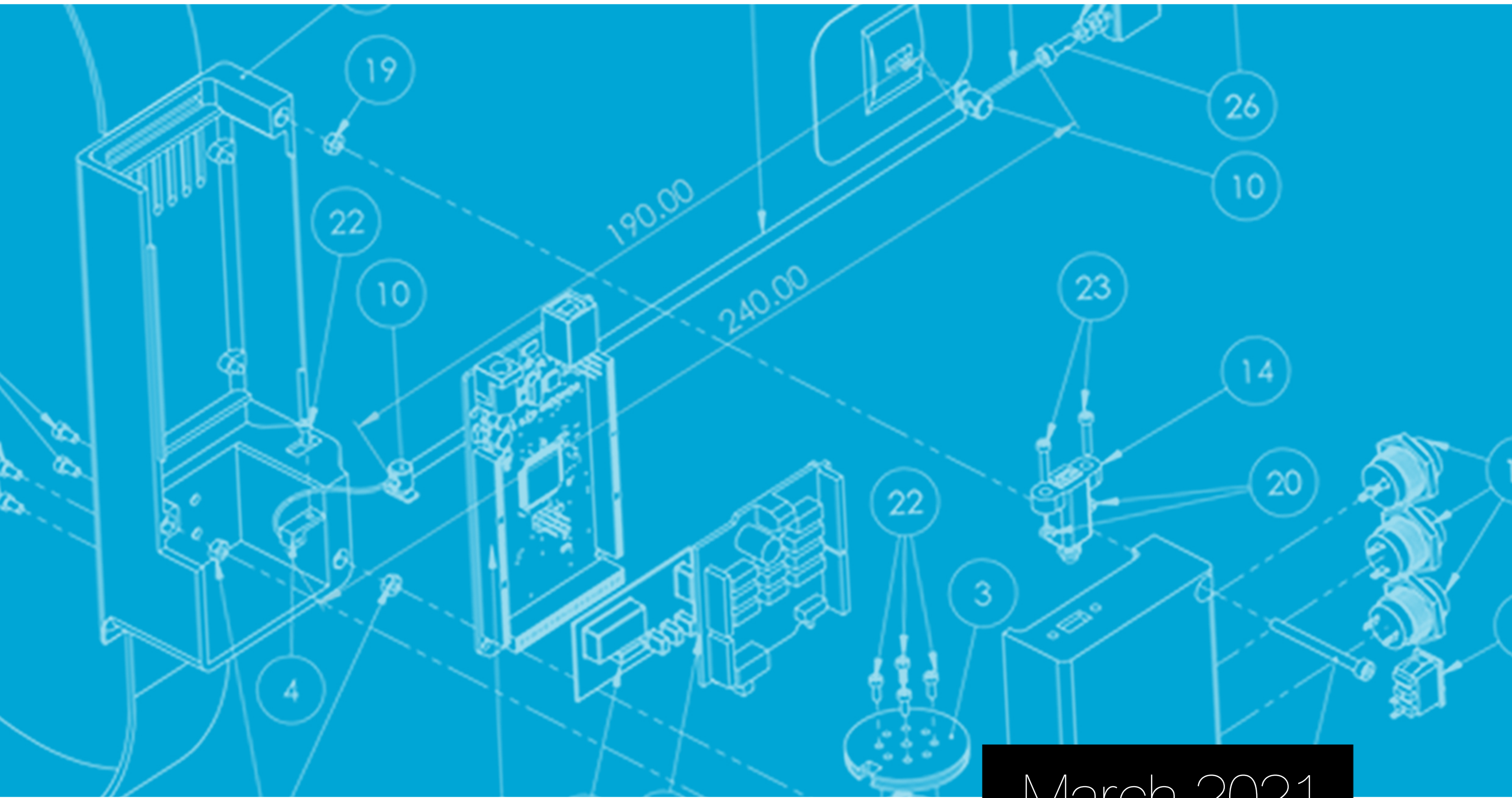
An Empirical Evaluation of Stiffness Perception using a Shoulder-Worn Haptic Interface

G.E.M. Leseman



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

by

G.E.M Leseman

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Preface

I have always been interested in medical technology, so I was excited to be able to contribute to this field with my thesis project. For the past year I worked on the development of a new haptic interface which could sense force commands from the user and provide them with positional feedback. I designed and produced all parts for a functional prototype, after which I developed a digital application to experimentally test the haptic interface. In the experiment I evaluated the ability of the participants to perceive stiffness while using my interface, where I focused especially on the added benefit of the haptic feedback. The results of this experiment can be found in this report.

I would like to thank my parents for their continuous love and support during the course of my studies. I also want to thank and all of my friends and colleagues for their contribution to what have been 8.5 amazing years of student life, but most of all I'd thank 'the Squad' for peer-pressuring me into actually studying, the loving criticism and most importantly the very long study breaks. Thank you all!

G.E.M Leseman
Delft, March 2021

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1

Paper

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

Gailey E. M. Leseman

***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]

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

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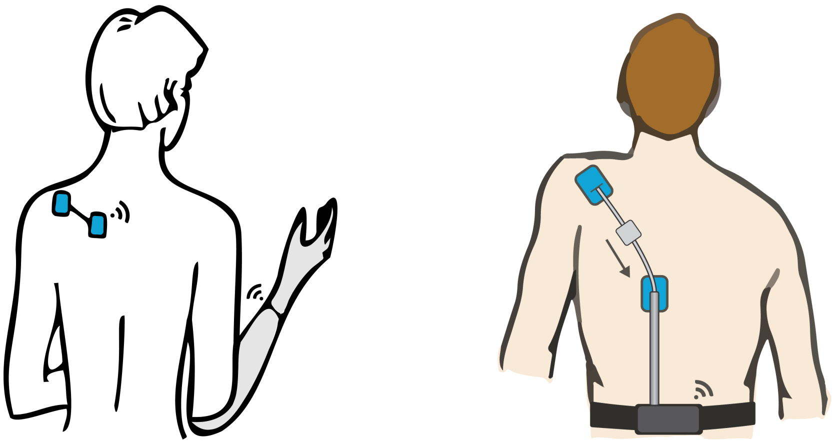


(a) Proposal Vardy *et al.* [4] (b) Haptic Interface

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

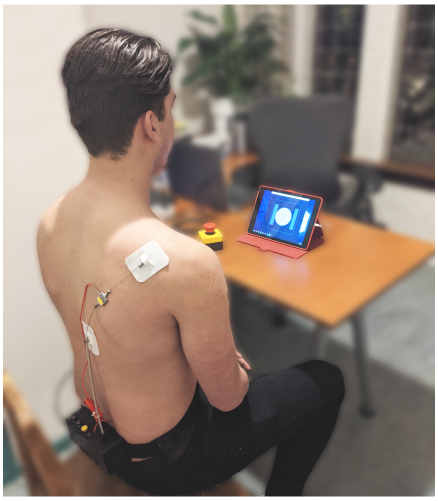


Figure 2. Experimental set-up. The haptic interface is fitted to the participant's back, with the adhesive skin anchors (white rectangles) positioned next to the vertebrae and on the dominant shoulder. The participant is seated in front of a display, providing them with visual feedback during the appropriate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

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).

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.

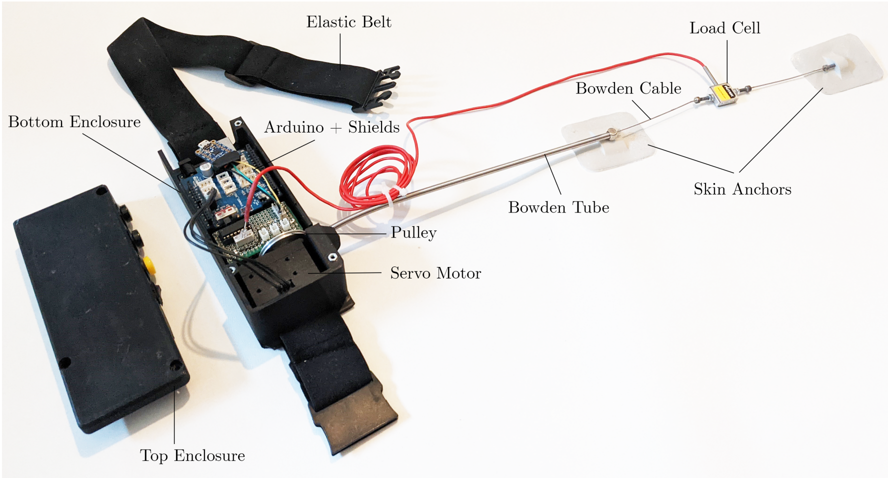


Figure 3. Overview of the components of the Haptic interface. An interrupted Bowden cable runs from the upper skin anchor to the pulley attached to the horn of the servo motor. The second skin anchor is connected to the Bowden tube. A load cell measures the force on the cable. The Arduino handles the 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.

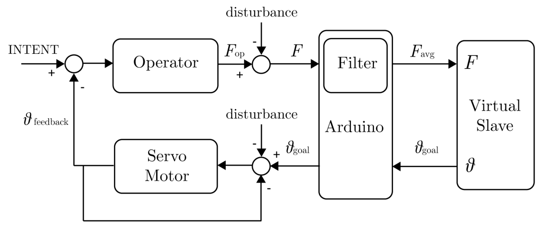


Figure 4. System Architecture of the haptic interface. The human operator forms a input force F_{op} based on their intent and the positional feedback provided by the haptic interface. The measured force F is filtered and the resulting F_{avg} is used as an input for the virtual slave. The virtual slave 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.

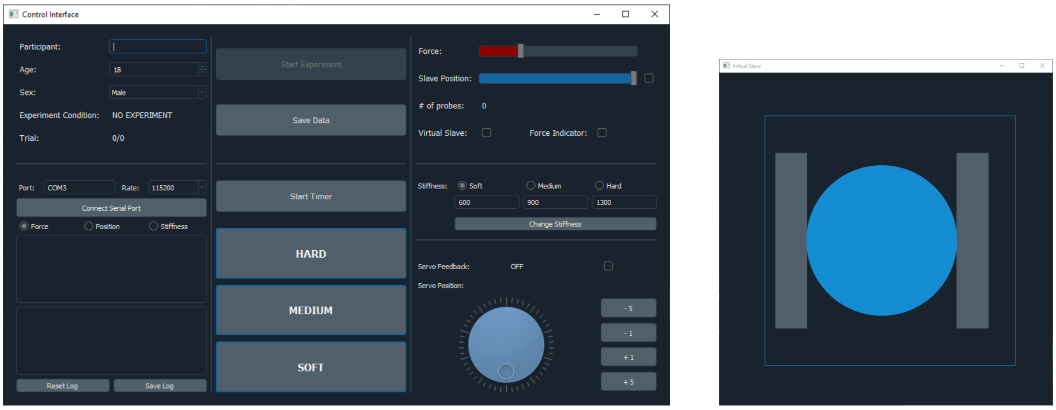
The experiment mimics a voluntary-closing force-controlled prosthetic hand by controlling a virtual slave, as depicted in fig.5b The virtual slave consists of two bars that compress a 'ball' which is modelled as a perfect linear spring with initial length l_0 = 60 mm. The virtual stiffness of the spring 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 ($F_{\text{avg}} < 1.5\text{N}$) 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%,

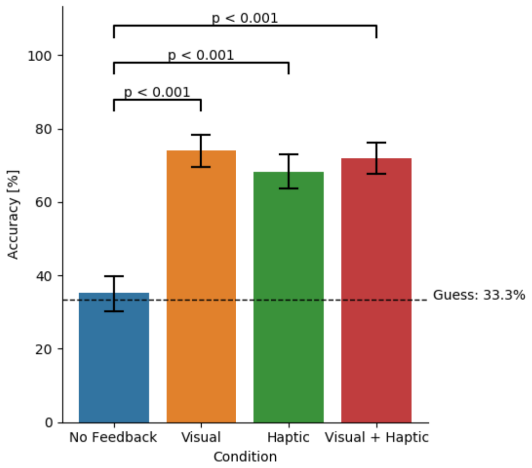


Figure 6. Estimated marginal means for the identification accuracy per condition after correcting for the covariate effects. The error bars represent the standard deviation. A significant effect was found for three pairwise comparisons.

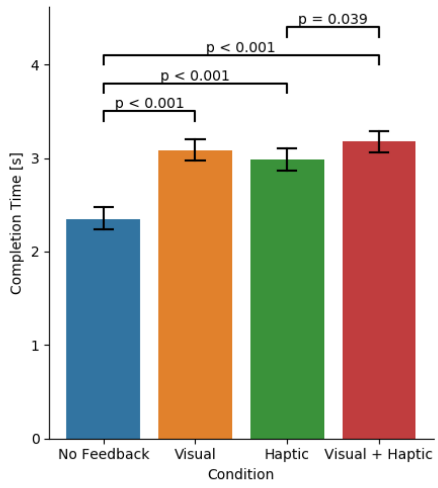


Figure 7. Estimated marginal means for the task completion time per condition after correcting for the covariate effects. The error bars represent the standard deviation. A significant effect was found for four pairwise comparisons.

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.

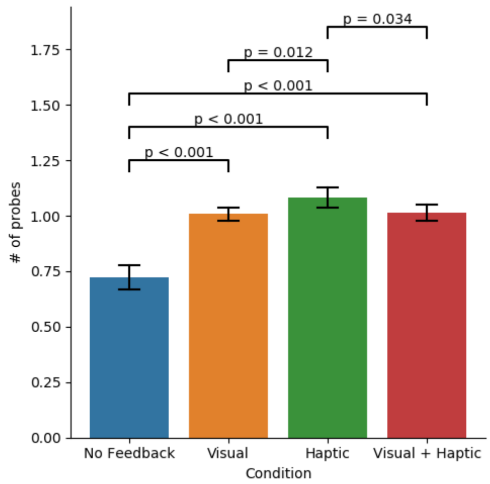


Figure 8. Estimated marginal means for the number of probes per condition after correcting for the covariate effects. The error bars represent the standard deviation. A significant effect was found for five pairwise comparisons.

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 (β = 0.28, SE = 0.024, p < 0.001), haptic feedback (β = 0.36, SE = 0.024, p < 0.001) or both (β = 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 (β = 0.067, SE = 0.024, p = 0.034) or visual feedback alone (β = 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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A

Additional Figures and Tables

A.1. Identification Accuracy

A.1.1. ANOVA Table

Table A.1: Identification Accuracy: Test of Between-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Intercept	Hypothesis	28.891	1	28.891	127.220	0.000	0.293
	Error	69.697	306.904	.227a			
trial_order	Hypothesis	3.481	1	3.481	17.074	0.000	0.011
	Error	317.441	1557	.204b			
trial_set	Hypothesis	0.090	1	0.090	0.443	0.4506	0.000
	Error	317.441	1557	.204b			
condition_order	Hypothesis	0.087	1	0.087	0.429	0.4513	0.000
	Error	317.441	1557	.204b			
condition	Hypothesis	39.774	3	13.258	40.186	0.000	0.818
	Error	8.832	26.769	.330c			
participant	Hypothesis	5.147	9	0.4572	1.733	0.130	0.369
	Error	8.820	26.719	.330d			
condition * participant	Hypothesis	8.884	27	0.329	1.614	0.024	0.027
	Error	317.441	1557	.204b			

a. .063 MS(participant) + .937 MS(Error)
b. MS(Error)
c. 1.007 MS(condition * participant) - .007 MS(Error)
d. 1.009 MS(condition * participant) - .009 MS(Error)

A.1.2. Pairwise comparisons

Table A.2: Identification Accuracy: pairwise comparison of the estimated marginal means

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
Haptic	No Feedback	.329*	0.032	0.000	0.266	0.392
	Visual	-0.058	0.032	0.069	-0.121	0.005
	Visual + Haptic	-0.039	0.032	0.226	-0.101	0.024
No Feedback	Haptic	-.329*	0.032	0.000	-0.392	-0.266
	Visual	-.387*	0.032	0.000	-0.450	-0.324
	Visual + Haptic	-.367*	0.032	0.000	-0.430	-0.305
Visual	Haptic	0.058	0.032	0.069	-0.005	0.121
	No Feedback	.387*	0.032	0.000	0.324	0.450
	Visual + Haptic	0.019	0.032	0.4544	-0.043	0.082
Visual + Haptic	Haptic	0.039	0.032	0.226	-0.024	0.101
	No Feedback	.367*	0.032	0.000	0.305	0.430
	Visual	-0.019	0.032	0.4544	-0.082	0.043

A.1.3. Covariate Effects

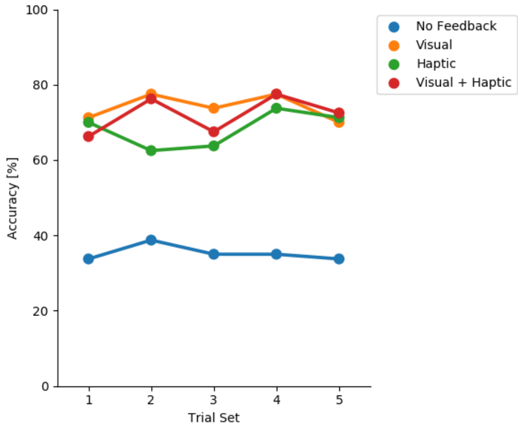


Figure A.1: Mean identification accuracy per condition for each of the five sets of conditions in the experiment.

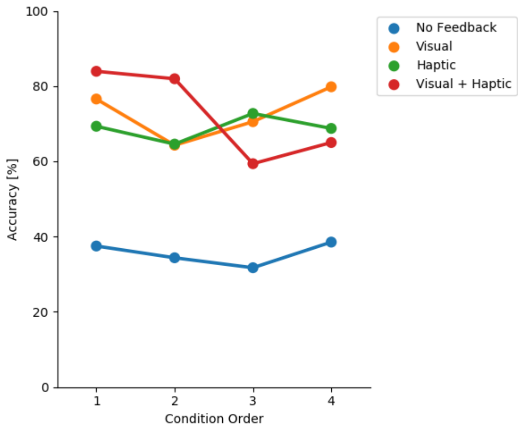


Figure A.2: Mean identification accuracy per condition for the order in which the conditions were presented within each set.

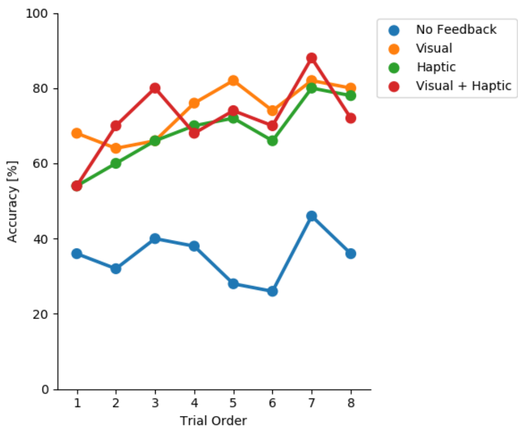


Figure A.3: Mean identification accuracy per condition for the order in which the trials were presented within each condition.

A.2. Completion Time

A.2.1. ANOVA Table

Table A.3: Completion Time: Test of Between-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Intercept	Hypothesis	1250.144	1	1250.144	283.823	0.000	0.953
	Error	61.414	13.943	4.405a			
trial_order	Hypothesis	17.152	1	17.152	18.547	0.000	0.012
	Error	1439.943	1557	.925b			
trial_set	Hypothesis	105.639	1	105.639	114.226	0.000	0.068
	Error	1439.943	1557	.925b			
condition_order	Hypothesis	3.948	1	3.948	4.269	0.039	0.003
	Error	1439.943	1557	.925b			
condition	Hypothesis	168.060	3	56.020	7.228	0.001	0.446
	Error	208.918	26.955	7.751c			
participant	Hypothesis	504.849	9	56.094	7.228	0.000	0.707
	Error	209.122	26.945	7.761d			
condition * participant	Hypothesis	207.989	27	7.703	8.330	0.000	0.126
	Error	1439.943	1557	.925b			

a. .063 MS(participant) + .937 MS(Error)
b. MS(Error)
c. 1.007 MS(condition * participant) - .007 MS(Error)
d. 1.009 MS(condition * participant) - .009 MS(Error)

A.2.2. Pairwise comparisons

Table A.4: Completion Time: pairwise comparison of the estimated marginal means

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
Haptic	No Feedback	.639*	0.068	0.000	0.459	0.818
	Visual	-0.098	0.068	0.890	-0.278	0.081
	Visual + Haptic	-.185*	0.068	0.039	-0.365	-0.006
No Feedback	Haptic	-.639*	0.068	0.000	-0.818	-0.459
	Visual	-.737*	0.068	0.000	-0.917	-0.4557
	Visual + Haptic	-.824*	0.068	0.000	-1.004	-0.4544
Visual	Haptic	0.098	0.068	0.890	-0.081	0.278
	No Feedback	.737*	0.068	0.000	0.4557	0.917
	Visual + Haptic	-0.087	0.068	1.000	-0.267	0.093
Visual + Haptic	Haptic	.185*	0.068	0.039	0.006	0.365
	No Feedback	.824*	0.068	0.000	0.4544	1.004
	Visual	0.087	0.068	1.000	-0.093	0.267

A.2.3. Covariate Effects

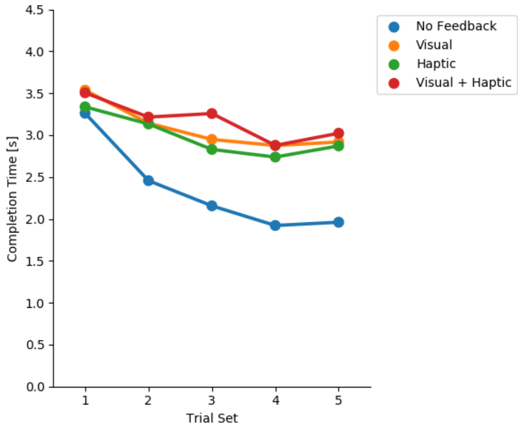


Figure A.4: Mean completion time per condition for each of the five sets of conditions in the experiment.

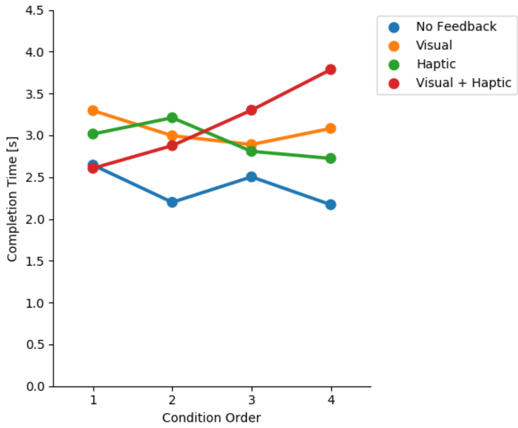


Figure A.5: Mean completion time per condition for the order in which the conditions were presented within each set.

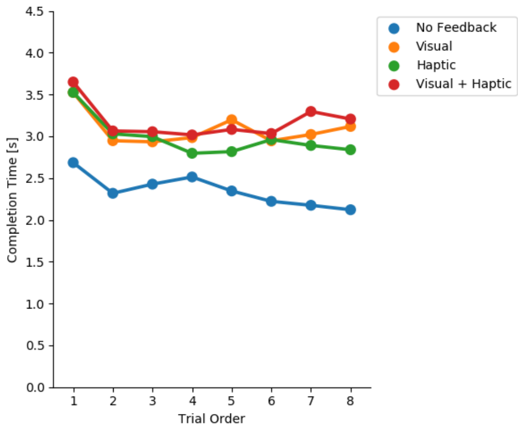


Figure A.6: Mean completion time per condition for the order in the trials were presented within each condition.

A.3. Number of Probes

A.3.1. ANOVA Table

Table A.5: Number of Probes: Test of Between-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Intercept	Hypothesis	152.396	1	152.396	422.835	0.000	0.958
	Error	6.648	18.445	.360a			
trial_order	Hypothesis	0.803	1	0.803	6.915	0.009	0.004
	Error	180.796	1557	.116b			
trial_set	Hypothesis	10.125	1	10.125	87.196	0.000	0.053
	Error	180.796	1557	.116b			
condition_order	Hypothesis	0.877	1	0.877	7.556	0.006	0.005
	Error	180.796	1557	.116b			
condition	Hypothesis	30.414	3	10.138	4.541	0.011	0.336
	Error	60.232	26.980	2.232c			
participant	Hypothesis	35.903	9	3.989	1.784	0.118	0.373
	Error	60.309	26.976	2.236d			
condition * participant	Hypothesis	59.880	27	2.218	19.099	0.000	0.249
	Error	180.796	1557	.116b			

a. .063 MS(participant) + .937 MS(Error)
b. MS(Error)
c. 1.007 MS(condition * participant) - .007 MS(Error)
d. 1.009 MS(condition * participant) - .009 MS(Error)

A.3.2. Pairwise comparisons

Table A.6: Number of probes: pairwise comparison of the estimated marginal means

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
Haptic	No Feedback	.359*	0.024	0.000	0.295	0.422
	Visual	.074*	0.0r24	0.012	0.011	0.138
	Visual + Haptic	.067*	0.024	0.034	0.003	0.131
No Feedback	Haptic	-.359*	0.024	0.000	-0.422	-0.295
	Visual	-.284*	0.024	0.000	-0.348	-0.221
	Visual + Haptic	-.292*	0.024	0.000	-0.356	-0.228
Visual	Haptic	-.074*	0.024	0.012	-0.138	-0.011
	No Feedback	.284*	0.024	0.000	0.221	0.348
	Visual + Haptic	-0.008	0.024	1.000	-0.071	0.056
Visual + Haptic	Haptic	-.067*	0.024	0.034	-0.131	-0.003
	No Feedback	.292*	0.024	0.000	0.228	0.356
	Visual	0.008	0.024	1.000	-0.056	0.071

A.3.3. Covariate Effects

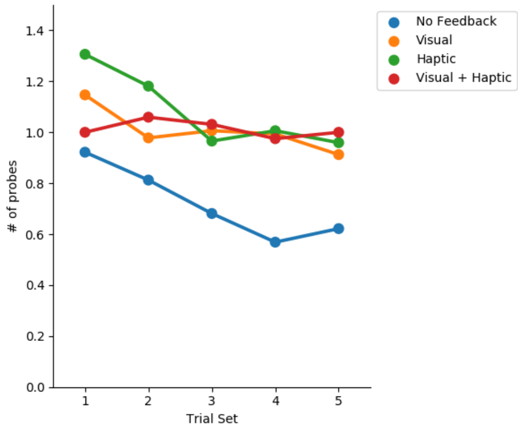


Figure A.7: Mean number of probes per condition for each of the five sets of conditions in the experiment.

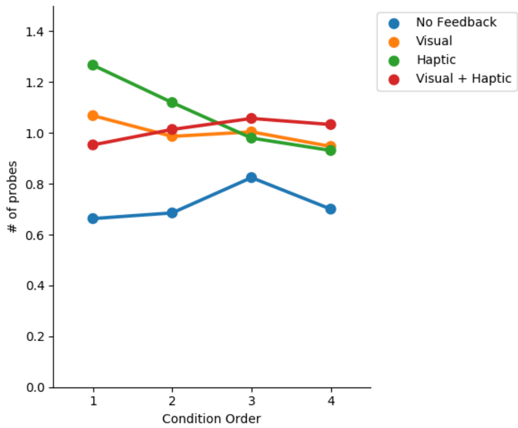


Figure A.8: Mean number of probes per condition for the order in which the conditions were presented within each set.

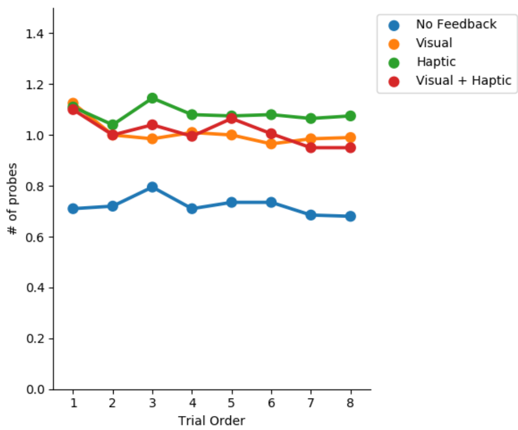


Figure A.9: Mean number of probes per condition for the order in the trials were presented within each condition.

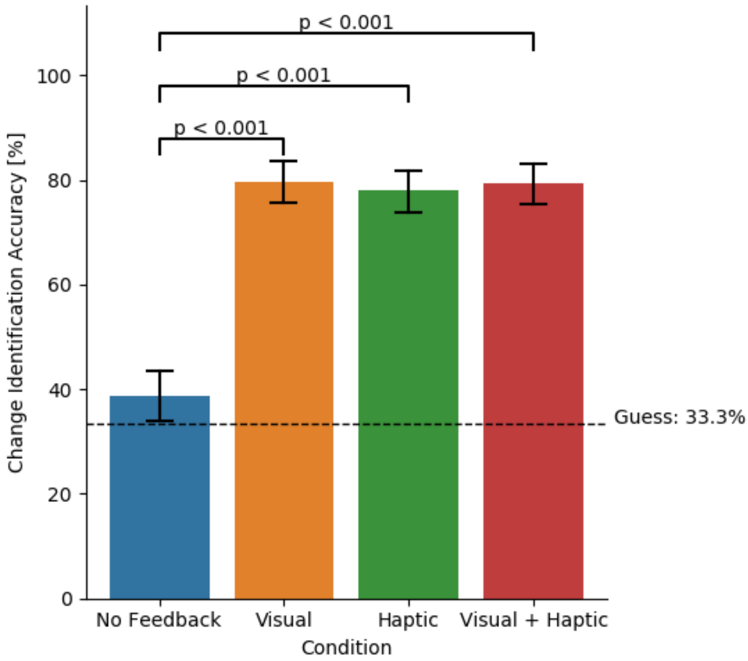


Figure A.10: Change Identification accuracy per condition.

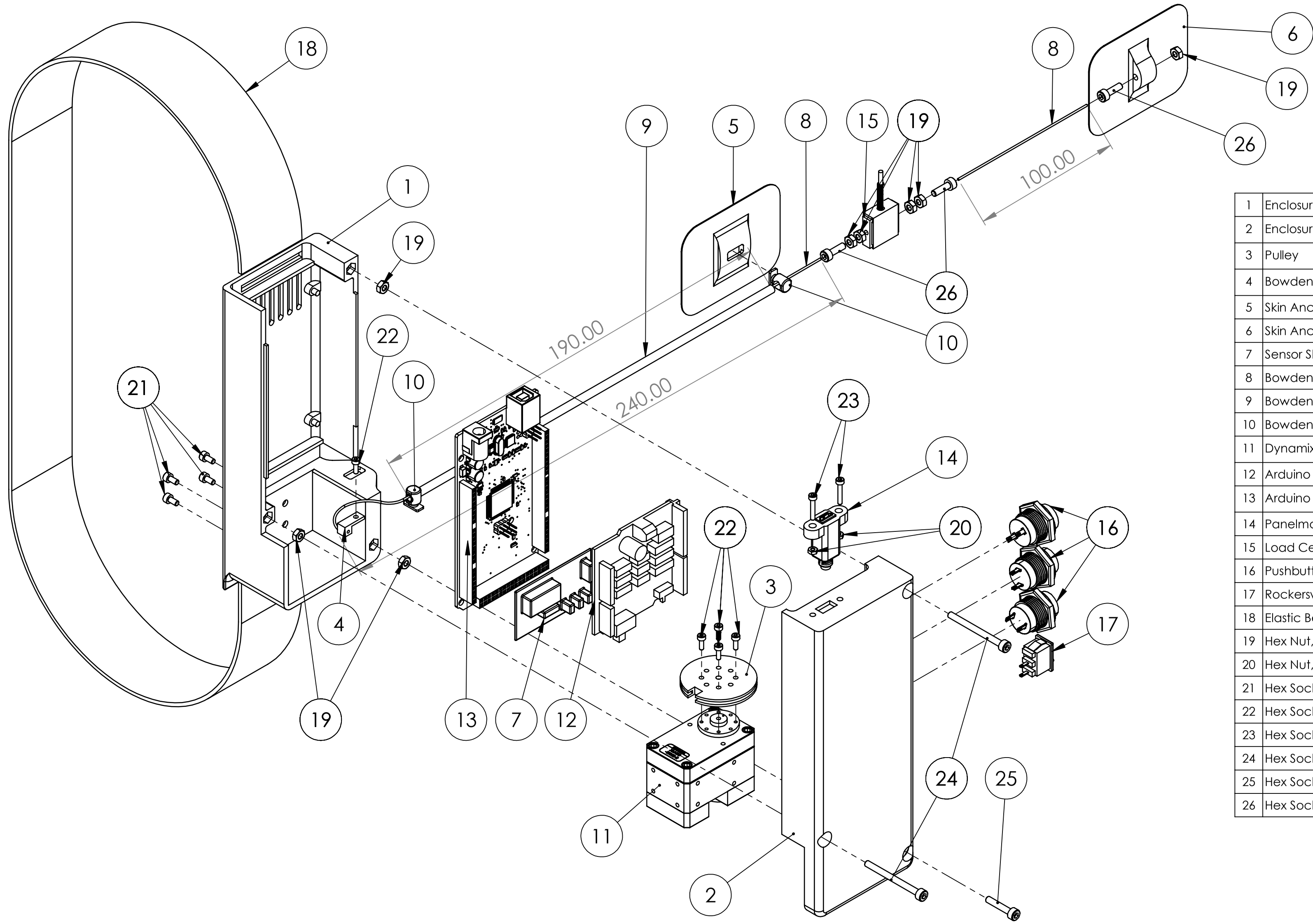
A.3.4. Alternative Analyses

Change Identification Accuracy

An additional analysis was done on the participants' capability to detect a change in stiffness rather that the level. There are three possible configurations ('equal', 'harder', 'softer'). An example: If the participant categorised a previous trial as 'hard', both 'medium' and 'soft' are logged as 'softer'. Similarly, if the participant categorised a previous trial as 'soft', both 'medium and 'hard' are logged as harder. The results of this analysis are depicted in fig. A.10

B

Technical Drawings



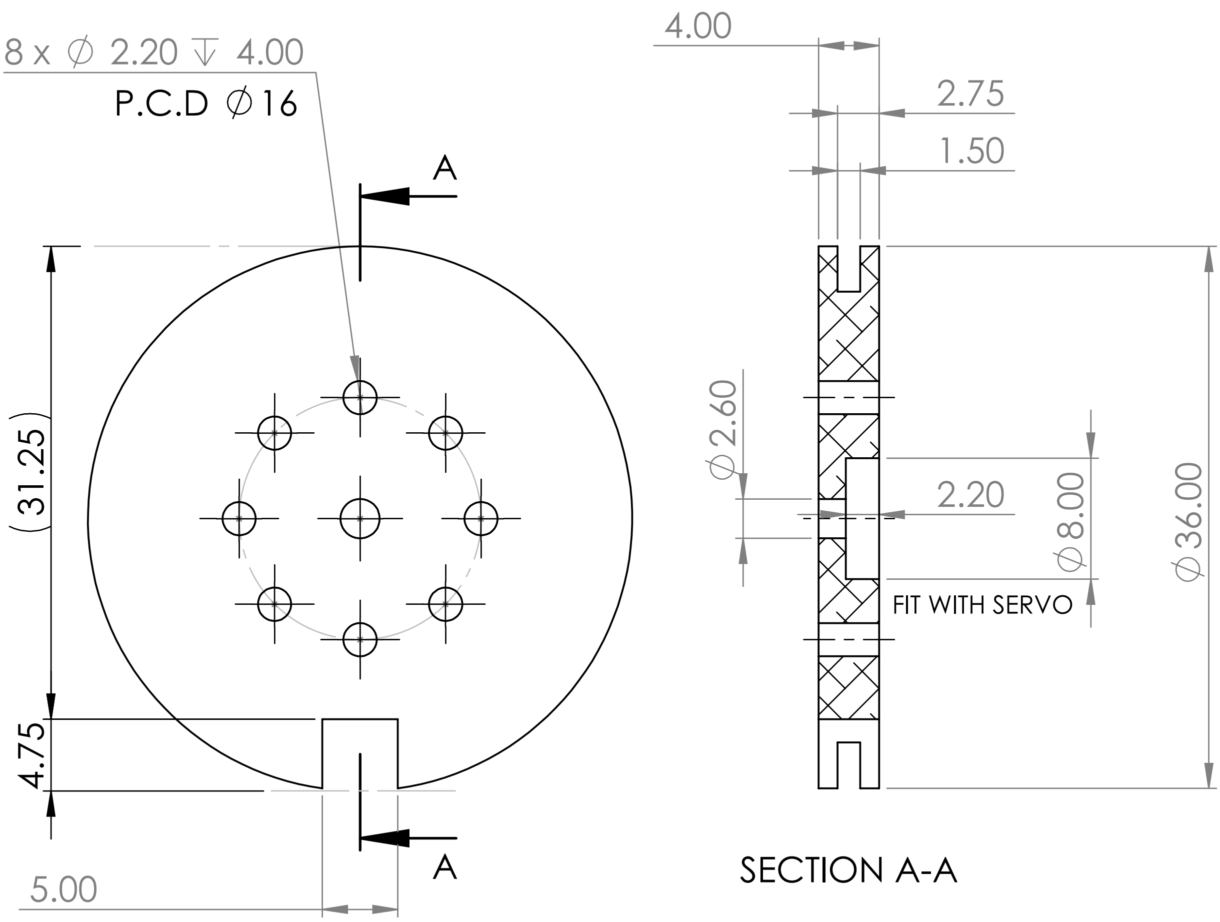
1	Enclosure Bottom	1	Custom
2	Enclosure Top	1	Custom
3	Pulley	1	Custom
4	Bowden Endstop	1	Custom
5	Skin Anchor Shoulder	1	Custom
6	Skin Anchor Back	1	Custom
7	Sensor Shield (Burr-Brown INA125)	1	Custom
8	Bowden Cable	2	BioRobotics Lab
9	Bowden Tube	1	BioRobotics Lab
10	Bowden Connector	2	BioRobotics Lab
11	Dynamixel XM430-W350-R	1	Robotis
12	Arduino Shield	1	Robotis
13	Arduino Mega2560 Rev3	1	Arduino
14	Panelmount USB 3258	1	Adafruit
15	Load Cell LSB200	1	Futek
16	Pushbutton R13-507	3	Generic
17	Rockerswitch KCD11	1	Generic
18	Elastic Belt	1	Generic
19	Hex Nut, M3 x 0.5	8	Generic
20	Hex Nut, M2 x 0.4	2	Generic
21	Hex Socket Head M2.5x0.45x5	4	Generic
22	Hex Socket Head M2x0.4x6	5	Generic
23	Hex Socket Head M2x0.4x12	2	Generic
24	Hex Socket Head M3x0.5x35	2	Generic
25	Hex Socket Head M3x0.5x16	1	Generic
26	Hex Socket Head M3x0.5x10	3	Generic

ASSEMBLY DRAWING		
	NAME	DATE
DRAWN	Gailey Leseman	08/02/2021
REV.	A	
APPV'D		

TITLE: Haptic Interface

DWG NO. A-001 A3

SCALE:1:5 SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

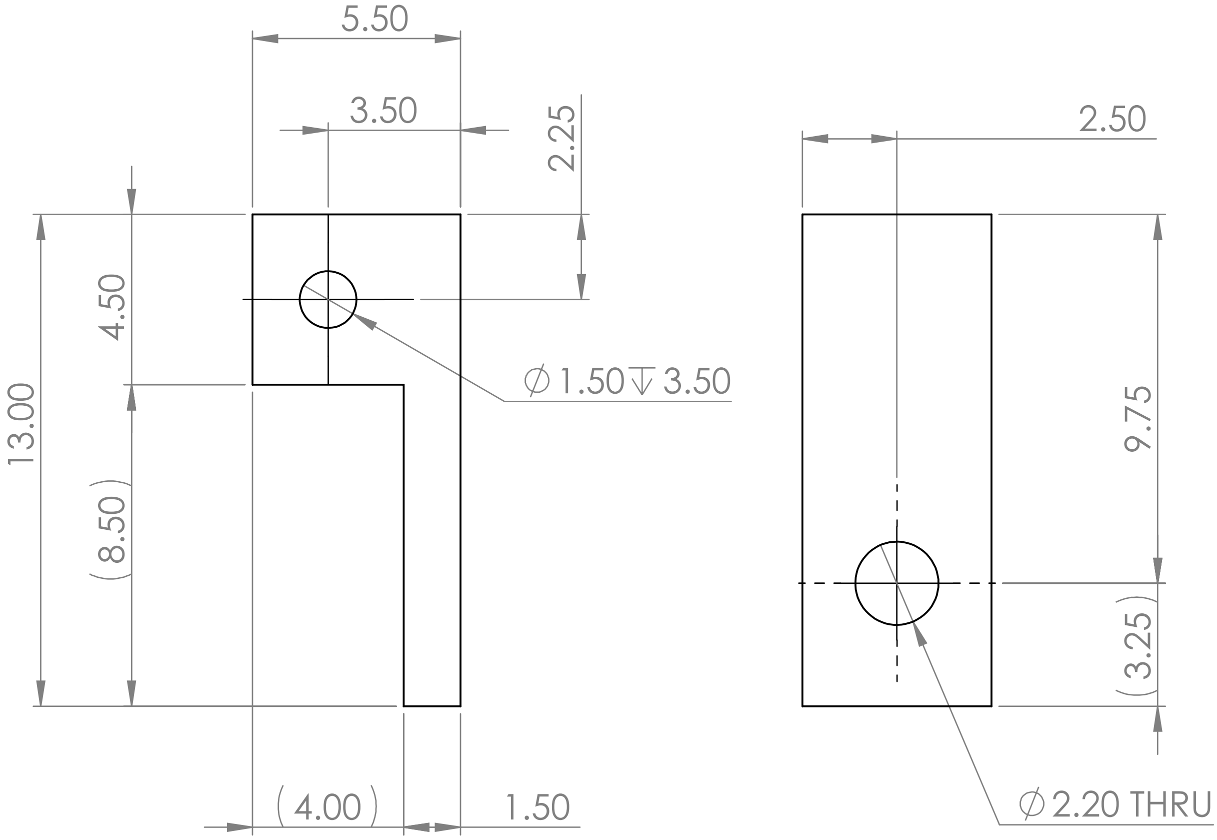
001-Pulley

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

002-Endstop

A4

WEIGHT:

SCALE:5:1

SHEET 1 OF 1

C

HREC Application

Delft University of Technology
ETHICS REVIEW CHECKLIST FOR HUMAN RESEARCH
(Version 18.06.2020)

This checklist should be completed for every research study that involves human participants and should be submitted before potential participants are approached to take part in your research study. This also applies for students doing their Master-thesis.

In this checklist we will ask for additional information if need be. Please attach this as an Annex to the application. The data steward of your faculty can help you with any issues related to the protection of personal data. Please note that research related to medical questions/health may require special attention. See also the website of the CCMO.

Please upload the documents (go to this page for instructions).

Thank you and please check our website for guidelines, forms, best practices, meeting dates of the HREC, etc.

I. Basic Data

Project title:	Haptic Interface with Proprioceptive Feedback for Prosthesis Control
Name(s) of researcher(s):	Gailey Leseman
Research period (planning)	September 2020 – December 2020
E-mail contact person	g.e.m.leseman@student.tudelft.nl
Faculty/Dept.	Mechanical, Maritime and Materials Engineering BioMechanical Engineering
Position researcher(s):[1]	student
Name of supervisor (if applicable):	Dick Plettenburg
Role of supervisor (if applicable):	Assistant Professor

II. A) Summary Research

A newly developed haptic interface will be attached to the participant using two 'skin anchors' on the participant's shoulder and back. With this interface the participant will be able control a virtual prosthesis. In the experiment, the participant will receive haptic feedback through the interface. The interface will be tested on 3 - 10 (subject to COVID-19 regulations) participants with varying conditions (i.e. stiffness, feedback on/off) to test the effect of the feedback with respect to identification accuracy and completion times.

B) Risk assessment & risk management

The operating forces during the experiment are a fraction of the maximum exertable forces of the human shoulder. All control of the servo-motor is done without the laptop connection to prevent errors via the serial communication line. Software checks are in place to check for unexpected stiffness values, large displacements or large currents. Nevertheless, as an additional safety measure a switch can be pressed to cut all power from the haptic interface. The skin anchors will be attached with a dermatologically safe adhesive tape.

COVID-19

The consent form for the participant includes a questionnaire on COVID-19 symptoms. When either the participant or the researcher show any symptoms, the experiment is canceled or rescheduled. The research location (F-1-380[2]) will be cleaned with disinfectant after every participant and when entering the location the participant is asked to disinfect his or her hands. Both the researcher and the participant will wear mouth masks at all times. When applying the skin anchors to the participant's back the researcher will wear disposable gloves.

---

[1] For example: student, PhD, post-doc

[2] Alternatively the research location can be moved off-campus to reduce campus traffic.

III. Checklist

Question	Yes	No
1. Does the study involve participants who are particularly vulnerable or unable to give informed consent? (e.g., children, people with learning difficulties, patients, people receiving counselling, people living in care or nursing homes, people recruited through self-help groups).		x
2. Are the participants, outside the context of the research, in a dependent or subordinate position to the investigator (such as own children or own students)?[3]		x
3. Will it be necessary for participants to take part in the study without their knowledge and consent at the time? (e.g., covert observation of people in non-public places).		x
4. Will the study involve actively deceiving the participants? (For example, will participants be deliberately falsely informed, will information be withheld from them or will they be misled in such a way that they are likely to object or show unease when debriefed about the study).		x
5. Sensitive personal data • Will the study involve discussion or collection of personal sensitive data (e.g., financial data, location data, data relating to children or other vulnerable groups)? Definitions of sensitive personal data, and special cases thereof are provided here.		X
6. Will drugs, placebos, or other substances (e.g., drinks, foods, food or drink constituents, dietary supplements) be administered to the study participants?		x
7. Will blood or tissue samples be obtained from participants?		x
8. Is pain or more than mild discomfort likely to result from the study?		x
9. Does the study risk causing psychological stress or anxiety or other harm or negative consequences beyond that normally encountered by the participants in their life outside research?		x
10. Will financial inducement (other than reasonable expenses and compensation for time) be offered to participants?		x
Important: if you answered 'yes' to any of the questions mentioned above, please submit a full application to HREC (see: website for forms or examples).		
11. Will the experiment collect and store videos, pictures, or other identifiable data of human subjects?[4] .	x	
12. Will the experiment involve the use of devices that are not 'CE' certified? *Only, if 'yes': continue with the following questions:*	x	

[3] **Important note concerning questions 1 and 2.** Some intended studies involve research subjects who are particularly vulnerable or unable to give informed consent .Research involving participants who are in a dependent or unequal relationship with the researcher or research supervisor (e.g., the researcher's or research supervisor's students or staff) may also be regarded as a vulnerable group . If your study involves such participants, it is essential that you safeguard against possible adverse consequences of this situation (e.g., allowing a student's failure to complete their participation to your satisfaction to affect your evaluation of their coursework). This can be achieved by ensuring that participants remain anonymous to the individuals concerned (e.g., you do not seek names of students taking part in your study). If such safeguards are in place, or the research does not involve other potentially vulnerable groups or individuals unable to give informed consent, it is appropriate to check the NO box for questions 1 and 2. Please describe corresponding safeguards in the summary field.

[4] Note: you have to ensure that collected data is safeguarded physically and will not be accessible to anyone outside the study. Furthermore, the data has to be de-identified if possible and has to be destroyed after a scientifically appropriate period of time. Also ask explicitly for consent if anonymised data will be published as open data.

Question	Yes	No
➢ Was the device built in-house?	x	
➢ Was it inspected by a safety expert at TU Delft? (*Please provide device report, see: HREC website*)	x	
➢ If it was not built in house and not CE-certified, was it inspected by some other, qualified authority in safety and approved? *(Please provide records of the inspection).*		x
13. Has or will this research be submitted to a research ethics committee other than this one? (*if so, please provide details and a copy of the approval or submission).*		x

IV. Enclosures

Please, tick the checkboxes for submitted enclosures.

Required enclosures

- A Data Management Plan reviewed by a data-steward.

Conditionally required enclosures

- An Informed Consent Form (with Information Letter)
- A Device Report

V. Signature(s

Signature(s) of researcher(s): Gailey E.M. Leseman

Date: 06/11/20

Signature (or upload consent by mail) research supervisor (if applicable)

Date: 2020 11 10

Date 20.10.2020
Contact person G.E.M. Leseman
Telephone +31 (0)6 4632 99 15
E-mail G.E.M.Leseman@student.tudelft.nl
Subject MSc. Research Haptic Interface

TUDelft

Faculty of Mechanical,
Maritime and Materials
Engineering (3mE)

Department:
BioMechanical
Engineering

Group:
Delft Institute of
Prosthetics and
Orthotics (DIPO)

PARTICIPANT INFORMATION LETTER
(Version 20.10.2020)

Haptic Interface with Proprioceptive Feedback for Prosthesis Control

October 20th, 2020

Dear Sir / Madam,

You have been asked to participate in a study on stiffness discrimination using a haptic interface with proprioceptive feedback. In this letter you will find information about the research. If you have any questions, please contact the persons listed at the bottom of this letter.

Background of the research

Many patients with an upper limb deficiency choose not to wear a prosthetic device. Many of them would reconsider prosthetic use if technological improvements were made, which makes this an interesting field of research. The current designs for active upper-limb prosthetics can roughly be divided into two main groups, each with its own (dis)advantages. Body-powered prostheses, which utilize a harnessing system to capture body movements, provide intuitive control but these prostheses are uncomfortable and require high operating forces. Myo-electric prostheses use an external power source, but the control method using electromyographic (EMG) signals is unintuitive and leads to high mental loads. Because of the lack of proprioceptive feedback it is also notoriously hard to adjust your grip strength properly using myo-electric prostheses.

In this research we look into the development of a hybrid system that combines the best of both worlds. The device will make use of 'skin anchors' instead of a shoulder harness, removing a common source of discomfort. Prosthesis movement is still closely coupled to body movements, providing proprioceptive feedback and thus keeping the intuitive control method of a body-powered prosthesis. By using an externally powered controller the control forces can be kept a comfortable range.

Purpose of the research

An initial prototype has been developed to provide proprioceptive feedback to the user. With proper feedback the user would be able to adjust his/her grip force more intuitively. To evaluate the effect of the proprioceptive feedback of the new prototype a stiffness discrimination experiment has been designed. Better stiffness discrimination may lead to more intuitive control and options to further develop this type of hybrid prosthesis systems.

Risks of participating
The participants may experience mild physical discomfort when operating the device.

What does participation in the research involve?
Two 'skin anchors' are attached directly to the participant's skin using skin-friendly adhesive tape. The rest of the interface is worn at hip height using a elastic belt. Using a force sensor the interface can be used to control a device. Information is fed back to the participant using a small servo motor.

The participant is asked to use the haptic interface to control a virtual slave. The virtual slave will squeeze into a ball with a variating stiffness. Depending on the experiment condition, the participant will receive visual and/or proprioceptive feedback, or no feedback at all. The participant is then asked to determine whether the ball is 'hard', 'medium' or 'soft'. These answers are logged by the researcher in the digital experiment interface. Other than the stiffness identification, the interface also logs the elapsed time until an answer has been given as well as the number of probes by the participant. The total experiment will take up to 1 hour to complete.

Procedures for withdrawal from the study
Your cooperation in this research is voluntary. If you give your consent to this research, you have the freedom at all times (also during the experiment) to come back on this decision. You do not have to give an explanation for your decision. You can do this by contacting Gailey Leseman via g.e.m.leseman@student.tudelft.nl

Confidentiality of data
This investigation requires that the following personal data are collected and used:

Name, e-mail address, age, sex

To safeguard and maintain confidentiality of your personal information, necessary security steps will be taken. Your data will be stored in a secure storage environment at TU Delft. All data will be processed confidentially and stored using a participant number only. Data will only be accessible for the DIPO research group.

Your name will be linked not be linked to the participant number. The informed consent form will be scanned and stored in a separate and secure location. This way all your details remain confidential.

The results will be published in possible future scientific publications.

Contact Information
If you have any complaints regarding confidentiality of your data, you can contact the TU Delft Data Protection Officer (Erik van Leeuwen) via privacy-tud@tudelft.nl.

On behalf of the researcher(s), thank you in advance for your possible cooperation.

Gailey Leseman
G.E.M.Leseman@student.tudelft.nl

Date 20.10.2020
Contact person G.E.M. Leseman
Telephone +31 (0)6 4632 99 15
E-mail G.E.M.Leseman@student.tudelft.nl
Subject MSc. Research Haptic Interface

Faculty of Mechanical,
Maritime and Materials
Engineering (3mE)

Department:
BioMechanical Engineering

Group:
Delft Institute of Prosthetics
and Orthotics (DIPO)

INFORMED CONSENT FORM
(Version 20.10.2020)

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study information dated 20/10/2020, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
I understand that taking part in the study involves a series of tests on stiffness discrimination using visual and haptic feedback. I understand the experiment involves taping two 'skin anchors' to my shoulder and back. During the experiment my verbal cues will be recorded by the researcher in a digital log.	☐	☐
Risks associated with participating in the study I understand that taking part in the study involves the following risks: mild physical discomfort	☐	☐
Use of the information in the study		
I understand that information I provide will be used for the MSc thesis report of G.E.M. Leseman, as well as possible future scientific publications.	☐	☐
I understand that personal information collected about me, such as my name, contact details, sex and age, will not be shared beyond the study team.	☐	☐

Future use and reuse of the information by others

I give permission for the (digitalized) verbal answers that I provide to be archived in the TU Delft Gitlab repository so it can be used for future research and learning. These cues will be linked to the timing of the cues as well as the participant's age and sex. I understand that the data collected is anonymised and cannot be traced to my consent form.	☐	☐
I give permission to file my informed consent form on the internal TU Delft network storage, in case future researchers wish to contact me again.	☐	☐

COVID-19:

Did you have one or more of these complaints in the past 24 hours?		
a cough	☐	☐
a nose cold	☐	☐
a fever (≥ 38 °C)	☐	☐
shortness of breath	☐	☐
Do you currently have a roommate with a fever and/or shortness of breath?	☐	☐
Did you have the COVID-19 virus and has it been diagnosed in the past 7 days?	☐	☐
Do you have a roommate/family member with the COVID-19 virus and have you had contact with him/her in the past 14 days while he/she still had complaints?	☐	☐
Are you in quarantine because you had direct contact with someone who has been diagnosed with the COVID-19 virus?	☐	☐

Signatures

________________________	__________________	________
Name of Participant	*Signature*	*Date*

Contact:

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Gailey Leseman	__________________	_______
Researcher name	*Signature*	*Date*

Study contact details for further information:
G.E.M.Leseman@student.tudelft.nl

Date	20.10.2020
Contact person	G.E.M. Leseman
Telephone	+31 (0)6 4632 99 15
E-mail	G.E.M.Leseman@student.tudelft.nl
Subject	MSc. Research Haptic Interface

Faculty of Mechanical, Maritime and Materials Engineering (3mE)

Department:
BioMechanical Engineering

Group:
Delft Institute of Prosthetics and Orthotics (DIPO)

DATA MANAGEMENT PLAN

(Version 20.10.2020)

I. BASIC DATA

Project title:	Haptic Interface with Proprioceptive Feedback for Prosthesis Control
Name(s) of researcher(s):	Gailey Leseman
E-mail contact person	g.e.m.leseman@student.tudelft.nl
Faculty/Dept.	Mechanical, Maritime and Materials Engineering BioMechanical Engineering
Position researcher(s):	student
Name of supervisor:	Dick Plettenburg
Role of supervisor:	Assistant Professor
Last modified:	October 20th, 2020
Data Steward:	Yasemin Türkyilmaz-van der Velden
Consulted on:	August 19th, 2020

II. GENERAL TU DELFT DATA MANAGEMENT QUESTIONS

1) Is TU Delft the lead institution for this project?

Yes, TU Delft is the only institution involved.

2) If you leave TU Delft (or are unavailable), who is going to be responsible for the data resulting from this project?

Name	Prof. dr. F.C.T van der Helm
Function:	Professor at Faculty of Mechanical, Maritime and Materials Engineering, BioMechanical Engineering Department | Biomechatronics & Human-Machine Control
E-mail Address:	f.c.t.vanderhelm@tudelft.nl

3) Where will the data (and code, if applicable) be stored and backed-up during the project lifetime?

TU Delft GitLab repository: https://gitlab.tudelft.nl/gemleseman/msc-project-haptic-interface

4) How much data storage will you require during the project lifetime?

< 250 GB

5) What data will be shared in a research data repository?

N/A. This research is conducted as a part of the MSc degree and is not part of a larger research group and therefore it is not deemed necessary to share the data in a research data repository.

6) How much of your data will be shared in a research data repository?

N/A. See question 5.

7) How will you share your research data (and code)?

N/A. See question 5.

8) Does your research involve human subjects?

Yes.

9) Will you process any personal data? List all that apply.

- Gender
- Age
- Name
- Email address

III. TU DELFT QUESTIONS ABOUT MANAGEMENT OF PERSONAL RESEARCH DATA

1. Please detail what type of personal data you will collect, for what purpose, how you will store and protect that data, and who has access to the data.

Type of Data	How will the data be collected?	Purpose of Processing	Storage Location	Who will have access to the data
Gender	Digital Experiment Interface (see fig. 1)	Document the research demographic	TU Delft GitLab repository	DIPO Research Group
Age	Digital Experiment Interface (see fig. 1)	Document the research demographic	TU Delft GitLab repository	As above
Name	Signed Form (digital scan)	Ask consent	Internal Storage (M-)Drive TU Delft	As above
E-Mail address	Signed Form (digital scan)	Ask consent, store contact details	Internal Storage (M-)Drive TU Delft	As above

2. Will you be sharing personal data with individuals/organisations outside of the EEA (European Economic Area)?
No.

3. What is the legal ground for personal data processing?
Informed consent. All participants will sign an informed consent form, this form and the corresponding information letter are included in the HREC application.

4. Will the personal data be shared with others after the end of the research project, and if so, how and for what purpose?
No.

5. Does the processing of the personal data results in a high risk to the data subjects?
No.

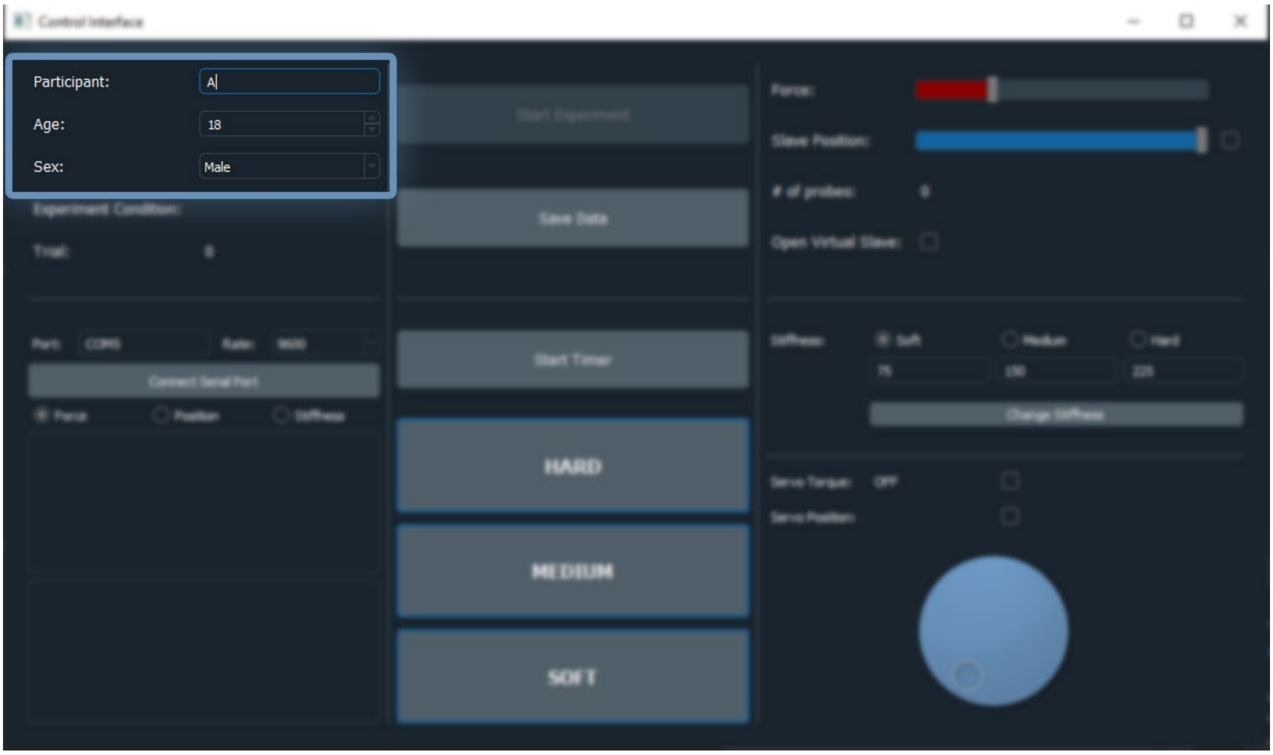


Figure 1: Digital Experiment Interface.

Each participant is asked to disclose their age (in years) and their sex (male/female/other) before the experiment starts. This data is entered into the interface by the researcher. The age and sex are connected to the other recorded data such as identification accuracy and completion times. The participants are identified with letters (A, B, C, etc.) such that there exists no link between the informed consent forms and the research data, the research data is thus anonymous.

Delft University of Technology
INSPECTION REPORT FOR DEVICES TO BE USED IN CONNECTION WITH HUMAN SUBJECT RESEARCH

This report should be completed for every experimental device that is to be used in interaction with humans and that is not CE certified or used in a setting where the CE certification no longer applies[1].

The first part of the report has to be completed by the researcher and/or a responsible technician.

Then, the safety officer (Heath, Security and Environment advisor) of the faculty responsible for the device has to inspect the device and fill in the second part of this form. An actual list of safety-officers is provided on this webpage.

Note that in addition to this, all experiments that involve human subjects have to be approved by the Human Research Ethics Committee of TU Delft. Information on ethics topics, including the application process, is provided on the HREC website.

Device identification (name, location):

Configurations inspected[2]: **N/A**

Type of experiment to be carried out on the device:[3] **haptic control**

Name(s) of applicants(s): **Dick Plettenburg (on behalf of Gailey Leseman)**

Job title(s) of applicants(s): **Assistant Professor**

(Please note that the inspection report should be filled in by a TU Delft employee. In case of a BSc/MSc thesis project, the responsible supervisor has to fill in and sign the inspection report.)

Date: 20201110

Signature(s): ________________

1 Modified, altered, used for a purpose not reasonably foreseen in the CE certification

2 If the devices can be used in multiple configurations, otherwise insert NA

3 e.g. driving, flying, VR navigation, physical exercise, ...

Setup summary

1) Main Components

The enclosure (depicted in red, see figure 1) holds most components. The Arduino ATMEGA2560 microcontroller is used in combination with the Robotis DYNAMIXEL Arduino Shield to control the Robotis DYNAMIXEL XM430-W210-T servo motor. This enclosure is attached to a elastic belt (figure 4) which is worn at hip height. There are some additional electronics attached to the microcontroller to connect the FUTEK LSB-200 force sensor, the three push buttons, the rocker switch and a serial-to-USB-converter (Adafruit CP2104).

A small pulley is mounted tot the servo motor, which is attached to the inner cable of a Bowden-cable system, see figure 3a. The outer cable of the Bowden-cable system is directly attached to the enclosure and to the skin anchor with the T-style connectors (figure 3b).

There are two 'skin anchors', thin plastic devices that are attached to the shoulder and back using a skin-friendly adhesive tape. Between the two skin anchors there is a FUTEK force sensor, attached with M3-bolts which are soldered onto the inner cable of the Bowden-cable system. (figure 5)

The system will be powered by the Robotis SMPS 12V/5A power supply. There will be a power-switch on the line to the power supply such that all power can be cut off in case of an emergency.

The serial-to-USB converter is connected to a USB panel mount (figure 6). With a 5m USB cable the system is connected to the experiment laptop for control of the virtual slave.

2) Working Principle

By moving the shoulder, the user can increase the tension force on the inner cable, which is measured by the FUTEK force sensor. This force is used as an input for a prosthesis or virtual slave. The force-controlled slave will have a certain displacement, depending on the impedance of the environment. This displacement is then fed back to the user by moving the servo motor. When the servo-motor turns, the inner cable will wind up on the pulley and it will pull back the upper skin anchor.

During the experiment the user will control a virtual slave to determine the stiffness of a virtual ball under varying feedback conditions. An example of the virtual slave is depicted in figure 7.

The buttons on the enclosure are to set the neutral position at the beginning of the experiment. This position will be different for each participant depending on the length of their back.

Risk checklist

Please fill in the following checklist and consider these hazards that are typically present in many research setups. If a hazard is present, please describe how it is dealt with.

Also, mention any other hazards that are present.

Hazard type	Present	Hazard source	Mitigation measures
Mechanical (sharp edges, moving equipment, etc.)	X	Moving Servo Motor (Robotis Dynamixel)	Moving parts are mounted into in an enclosure that prevents contact with the moving parts. In the software the servo-motor has limitations on the possible positions and currents. A validity check is performed on the stiffness-values and the servo is turned off when no connection can be established between the micro-controller and the experiment laptop. Furthermore a power-switch will be available to cut all power from the system.
Electrical	X		The original Robotis SMPS power supply is used to power the microcontroller and the servo.
Structural failure			
Touch Temperature			
Electromagnetic radiation			
Ionizing radiation			
(Near-)optical radiation (lasers, IR-, UV-, bright visible light sources)			
Noise exposure			
Materials (flammability, offgassing, etc.)			
Chemical processes			
Fall risk			

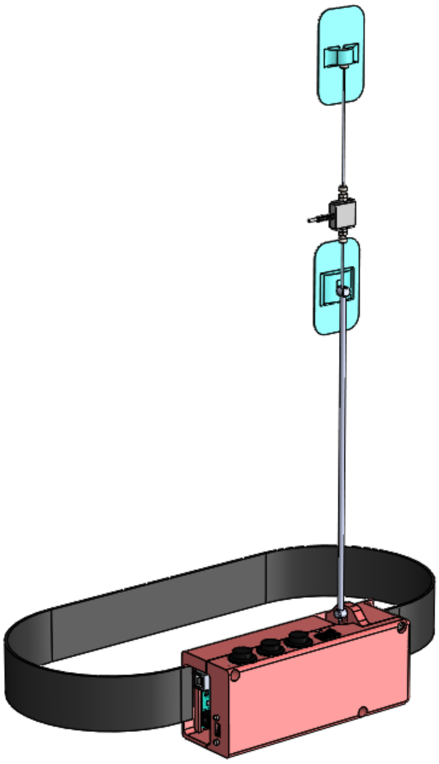
Figure 1

Overview:

Red:
Enclosure

Light Blue:
Skin Anchors

Black:
Elastic belt



Example of an earlier prototype of the apparatus worn by a human. As shown above the final design will be fully closed and wiring will be tied up.

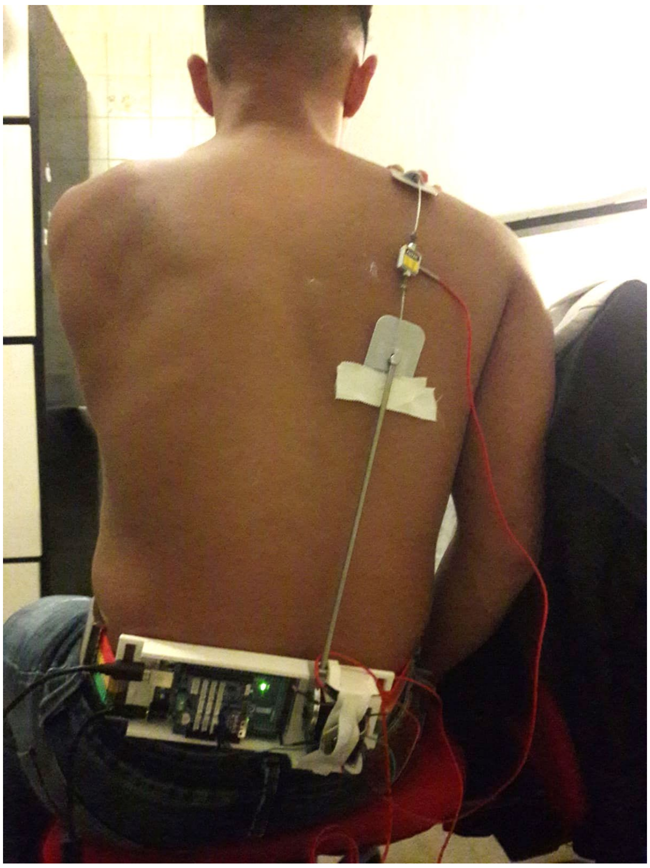


Figure 2

3D-printed enclosure for the microcontroller and servo-motor

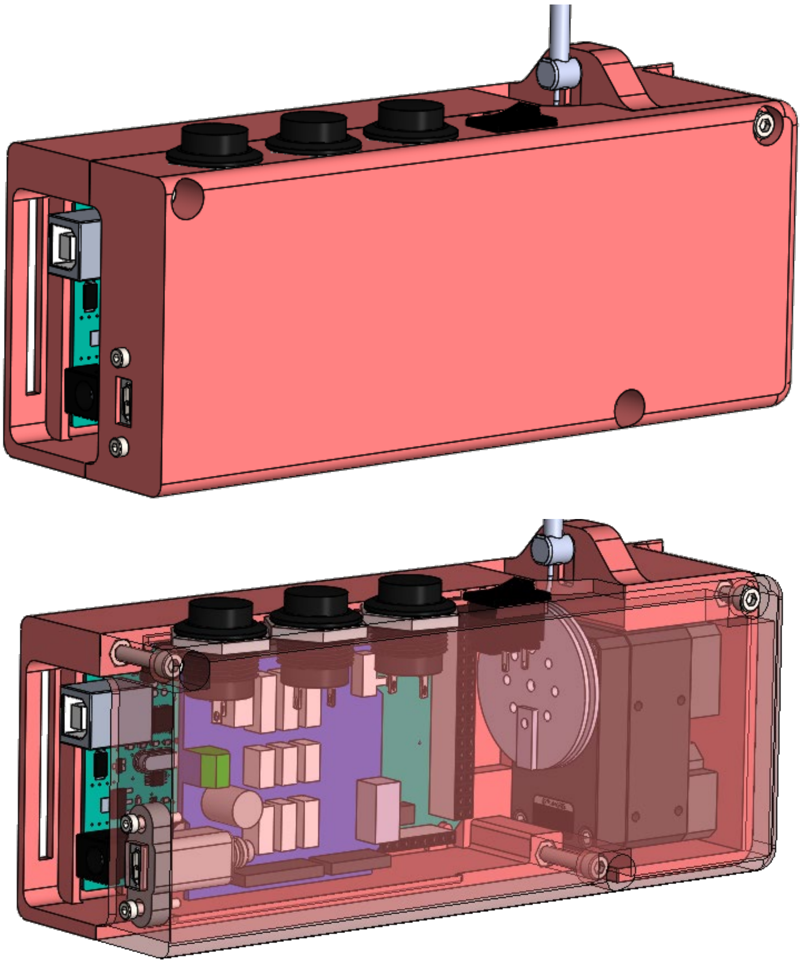


Figure 3

left:
Connection of servo-motor to pulley and Bowden-cable system.

right:
T-style connector of the Bowden-cable system.

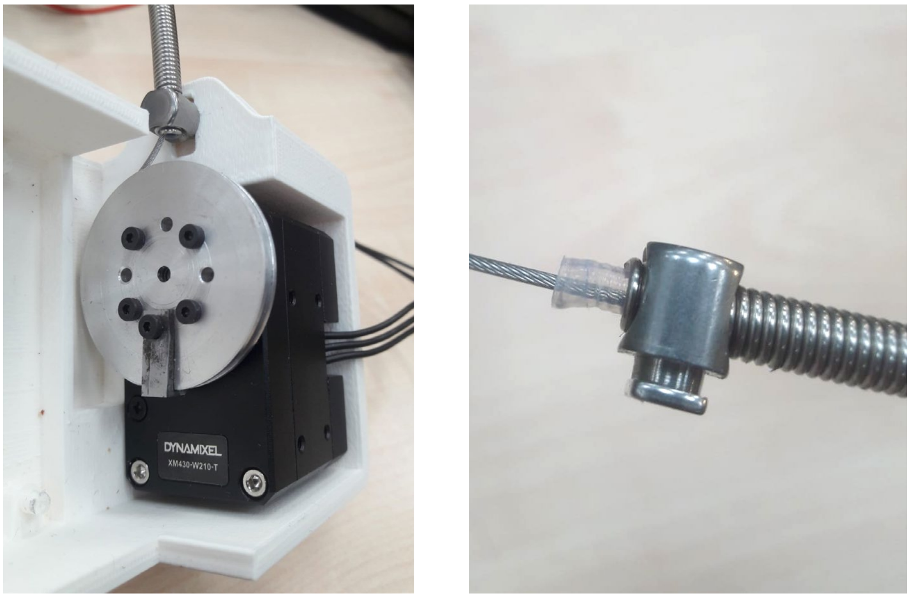


Figure 4

Adjustable elastic belt, to be attached to the enclosure.

Figure 5

3D-printed 'Skin Anchors' after the design of Debra LaTour

The force sensor can measure the tension on the inner cable.

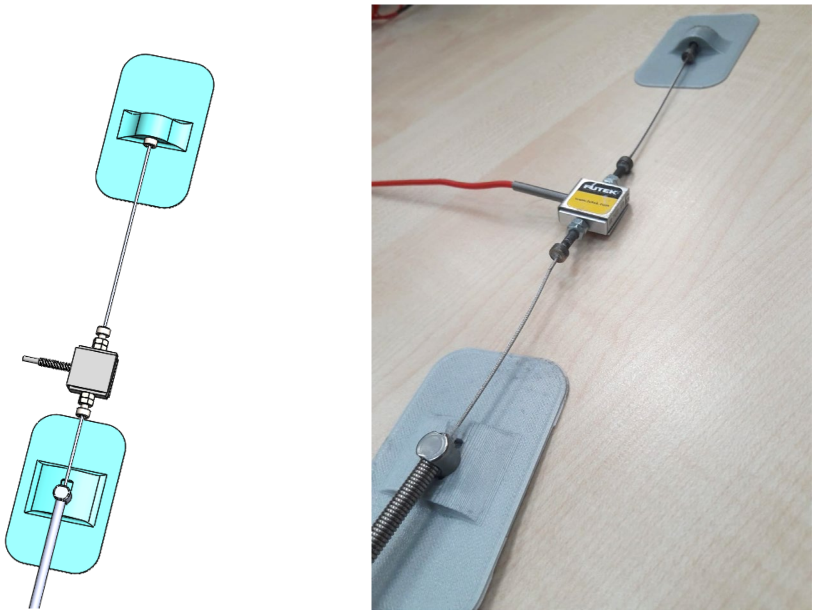


Figure 6

left:
SMPS power connector in back. USB-connectors for the Arduino (USB-B) and communication (micro-usb) in grey.

right:
Panel-mount USB connector.

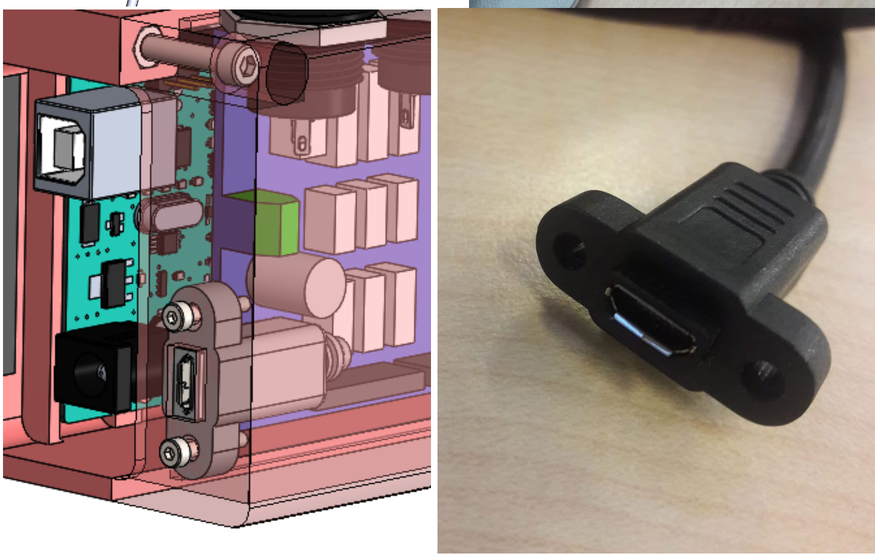
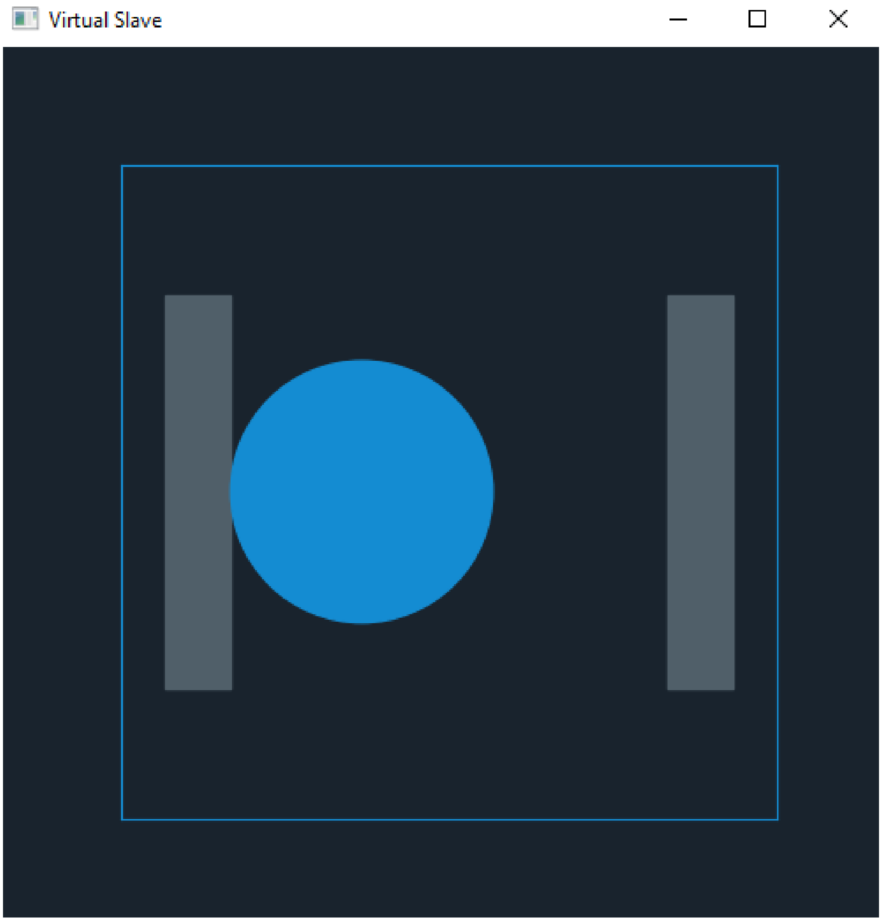


Figure 7

Virtual Slave



Device inspection
(to be filled in by the AMA advisor of the corresponding faculty)

Name: Peter Kohne

Faculty: 3mE/IO

The device and its surroundings described above have been inspected. During this inspection I could not detect any extraordinary risks.

(Briefly describe what components have been inspected and to what extent (i.e. visually, mechanical testing, measurements for electrical safety etc.)

Date: 04-11-2020

Signature:

Inspection valid until[4]:

Note: changes to the device or set-up, or use of the device for an experiment type that it was not inspected for require a renewed inspection

---

4 Indicate validity of the inspection, with a maximum of 3 years

D
Code

All code can be found in the GitLab repository.

D.1. Arduino

Packages to be installed:

D.1.1. master.ino

```
#include <Dynamixel2Arduino.h>
#include <filters.h>

// Setup for Arduino MEGA board
#define DXL_SERIAL Serial
#define COMM_SERIAL Serial2
const uint8_t DXL_DIR_PIN = 2;     // DYNAMIXELShield DIR PIN

// Setup DYNAMIXEL
const uint8_t DXL_ID = 1;
const float DXL_PROTOCOL_VERSION = 2.0;
Dynamixel2Arduino dxl(DXL_SERIAL, DXL_DIR_PIN);

// Setup Arduino Pins
const int btnUp = 41;
const int btnDown = 35;

// Variables
float r = 0.015;
float k = 750;     // stiffness prior to experiment
double u0 = 0.060;
float theta0 = 270;
bool feedback = true;

const int num_measurements = 10;
float log_F[num_measurements] = {0};

float measureForce(){
  int forceSensor = analogRead(A8);          // [bytes]  read the input on analog pin 0
  float F = 0.0225 * forceSensor + 0.5976;   // [N]      calculate force using calibration formula
  return F;
}

float averageForce(int num_measurements, float new_F, float logF[]) {
  float sum_F = 0;
  for (int i = 0; i < num_measurements - 1; ++i) {
    log_F[i] = log_F[i + 1];               // move every logged value 1 step back
    sum_F += log_F[i + 1];                 // add every logged value to cumulative sum
  }
  log_F[num_measurements - 1] = new_F;     // add latest measurement to log array
  sum_F += new_F;
  float avg_F = sum_F / num_measurements; // calculate average of measurements
  return avg_F;
}


void setup() {
  // put your setup code here, to run once:
  pinMode(btnUp, INPUT);
  pinMode(btnDown,INPUT);

  // Use extra UART port of DYNAMIXEL shield for communication with receiver/laptop
  COMM_SERIAL.begin(115200);

  dxl.begin(57600);    // has to match with DYNAMIXEL baudrate
  dxl.setPortProtocolVersion(DXL_PROTOCOL_VERSION);
  dxl.ping(DXL_ID);    // get DYNAMIXEL information

  // Turn of torque when configuring items in EEPROM area
  dxl.torqueOff(DXL_ID);
  dxl.setOperatingMode(DXL_ID, OP_POSITION); // position mode
  dxl.torqueOn(DXL_ID);
}
```

```
void loop() {
  unsigned long t_start = millis();
  float F = measureForce();              // measure force from analog sensor input and calibrate
  float avg_F = averageForce(num_measurements, F, log_F);    // average measurements to prevent jitter

  float du = avg_F / k;                  // calculate displacement
  float dtheta = du / r * (180/PI);      // convert to degrees
  float u = u0 - du;                     // position of virtual slave
  float goalPos = theta0 - dtheta;       // position of servo motor

  // receive serial messages from interface
  char serial_command[10];        // empty array to store data (7 bytes) from serial read

  if (COMM_SERIAL.available() > 0) {
    int incomingBytes = COMM_SERIAL.readBytes(serial_command,7);
    String cmd = String(serial_command);
    char cmd_key = cmd[0];                 // first character defines type of command
    String cmd_data = cmd.substring(1);    // rest of byte array defines value

    if (cmd_key == 'k'){
        k = cmd_data.toFloat();    // change stiffness of virtual spring
    } else if (cmd_key == 'F'){    // for conditions with force feedback
      feedback = true;
    } else if (cmd_key == 'f'){    // for conditions without force feedback
      feedback = false;
    } else if (cmd_key == 'p'){    // move servo forward
      theta0 = theta0 + cmd_data.toFloat();
    } else if (cmd_key == 'm'){    // move servo backward
      theta0 = theta0 - cmd_data.toFloat();
    }
  }

  if (feedback) {
    dxl.setGoalPosition(DXL_ID, goalPos, UNIT_DEGREE);
  } else {
    dxl.setGoalPosition(DXL_ID, theta0, UNIT_DEGREE);
  }

  if (digitalRead(btnUp) == HIGH){
    theta0 = theta0 + 1;
  } else if (digitalRead(btnDown) == HIGH){
    theta0 = theta0 - 1;
  }

  float presentPos = dxl.getPresentPosition(DXL_ID,UNIT_DEGREE);
  unsigned long currentTime = millis();


  // Print data to serial communication port
  COMM_SERIAL.print(String(avg_F,4));
  COMM_SERIAL.print(",□");
  COMM_SERIAL.print(String(u*1000, 4));
  COMM_SERIAL.print(",□");
  COMM_SERIAL.print(String(k, 2));
  COMM_SERIAL.print(",□");
  COMM_SERIAL.print(String(feedback));
  COMM_SERIAL.print(",□");
  COMM_SERIAL.print(String(presentPos, 2));
  COMM_SERIAL.print(",□");
  COMM_SERIAL.print(String(F,4));
  COMM_SERIAL.print(",□");
  COMM_SERIAL.println(String(currentTime, 10));

  int tau = 20;    // sample time of 20 ms, sampling frequency of 50 Hz
  unsigned long t_passed = millis() - t_start;
  int t_delay = tau - t_passed;
  t_delay = max(0, t_delay);
  delay(t_delay);

}
```

D.2. Python

Packages to be installed:

D.2.1. experiment_interface.py

```python
import sys
import pathlib

from virtual_slave import *
from experiment_interface_parts import *

from PyQt5 import QtCore, QtSerialPort
from PyQt5.QtWidgets import *
import qdarkstyle

import pandas as pd
import random
import time


class ExperimentInterface(QMainWindow):
    def __init__(self, parent=None):
        super(ExperimentInterface, self).__init__(parent)

        self.setWindowTitle("Control Interface")
        self.setGeometry(200, 200, 900, 600)

        # Set Variables
        self.stiffness_values = ["600", "900", "1300"]  # [N/m]
        self.u = 60  # [mm]
        self.u_probe_threshold_low = 50  # [mm]
        self.u_probe_threshold_high = 55  # [mm]

        # Initialize other variables
        self.F = 5
        self.raw_F = 0
        self.k = int(self.stiffness_values[0])
        self.condition = "NO EXPERIMENT"
        self.trial = 0
        self.t_start = 0
        self.num_probes = 0
        self.feedbackStatus = 0
        self.servoPos = "0"
        self.log = pd.DataFrame(columns=['trial', 'condition', 'F', 'u', 'k', 'FEEDBACK', 'servoPos', 'raw_F', 'time'])
        self.log_i = 0
        self.n_total_trials = 0
        self.running_experiment = False

        # Experiment Info
        self.experiment_info = ExperimentInfo(self)
        self.experiment_info.update_labels(self.condition, self.trial, self.n_total_trials)

        # Start / Save Buttons
        self.startsave = StartSave(self)

        # Time and Stiffness Choice Buttons
        self.timer_btn = InteractButton("Start Timer")
        self.timer_btn.clicked.connect(self.start_timer)
        self.hard_btn = StiffnessButton(self, "HARD")
        self.hard_btn.clicked.connect(lambda: self.make_choice("Hard"))
        self.medium_btn = StiffnessButton(self, "MEDIUM")
        self.medium_btn.clicked.connect(lambda: self.make_choice("Medium"))
        self.soft_btn = StiffnessButton(self, "SOFT")
        self.soft_btn.clicked.connect(lambda: self.make_choice("Soft"))

        self.stiffness_btns = QVBoxLayout()
        self.stiffness_btns.addWidget(self.hard_btn)
        self.stiffness_btns.addWidget(self.medium_btn)
        self.stiffness_btns.addWidget(self.soft_btn)
        self.stiffness_btns.setSpacing(10)
        self.experiment_interface = QVBoxLayout()
        self.experiment_interface.addWidget(self.timer_btn)
        self.experiment_interface.addLayout(self.stiffness_btns)
        self.experiment_interface.setSpacing(25)

        # Slave Debug / Control
        self.num_probes_txt = InfoLabel(str(self.num_probes))
        self.force_slider = ForceSlider(self)
        self.slave_slider = PositionSlider(self)

        self.slave_pos_override = QCheckBox()
        self.slave_pos_override.stateChanged.connect(self.check_position_slave)
        self.position_override = False
        self.slave_slider.valueChanged.connect(self.positioning_slave)
        self.slave_open_override = QCheckBox()
        self.slave_open_override.stateChanged.connect(self.check_opening_slave)
        self.force_indicator_open = QCheckBox()
        self.force_indicator_open.stateChanged.connect(self.check_opening_force_indicator)

        self.slave_debug = QGridLayout()
        self.slave_debug.addWidget(InfoLabel("Force: "), 0, 0)
        self.slave_debug.addWidget(self.force_slider, 0, 1, 1, 3)
        self.slave_debug.addWidget(InfoLabel("Slave Position:"), 1, 0)
        self.slave_debug.addWidget(self.slave_slider, 1, 1, 1, 3)
        self.slave_debug.addWidget(self.slave_pos_override, 1, 4)
        self.slave_debug.addWidget(InfoLabel("# of probes:"), 2, 0)
        self.slave_debug.addWidget(self.num_probes_txt, 2, 1)
        self.slave_debug.addWidget(InfoLabel("Virtual Slave:"), 3, 0)
        self.slave_debug.addWidget(self.slave_open_override, 3, 1)
        self.slave_debug.addWidget(InfoLabel("Force Indicator:"), 3, 2)
        self.slave_debug.addWidget(self.force_indicator_open, 3, 3)

        # Serial Communication
        self.serial_connect_info = SerialConnectInfo(self)
        self.connect_btn = QPushButton(
            text="Connect Serial Port",
            checkable=True,
```

```
            toggled=self.on_toggled
        )
        self.connect_btn.setMinimumHeight(30)

        self.serial_display = SerialDisplay(self)
        self.serial = QtSerialPort.QSerialPort(
            'COM3',
            baudRate=QtSerialPort.QSerialPort.Baud115200,
            readyRead=self.receive
        )

        self.serial_connect = QVBoxLayout()
        self.serial_connect.addLayout(self.serial_connect_info)
        self.serial_connect.addWidget(self.connect_btn)
        self.serial_connect.addLayout(self.serial_display)

        # Stiffness and Servo Section
        self.servo_debug = QVBoxLayout()
        self.change_stiffness = ChangeStiffness(self.stiffness_values)
        self.change_stiffness.send_stiffness_btn.clicked.connect(self.send_stiffness)

        self.servo_control = ServoControl(self)
        self.servo_control.feedback_btn.stateChanged.connect(self.change_feedback)
        self.servo_debug.addLayout(self.change_stiffness)
        self.servo_debug.addLayout(self.servo_control)

        # Bringing the layout together
        layout = InterfaceLayout()
        layout.addLayout(self.experiment_info, 0, 0)
        layout.addLayout(self.serial_connect, 2, 0)
        layout.addLayout(self.startsave, 0, 2)
        layout.addLayout(self.experiment_interface, 2, 2)
        layout.addLayout(self.slave_debug, 0, 4)
        layout.addLayout(self.servo_debug, 2, 4)

        widget = QWidget()
        widget.setLayout(layout)
        self.setCentralWidget(widget)

        # Create Virtual Slave Object
        self.virtual_slave = VirtualSlave(self)
        self.virtual_slave.setStyleSheet(qdarkstyle.load_stylesheet(qt_api='pyqt5'))
        # Create Force Indicator Object
        self.force_indicator = ForceIndicator(self)
        self.force_indicator.setStyleSheet(qdarkstyle.load_stylesheet(qt_api='pyqt5'))

    def start_experiment(self):
        self.serial_display.logger.reset_log(self)
        self.running_experiment = True
        self.disable_debug_buttons(True)
        self.serial_display.serial_display_F.setChecked(True)
        self.participant = self.experiment_info.participant.text()
        self.age = str(self.experiment_info.age.value())
        self.sex = self.experiment_info.sex.currentText()
        self.experiment_info.participant.setReadOnly(True)
        print("Started experiment with participant " + self.participant + ".")

        k_soft = int(self.change_stiffness.soft_value.text())
        k_medium = int(self.change_stiffness.medium_value.text())
        k_hard = int(self.change_stiffness.hard_value.text())

        print("Ball stiffnesses are: ")
        print("    Soft: " + str(k_soft) + " N/m")
        print("    Medium: " + str(k_medium) + " N/m")
        print("    Hard: " + str(k_hard) + " N/m")

        balls = [k_soft, k_medium, k_hard] * 4
        stiffness = {
            k_soft: "Soft",
            k_medium: "Medium",
            k_hard: "Hard"
        }
        conditions = ['Visual + Haptic', 'Visual', 'Haptic', 'No Feedback']

        n_conditions = len(conditions)  # number of different conditions
        n_sets = 5  # number of sets of trials
        n_balls_set = 8  # number of balls per set
        self.n_total_trials = n_conditions * n_sets * n_balls_set

        print("Experiment will have " + str(n_sets) + " sets with " +
              str(n_conditions) + " conditions each. There will be " + str(n_balls_set) +
              " trials per condition, giving a total of " + str(self.n_total_trials) + " trials.")

        self.df = pd.DataFrame(columns=['participant', 'age', 'sex',
                                        'trial', 'condition',
                                        'k', 'stiffness', 'choice',
                                        'completion-time', 'num-probes'])

        self.trial = 0

        for i in range(0, n_sets):

            if i != 0:
                print("Set of conditions completed. Take a 60s break.")
                self.condition = "BREAK"
                self.disable_choice_btns(True)
                self.experiment_info.update_labels(self.condition, self.trial, self.n_total_trials)
                t_wait = 60
                time_waited = 0
                while time_waited < t_wait:
                    QApplication.processEvents()  # keeps background processes working
                    time.sleep(1)
                    time_waited += 1
                    if time_waited % 10 == 0:
                        print("{0} seconds left.".format(t_wait - time_waited))

            print("New set of conditions started.")

            trialset_conditions = conditions.copy()
            for j in range(0, n_conditions):
                bins = {"Soft": [], "Medium": [], "Hard": []}
                self.condition = random.choice(trialset_conditions)  # select condition at random
```

```
trialset_conditions.remove(self.condition)  # remove condition from options
trial_balls = random.sample(balls, n_balls_set)  # sample subset from all balls
print("Set of trials [" + str(i + 1) + "/" + str(n_sets) +
      "]. Condition [" + str(j + 1) + "/" + str(n_conditions) +
      "]: " + self.condition)

# only show virtual slave for visual feedback conditions
if self.condition is "Visual" or self.condition is "Visual + Haptic":
    self.virtual_slave.show()
else:
    self.virtual_slave.close()

if self.condition is "Haptic" or self.condition is "Visual + Haptic":
    serial_condition = "F0"  # create string for Servo Feedback On command
    feedback = 1
else:
    serial_condition = "f0"  # create string for Servo Feedback Off command
    feedback = 0

count = 0
while not feedback == self.feedbackStatus:
    QApplication.processEvents()  # keeps background processes working
    self.send(serial_condition)  # send the force condition over serial
    time.sleep(0.1)
    count += 1
    if count % 5 == 0:
        print("[WAIT] Haptic Feedback not updated.")



for k in range(0, n_balls_set):
    if not self.running_experiment:
        break
    self.trial += 1
    self.experiment_info.update_labels(self.condition, self.trial, self.n_total_trials)
    self.ball = random.choice(trial_balls)  # select random ball from available options
    trial_balls.remove(self.ball)  # remove ball from available options

    while not self.F < 1.5:  # wait for rest position
        print("[WAIT] Interface not in rest position.")
        QApplication.processEvents()  # keeps background processes working
        self.disable_choice_btns(True)
        self.timer_btn.setDisabled(True)
        time.sleep(0.1)

    self.send_stiffness()  # send the new stiffness over serial

    count = 0
    while not self.k == self.ball:  # wait for updated stiffness
        QApplication.processEvents()  # keeps background processes working
        self.disable_choice_btns(True)
        self.timer_btn.setDisabled(True)
        count += 1
        time.sleep(0.1)
        if count % 10 == 0:
            print("[WAIT] Stiffness not updated.")
            self.send_stiffness()  # send the new stiffness over serial


    self.timer_btn.setDisabled(False)
    self.num_probes = 0  # reset the number of probes
    self.timer_started = False
    self.choice_made = False
    self.probe_check_low = False
    self.probe_check_high = False

    while not self.timer_started:  # waits for the timer to be started
        QApplication.processEvents()  # keeps background processes working
        self.disable_choice_btns(True)
        self.timer_btn.setDisabled(False)
        time.sleep(0.01)

    while not self.choice_made:  # waits for user to make a decision
        QApplication.processEvents()  # keeps background processes working
        self.disable_choice_btns(False)
        self.timer_btn.setDisabled(True)

        # Count number of probes, divided into quarts with two thresholds
        if self.u < self.u_probe_threshold_high and not self.probe_check_high:
            self.probe_check_high = True
            self.num_probes += 0.25
        if self.u < self.u_probe_threshold_low and not self.probe_check_low:
            self.probe_check_low = True
            self.num_probes += 0.25
        if self.u > self.u_probe_threshold_high and self.probe_check_high:
            self.probe_check_high = False
            self.num_probes += 0.25
        if self.u > self.u_probe_threshold_low and self.probe_check_low:
            self.probe_check_low = False
            self.num_probes += 0.25

        time.sleep(0.01)

    completion_time = self.t_trial

    trial_data = [self.participant, self.age, self.sex,
                  self.trial, self.condition,
                  self.ball, stiffness.get(self.ball), self.choice,
                  completion_time, self.num_probes]
    self.df.loc[self.trial] = trial_data
    bins[self.choice].append(stiffness.get(self.ball))
time.sleep(0.5)
print("Answers for '{0}':".format(self.condition, i + 1))
for value in ["Soft", "Medium", "Hard"]:
    print("  | ({0}) {1} |".format(len(bins[value]), value))
    print("  - {0} Soft | {1} Medium | {2} Hard".format(bins[value].count("Soft"),
                                                       bins[value].count("Medium"),
                                                       bins[value].count("Hard")))
self.serial_display.logger.save_log(self)  # save raw data to .csv
time.sleep(0.5)
if self.trial == self.n_total_trials:
    self.disable_choice_btns(True)
```

```
                self.condition = 'COMPLETED'
                self.experiment_info.update_labels(self.condition, self.trial, self.n_total_trials)
                print("The participant has completed the experiment.")
                break

    def make_choice(self, choice):
        if self.running_experiment:
            self.t_trial = time.time() - self.t_start  # logs the elapsed time
            print("Trial: " + str(self.trial) + " | Choice: " + str(choice))
            self.choice_made = True  # breaks the while loop
            self.choice = choice  # set internal variable to corresponding choice
            self.timer_started = False
            self.disable_choice_btns(True)

    def start_timer(self):
        self.t_start = time.time()
        self.timer_started = True

    def save_experiment(self):
        if self.trial < self.n_total_trials:
            warningOK = self.show_warning()
        else:
            warningOK = True

        if warningOK:
            # reset experiment information
            print("End of experiment at trial {}.".format(self.trial))
            self.experiment_info.participant.clear()
            self.experiment_info.participant.setReadOnly(False)
            self.experiment_info.update_labels('', 0, 0)

            file_name = "participant" + self.participant + "_" + time.strftime("%Y%m%d-%H%M") + ".csv"
            if self.trial < self.n_total_trials:
                file_name = "incomplete_" + file_name
            parent_directory = pathlib.Path(__file__).parent.parent
            file_location = parent_directory / "data" / file_name
            self.df.to_csv(file_location, index=False)  # save experiment data to .csv
            self.serial_display.logger.save_log(self)  # save raw data to .csv

            self.running_experiment = False  # if applicable, break the experiment loop
            self.disable_debug_buttons(False)
            del self.df  # delete the dataframe
            self.serial_display.logger.reset_log(self)  # reset the log
            print("Experiment data has been saved.")

    def update_debug_tools(self):
        self.num_probes_txt.setText(str(self.num_probes))
        self.force_slider.setValue(self.F)
        self.force_indicator.force_slider.setValue(self.F)
        self.slave_slider.setValue(self.u)
        if self.feedbackStatus == 1:
            self.servo_control.feedback_indicator.setText("ON")
        else:
            self.servo_control.feedback_indicator.setText("OFF")
        self.servo_control.position_indicator.setText(self.servoPos)
        self.servo_control.position_dial.setValue(float(self.servoPos))

    def check_opening_slave(self):
        if self.slave_open_override.isChecked():
            self.virtual_slave.show()
        else:
            self.virtual_slave.close()

    def check_opening_force_indicator(self):
        if self.force_indicator_open.isChecked():
            self.force_indicator.show()
        else:
            self.force_indicator.close()

    def check_position_slave(self):
        if self.slave_pos_override.isChecked():
            self.position_override = True
            self.positioning_slave()
        else:
            self.position_override = False

    def positioning_slave(self):
        if self.position_override:
            self.u = self.slave_slider.value()
            self.virtual_slave.u = self.u

    def disable_choice_btns(self, bool):
        self.hard_btn.setDisabled(bool)
        self.medium_btn.setDisabled(bool)
        self.soft_btn.setDisabled(bool)

    def send_stiffness(self):
        if self.running_experiment:
            stiffness = self.ball
        else:
            self.stiffness_values = [self.change_stiffness.soft_value.text(),
                                     self.change_stiffness.medium_value.text(),
                                     self.change_stiffness.hard_value.text()]
            stiffness = int(self.stiffness_values[self.change_stiffness.stiffness.checkedId()])
        message = "k" + "{:0>2f}".format(stiffness)
        self.send(message)

    def change_feedback(self):
        if self.servo_control.feedback_btn.isChecked():
            message = "F0"
            feedback = 1
        else:
            message = "f0"
            feedback = 0
        while not feedback == self.feedbackStatus:
            QApplication.processEvents()
            self.send(message)
            time.sleep(0.1)

    def disable_debug_buttons(self, value):
        self.startsave.start_btn.setDisabled(value)
        self.change_stiffness.send_stiffness_btn.setDisabled(value)
```

```
        self.servo_control.up_btn.setDisabled(value)
        self.servo_control.down_btn.setDisabled(value)
        self.servo_control.up_more_btn.setDisabled(value)
        self.servo_control.down_more_btn.setDisabled(value)

    def show_warning(self):
        msg = QMessageBox()
        msg.setIcon(QMessageBox.Warning)
        msg.setText("Not all trials have been completed, do you want to continue?")
        msg.setStandardButtons(QMessageBox.Ok | QMessageBox.Cancel)
        return_value = msg.exec_()
        return return_value == QMessageBox.Ok

    @QtCore.pyqtSlot()
    def receive(self):
        while self.serial.canReadLine():
            if not self.running_experiment:
                self.startsave.start_btn.setDisabled(False)
            try:
                serial_data = self.serial.readLine().data().decode().rstrip('\r\n').split(", ")
                self.log.loc[self.log_i] = [self.trial, self.condition] + serial_data
                self.F = float(serial_data[0])           # filtered force measurements
                self.k = float(serial_data[2])           # stiffness
                if not self.position_override:
                    self.u = float(serial_data[1])
                    self.virtual_slave.u = self.u        # position of virtual slave
                self.feedbackStatus = int(serial_data[3])  # haptic force on/off
                self.servoPos = serial_data[4]             # position of servo [deg]
                self.raw_F = serial_data[5]                # unfiltered force measurements
                self.serial_display.display.append(serial_data[self.serial_display.serial_display_group.checkedId()])
                self.log_i += 1
            except UnicodeDecodeError:
                print("Error in decoding the Serial System. Trying again.")
                print("    |" + self.serial.readLine().data().decode().rstrip('\r\n'))
                time.sleep(0.1)
            except ValueError:
                print("Error in values. Trying again.")
                print("    |" + self.serial.readLine().data().decode().rstrip('\r\n'))
                time.sleep(0.1)
            self.update_debug_tools()

    @QtCore.pyqtSlot()
    def send(self, message):
        self.serial.write(message.encode('utf-8'))
        self.serial_display.send_display.append(message)

    @QtCore.pyqtSlot(bool)
    def on_toggled(self, checked):
        self.connect_btn.setText("Disconnect" if checked else "Connect Serial Port")
        self.serial.setPortName(self.serial_connect_info.port.text())
        self.serial.setBaudRate(int(self.serial_connect_info.rate.currentText()))
        if checked:
            if not self.serial.isOpen():
                if not self.serial.open(QtCore.QIODevice.ReadWrite):
                    self.connect_btn.setChecked(False)
        else:
            self.serial.close()
            self.startsave.start_btn.setDisabled(True)


app = QApplication(sys.argv)  # create application instance
app.setStyleSheet(qdarkstyle.load_stylesheet(qt_api='pyqt5'))  # set to modern stylesheet

interface = ExperimentInterface()
interface.show()  # windows are hidden by default

# Start the event loop.
app.exec_()

# The application won't reach here until you exit and the event loop has stopped.
```

D.2.2. experiment_interface_parts.py

```
from PyQt5.QtWidgets import *
from PyQt5.QtCore import Qt
import time
import pathlib


class StiffnessButton(QPushButton):
    def __init__(self, parent=None, name="name"):
        super(StiffnessButton, self).__init__(parent)
        self.setText(name)
        self.setSizePolicy(QSizePolicy.Preferred, QSizePolicy.Expanding)
        self.setMaximumHeight(100)
        font = self.font()
        font.setPointSize(12)
        font.setBold(True)
        self.setFont(font)
        self.setStyleSheet(":enabled { border-color: #1464A0; border-width: 2px}")


class InteractButton(QPushButton):
    def __init__(self, parent=None):
        super(InteractButton, self).__init__(parent)
        font = self.font()
        font.setPointSize(10)
        self.setFont(font)
        self.setFixedHeight(50)


class StartSave(QVBoxLayout):
    def __init__(self, main):
        super(StartSave, self).__init__()
        self.start_btn = InteractButton("Start Experiment")
        self.start_btn.clicked.connect(main.start_experiment)
        self.start_btn.setDisabled(True)
        self.save_btn = InteractButton("Save Data")
        self.save_btn.clicked.connect(main.save_experiment)
        self.addWidget(self.start_btn)
        self.addWidget(self.save_btn)
        self.setSpacing(20)


class InfoLabel(QLabel):
    def __init__(self, parent=None):
        super(InfoLabel, self).__init__(parent)
        font = self.font()
        font.setPointSize(10)
        self.setFont(font)
        self.setFixedHeight(30)
        self.setMaximumWidth(200)


class ExperimentInfo(QGridLayout):
    def __init__(self, parent=None):
        super(ExperimentInfo, self).__init__(parent)
        self.addWidget(InfoLabel("Participant:"), 0, 0)
        self.addWidget(InfoLabel("Age:"), 1, 0)
        self.addWidget(InfoLabel("Sex:"), 2, 0)
        self.addWidget(InfoLabel("Experiment Condition: "), 3, 0)
        self.addWidget(InfoLabel("Trial: "), 4, 0)

        self.participant = QLineEdit()
        self.age = QSpinBox()
        self.age.setRange(18, 99)
        self.sex = QComboBox()
        self.sex.addItem("Male")
        self.sex.addItem("Female")
        self.sex.addItem("Other")
        self.condition = InfoLabel()
        self.trial = InfoLabel()

        self.addWidget(self.participant, 0, 1)
        self.addWidget(self.age, 1, 1)
        self.addWidget(self.sex, 2, 1)
        self.addWidget(self.condition, 3, 1)
        self.addWidget(self.trial, 4, 1)

    def update_labels(self, condition, trial, n_total_trials):
        self.condition.setText(condition)
        self.trial.setText(str(trial) + "/" + str(n_total_trials))


class SerialConnectInfo(QHBoxLayout):
    def __init__(self, parent=None):
        super(SerialConnectInfo, self).__init__(parent)
        self.port = QLineEdit("COM3")
        _port = QLabel("Port: ")
        self.rate = QComboBox()
        self.rate.addItem('9600')
        self.rate.addItem('19200')
        self.rate.addItem('38400')
        self.rate.addItem('57600')
        self.rate.addItem('115200')
        self.rate.setCurrentIndex(4)
        _rate = QLabel("Rate: ")
        self.addWidget(_port)
        self.addWidget(self.port)
        self.addWidget(_rate)
        self.addWidget(self.rate)


class SerialLogger(QHBoxLayout):
    def __init__(self, main):
        super(SerialLogger, self).__init__()
        self.startlog_btn = QPushButton("Reset Log")
        self.savelog_btn = QPushButton("Save Log")

        self.startlog_btn.clicked.connect(lambda: self.reset_log(main))
        self.savelog_btn.clicked.connect(lambda: self.save_log(main))
        self.addWidget(self.startlog_btn)
```

```
        self.addWidget(self.savelog_btn)

    def reset_log(self, main):
        main.log = main.log.iloc[0:0]
        main.log_i = 0

    def save_log(self, main):
        if main.running_experiment:
            file_name = "participant" + main.participant + "_log_" + str(main.trial) + time.strftime(
                "_%Y%m%d-%H%M") + ".csv"
        else:
            file_name = "debug_log_" + time.strftime("%Y%m%d-%H%M") + ".csv"
        parent_directory = pathlib.Path(__file__).parent.parent
        file_location = parent_directory / "logs" / file_name
        main.log.to_csv(file_location, index=False)  # save data to .csv file


class SerialDisplay(QVBoxLayout):
    def __init__(self, main):
        super(SerialDisplay, self).__init__()
        self.serial_display = QHBoxLayout()
        self.serial_display_F = QRadioButton(text="Force")
        self.serial_display_F.setChecked(True)
        self.serial_display_u = QRadioButton(text="Position")
        self.serial_display_k = QRadioButton(text="Stiffness")
        self.serial_display.addWidget(self.serial_display_F)
        self.serial_display.addWidget(self.serial_display_u)
        self.serial_display.addWidget(self.serial_display_k)
        self.serial_display_group = QButtonGroup()
        self.serial_display_group.addButton(self.serial_display_F, 0)
        self.serial_display_group.addButton(self.serial_display_u, 1)
        self.serial_display_group.addButton(self.serial_display_k, 2)

        self.display = QTextEdit(readOnly=True)
        self.send_display = QTextEdit(readOnly=True)
        self.logger = SerialLogger(main)

        self.addLayout(self.serial_display)
        self.addWidget(self.display)
        self.addWidget(self.send_display)
        self.addLayout(self.logger)


class InterfaceLayout(QGridLayout):
    def __init__(self, parent=None):
        super(InterfaceLayout, self).__init__(parent)

        # Create line objects
        vline = QFrame()
        vline.setFrameShape(QFrame.VLine)
        vline.setFrameShadow(QFrame.Raised)

        vline2 = QFrame()
        vline2.setFrameShape(QFrame.VLine)
        vline2.setFrameShadow(QFrame.Raised)

        hline = QFrame()
        hline.setFrameShape(QFrame.HLine)
        hline.setFrameShadow(QFrame.Raised)

        hline2 = QFrame()
        hline2.setFrameShape(QFrame.HLine)
        hline2.setFrameShadow(QFrame.Raised)

        hline3 = QFrame()
        hline3.setFrameShape(QFrame.HLine)
        hline3.setFrameShadow(QFrame.Raised)

        self.setContentsMargins(20, 20, 20, 20)
        self.setColumnMinimumWidth(0, 300)
        self.setColumnMinimumWidth(2, 300)
        self.setRowMinimumHeight(1, 40)

        self.addWidget(hline, 1, 0)
        self.addWidget(hline2, 1, 2)
        self.addWidget(hline3, 1, 4)

        self.addWidget(vline, 0, 1, 3, 1)
        self.addWidget(vline2, 0, 3, 3, 1)


class ForceSlider(QSlider):
    def __init__(self, parent=None):
        super(ForceSlider, self).__init__(parent)
        # set custom stylesheet for different colors
        style = """
                QSlider::groove::horizontal {
                height: 15px;
                margin 5px 0;
                }

                QSlider::handle::horizontal:hover {
                background: darkred
                }

                QSlider::sub-page:horizontal {
                background: darkred;}

                  """
        self.setOrientation(Qt.Horizontal)  # set orientation to horizontal
        self.setStyleSheet(style)  # adjust colors
        self.setRange(0, 20)  # adjust range [N]
        self.setValue(parent.F)
        self.setMinimumWidth(250)


class PositionSlider(QSlider):
    def __init__(self, parent=None):
        super(PositionSlider, self).__init__(parent)
        # set custom stylesheet for different colors
        style = """
                QSlider::groove::horizontal {
```

```
            height: 15px;
            margin 5px 0;
            }
            """
        self.setOrientation(Qt.Horizontal)  # set orientation to horizontal
        self.setStyleSheet(style)  # adjust colors
        self.setRange(0, 60)  # adjust range [m]
        self.setValue(parent.u)
        self.setMinimumWidth(250)


class ChangeStiffness(QGridLayout):
    def __init__(self, stiffness_values):
        super(ChangeStiffness, self).__init__()

        _stiffness = QLabel("Stiffness:")
        self.soft = QRadioButton(text="Soft")
        self.soft.setChecked(True)
        self.medium = QRadioButton(text="Medium")
        self.hard = QRadioButton(text="Hard")
        self.stiffness = QButtonGroup()
        self.stiffness.addButton(self.soft, 0)
        self.stiffness.addButton(self.medium, 1)
        self.stiffness.addButton(self.hard, 2)
        self.send_stiffness_btn = QPushButton("Change Stiffness")

        self.soft_value = QLineEdit(stiffness_values[0])
        self.medium_value = QLineEdit(stiffness_values[1])
        self.hard_value = QLineEdit(stiffness_values[2])

        hline = QFrame()
        hline.setFrameShape(QFrame.HLine)
        hline.setFrameShadow(QFrame.Raised)

        self.addWidget(_stiffness, 0, 0)
        self.addWidget(self.soft, 0, 1)
        self.addWidget(self.medium, 0, 2)
        self.addWidget(self.hard, 0, 3)
        self.addWidget(self.soft_value, 1, 1)
        self.addWidget(self.medium_value, 1, 2)
        self.addWidget(self.hard_value, 1, 3)
        self.addWidget(self.send_stiffness_btn, 2, 1, 2, 3)
        self.addWidget(hline, 3, 0, 3, 4)


class ServoControlBtn(QPushButton):
    def __init__(self, text):
        super(ServoControlBtn, self).__init__()
        self.setMaximumWidth(30)
        self.setMinimumHeight(30)
        self.setText(text)


class ServoControl(QGridLayout):
    def __init__(self, main):
        super(ServoControl, self).__init__()

        _position = QLabel("Servo Position:")
        self.position_indicator = QLabel("")
        self.position_indicator.setMinimumHeight(25)
        self.position_dial = QDial()
        self.position_dial.setNotchesVisible(True)
        self.position_dial.setWrapping(True)
        self.position_dial.setMinimumHeight(150)

        _feedback = QLabel("Servo Feedback:")
        self.feedback_indicator = QLabel("OFF")
        self.feedback_btn = QCheckBox()
        self.feedback_btn.setChecked(False)

        self.up_btn = ServoControlBtn("+ 1")
        self.up_more_btn = ServoControlBtn("+ 5")
        self.down_btn = ServoControlBtn("- 1")
        self.down_more_btn = ServoControlBtn("- 5")
        self.up_btn.clicked.connect(lambda: main.send("p1.0"))
        self.down_btn.clicked.connect(lambda: main.send("m1.0"))
        self.up_more_btn.clicked.connect(lambda: main.send("p5.0"))
        self.down_more_btn.clicked.connect(lambda: main.send("m5.0"))

        self.addWidget(_feedback, 0, 0)
        self.addWidget(self.feedback_indicator, 0, 1)
        self.addWidget(self.feedback_btn, 0, 2)

        self.addWidget(_position, 1, 0)
        self.addWidget(self.position_indicator, 1, 1)
        self.addWidget(self.down_more_btn, 2, 2)
        self.addWidget(self.down_btn, 3, 2)
        self.addWidget(self.up_btn, 4, 2)
        self.addWidget(self.up_more_btn, 5, 2)

        self.addWidget(self.position_dial, 2, 0, 4, 2)


class ForceIndicator(QMainWindow):
    def __init__(self, parent):
        super(ForceIndicator, self).__init__(parent)  # inherits properties from parent class

        self.setWindowTitle("Force Indicator")
        self.setGeometry(2075, 250, 750, 250)  # opens force indicator in second window
        self.force_slider = ForceSlider(parent)

        # set canvas as central widget
        self.layout = QHBoxLayout()
        self.layout.addWidget(self.force_slider)
        widget = QWidget()
        widget.setLayout(self.layout)
        self.setCentralWidget(widget)
```

D.2.3. virtual_slave.py

```
# Virtual Slave
# A QMainWindow with a FigureCanvas that takes a position (u) as input to plot the virtual slave as visual feedback.
# Gailey Leseman - aug 2020

from PyQt5 import QtCore
from PyQt5.QtWidgets import *

from matplotlib.backends.backend_qt5agg import FigureCanvasQTAgg as FigureCanvas
from matplotlib.figure import Figure
from matplotlib.patches import Ellipse
from matplotlib.patches import Rectangle


class MplCanvas(FigureCanvas):
    def __init__(self, width=8, height=8, dpi=100):
        fig = Figure(figsize=(width, height), dpi=dpi)
        fig.set_facecolor('#19232d')
        self.axes = fig.add_subplot(111)
        super(MplCanvas, self).__init__(fig)


class VirtualSlave(QMainWindow):
    def __init__(self, parent):
        super(VirtualSlave, self).__init__(parent)  # inherits properties from parent class

        self.setWindowTitle("Virtual Slave")
        self.setGeometry(1075, 25, 750, 750)        # opens virtual slave on second monitor

        # set canvas properties and colors
        self.canvas = MplCanvas(width=8, height=8, dpi=100)
        self.canvas.axes.get_xaxis().set_visible(False)
        self.canvas.axes.get_yaxis().set_visible(False)
        self.canvas.axes.spines['bottom'].set_color('#148CD2')
        self.canvas.axes.spines['top'].set_color('#148CD2')
        self.canvas.axes.spines['right'].set_color('#148CD2')
        self.canvas.axes.spines['left'].set_color('#148CD2')

        # set canvas as central widget
        self.layout = QHBoxLayout()
        self.layout.addWidget(self.canvas)
        widget = QWidget()
        widget.setLayout(self.layout)
        self.setCentralWidget(widget)

        # set some size parameters for the plot
        self.d0_ball = 60    # [mm]
        self.u = 65          # initial position
        self.axis_size = 100
        self.plot_layout()  # updates the plot properties
        self.grip_w = self.axis_size / 8
        self.grip_h = self.axis_size * 0.7
        self.d_ball_x = self.d0_ball
        self.d_ball_y = self.d0_ball

        # define coordinates
        self.grip_fixed_coordinates = (-self.grip_w, (self.axis_size - self.grip_h) / 2)  # do not change
        self.grip_moving_coordinates = (self.u, (self.axis_size - self.grip_h) / 2)
        self.ball_coordinates = (self.d_ball_x / 2, self.axis_size / 2)

        # define shapes
        self.ball = Ellipse(self.ball_coordinates, self.d_ball_x, self.d_ball_y, color='r')
        self.grip_moving = Rectangle(self.grip_moving_coordinates, self.grip_w, self.grip_h)
        self.grip_fixed = Rectangle(self.grip_fixed_coordinates, self.grip_w, self.grip_h)

        self.update_plot()

        # Setup a timer to trigger the redraw by calling update_plot.
        self.timer = QtCore.QTimer()
        self.timer.setInterval(20)
        self.timer.timeout.connect(self.update_plot)
        self.timer.start()

    def update_plot(self):
        # check if the ball is compressed and change width and height accordingly
        if self.u < self.d0_ball:
            self.d_ball_x = self.u
            self.d_ball_y = self.d0_ball + (self.d0_ball - self.u) / (
                    self.d0_ball / (self.grip_h - self.d0_ball))
        else:
            self.d_ball_x = self.d0_ball
            self.d_ball_y = self.d0_ball

        self.ball_coordinates = (self.d_ball_x / 2, self.axis_size / 2)  # update coordinates
        self.grip_moving_coordinates = (self.u, (self.axis_size - self.grip_h) / 2)  # update coordinates

        # Clear the canvas and redraw the shapes
        self.canvas.axes.cla()
        self.ball = Ellipse(self.ball_coordinates, self.d_ball_x, self.d_ball_y, color='#148CD2')
        self.grip_moving = Rectangle(self.grip_moving_coordinates, self.grip_w, self.grip_h, color='#505f69')
        self.grip_fixed = Rectangle(self.grip_fixed_coordinates, self.grip_w, self.grip_h, color='#505f69')
        self.canvas.axes.add_patch(self.grip_fixed)
        self.canvas.axes.add_patch(self.grip_moving)
        self.canvas.axes.add_patch(self.ball)

        # Trigger the canvas to update and redraw.
        self.plot_layout()
        self.canvas.draw()

    def plot_layout(self):
        ax = self.canvas.axes
        ax.set_xlim((-self.axis_size / 6, self.axis_size * (5 / 6)))
        ax.set_ylim((0, self.axis_size))
        ax.set_aspect('equal')
        ax.patch.set_alpha(0.0)
```

D.2.4. prep_data.py

```
import pathlib
import pandas as pd
import numpy as np

# Experiment Parameters
conditions = ['Visual + Haptic', 'Visual', 'Haptic', 'No Feedback']
n_conditions = len(conditions)  # number of different conditions
n_sets = 5  # number of sets of trials
n_balls_set = 8  # number of balls per set
parent_directory = pathlib.Path(__file__).parent.parent
file_location = pathlib.Path("./../data")

# Combine data from all participants
all_files = list(file_location.glob('participant*.csv'))
df_from_each_file = (pd.read_csv(f) for f in all_files)
experiment_data = pd.concat(df_from_each_file, ignore_index=True, sort=False)

experiment_data["accurate"] = (experiment_data["stiffness"] == experiment_data["choice"])
experiment_data["trial_order"] = ((experiment_data["trial"] - 1) % n_balls_set) + 1
experiment_data["trial_set"] = (experiment_data["trial"] - 1) // (n_conditions * n_balls_set) + 1
experiment_data["condition_order"] = ((experiment_data["trial"] - 1) // n_balls_set) % n_conditions + 1
experiment_data["prev_k"] = experiment_data['k'].shift()
experiment_data["prev_choice"] = experiment_data["choice"].shift()

conditions_k = [
    experiment_data['trial_order'] == 1,
    (experiment_data['trial_order'] > 1) & (experiment_data["k"] == experiment_data["prev_k"]),
    (experiment_data['trial_order'] > 1) & (experiment_data["k"] > experiment_data["prev_k"]),
    (experiment_data['trial_order'] > 1) & (experiment_data["k"] < experiment_data["prev_k"])
    ]

conditions_choice = [
    experiment_data['trial_order'] == 1,
    (experiment_data['trial_order'] > 1) & (experiment_data["choice"] == experiment_data["prev_choice"]),
    (experiment_data['trial_order'] > 1) &
    (experiment_data["choice"] == "Hard") & (experiment_data["prev_choice"] == "Medium"),
    (experiment_data['trial_order'] > 1) &
    (experiment_data["choice"] == "Hard") & (experiment_data["prev_choice"] == "Soft"),
    (experiment_data['trial_order'] > 1) &
    (experiment_data["choice"] == "Medium") & (experiment_data["prev_choice"] == "Soft"),
    (experiment_data['trial_order'] > 1) &
    (experiment_data["choice"] == "Medium") & (experiment_data["prev_choice"] == "Hard"),
    (experiment_data['trial_order'] > 1) &
    (experiment_data["choice"] == "Soft") & (experiment_data["prev_choice"] == "Medium"),
    (experiment_data['trial_order'] > 1) &
    (experiment_data["choice"] == "Soft") & (experiment_data["prev_choice"] == "Hard")
    ]

values_k = ["Base", "No Change", "Up", "Down"]
values_choice = ["Base", "No Change", "Up", "Up", "Up", "Down", "Down", "Down"]

experiment_data["stiffness_change"] = np.select(conditions_k, values_k)
experiment_data["stiffness_change_choice"] = np.select(conditions_choice, values_choice)
experiment_data["relative_accurate"] = (experiment_data["stiffness_change"] == experiment_data["stiffness_change_choice"])
experiment_data['num_accurate'] = experiment_data['accurate'].astype(int)*100
experiment_data['num_relative_accurate'] = experiment_data['relative_accurate'].astype(int)*100

# Save combined experiment data to CSV
file_name = 'all_experiment_data'
experiment_data.to_csv("./../data/" + file_name + ".csv", index=False)  # save data to .csv file

file_name = 'all_feedback_experiment_data'
feedback_data = experiment_data[experiment_data["condition"] != "No Feedback"]
feedback_data.to_csv("./../data/" + file_name + ".csv", index=False)  # save data to .csv file
```

E

Design Considerations

E.1. Requirements

E.1.1. Literature Study

Before starting on any project, one must have a decent understanding of the current designs and what factors need to be considered for the new design to be an improvement. Whilst the original thesis assignment prompt was 'wire-less control of prosthesis with electrical signals between adhesive plasters', the initial literature study showed that next to the control input, the feedback given to the user is a major indication for the satisfaction with the final product. Therefore, the literature study focused on the requirements for a haptic interface suitable for Extended Physiological Control (E.P.P). The literature study is included in full in appendix F. The following requirements were found:

The prosthesis system should ...

- use ate least two complimentary channels.
- be able to send controls with a bandwidth of at least 5 Hz.
- be able to receive feedback with a bandwidth of at least 8 Hz.
- have a latency of at most 50 ms.
- utilize position signals rather than velocity signals.

Furthermore, the haptic interface should ...

- utilize the combined movement of elevation/protraction.
- work within a working stroke of 30 mm.
- work with forces over 2 N.
- work with forces up to max. 15 N.

E.1.2. Shoulder Velocity Experiment

Methods

The pilot experiment was performed on three male participants aged 16, 17 and 48. Small square markers are cut from sports-tape and placed on the participant's back at locations similar to the markers in the study of Vardy *et al.* With a permanent marker, a black dot was drawn in the centre of the markers to allow for better tracking. The term uni-lateral shoulder elevation was explained and demonstrated to each participant. Only shoulder elevation was considered to keep the movement in a two-dimensional plane. The participants were seated in a chair with a low back such that their upper mobility is not restricted. A tripod with a video-camera was positioned behind the participant's chair. The participant was asked to elevate his or her shoulder and the height and the distance of the camera was altered such that the entire range of motion of the subject would be within the frame of the camera. The experiment set-up is depicted in fig. E.1 .

Participants were asked to perform three tasks:

1. STILL - Sitting as still as possible for approximately three seconds
2. NORMAL - Elevating the shoulder three times at a 'normal', comfortable speed
3. FAST - Elevating the shoulder three times as fast as they can

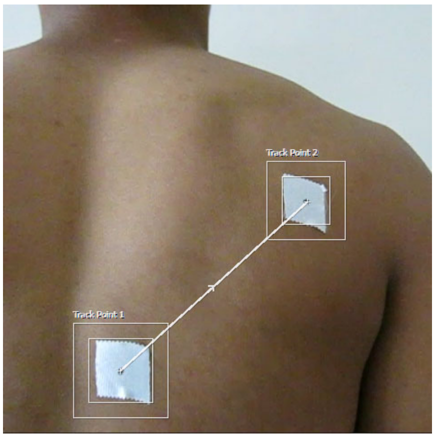
Before the first task the distance between the dots on the two markers was measured with an ruler. A separate video was recorded per task.

Figure E.1: Two markers are placed on the participants back. The participant was seated in a chair with a low back and his or her movements were recorded with a video-camera placed on a tripod.

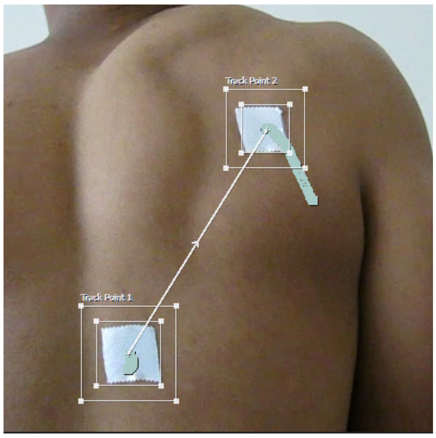
Data Acquisition
The participants' movements were recorded with a resolution of 640x480 at 120 frames per second using a camera (Canon G15) placed on a tripod. These video-files were imported into Adobe After Effects 2020, a software package for digital visual effects and motion graphics. The files were edited to the correct length and a motion tracking algorithm was applied. Here the 'Transform' track type was used, selecting both position and rotation, which yields two traceable points. The feature regions were scaled to the marker size and were placed such that the attach point corresponds with black dot drawn in the centre of the marker, as shown in fig. E.2a. Running the algorithm results in a set of keyframes containing position values for both points, as shown in fig. E.2b. The resulting keyframes were selected in the After Effects composition window and copied into a MATLAB data structure.

Velocity Calculation
Using two seconds (240 frames) of the STILL task, the mean of the distance between the two track points was calculated. The pixel-to-mm-ratio was then calculated using this difference and the measured distance between the two markers.

The measured distance in pixels was multiplied with this ratio to find the distance L between the data points. The difference ΔL was divided by the time step per frame ($\frac{1}{120}s$) to find the velocity in millimetres per second.



(a) track point placement



(b) resulting keyframes

Figure E.2: Example of the placement of the track points on the physical markers (left) and and resulting keyframes after tracking one shoulder elevation in Adobe After Effects (right).

Results

The distance L between the two markers is plotted in fig. E.3 for both the NORMAL and the FAST task. The three repetitions are easily distinguishable for all three participants. The relative velocity v between the two markers is plotted in fig.E.4 for both tasks. The maximum velocities found were in the range of 130 - 330 mm/s for the three participants.

Discussion

The number of experiments in this study is very limited, and the results can thus only give an qualitative estimate of the order of magnitude for the relative velocity between the two markers. The results show that, for uni-lateral shoulder elevation, the *maximum* relative velocity between marker pair placed on the back is in the order of magnitude of 300 mm/s. When the participants are asked to perform movements at a 'normal', comfortable pace these velocities are generally lower, with peak velocities in the range of 65-100 mm/s for the three subjects.

Limitations

The motion tracking and calculations were validated in a preliminary test with an object with a known constant velocity, a Numark TT1650 DJ turntable. This resulted in an error of <1%. However, an extra error might be introduced due to the inherent three-dimensionality of the human body, as only a two-dimensional movement is measured.

The graphs also indicate that the participants had different 'neutral' positions in each task. While it is imaginable that the participants do not always return to the same position, this could also be due to slight differences between the video recordings. The pixel-to-mm-ratio is only calculated once, and could thus also introduce a larger error. The locations on the participants' backs are not measured out to a standard. Different peak velocities might be reached for marker pairs at different locations.

Finally, the resolution (640x480) is quite poor, better results might be achieved with a camera capable shooting of high quality video at a high frame rate.

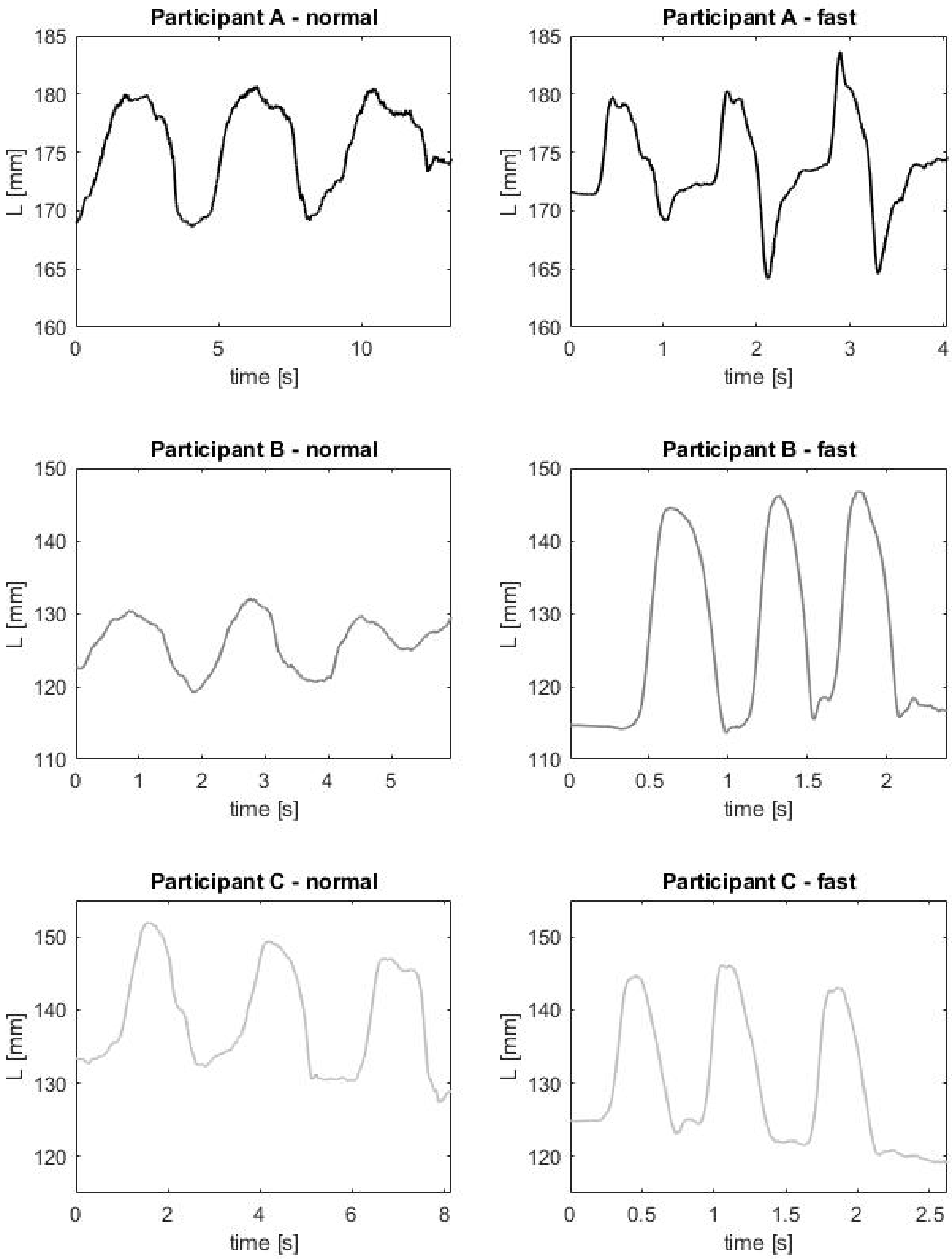


Figure E.3: Distance between the two marker points for both the NORMAL and the FAST task.

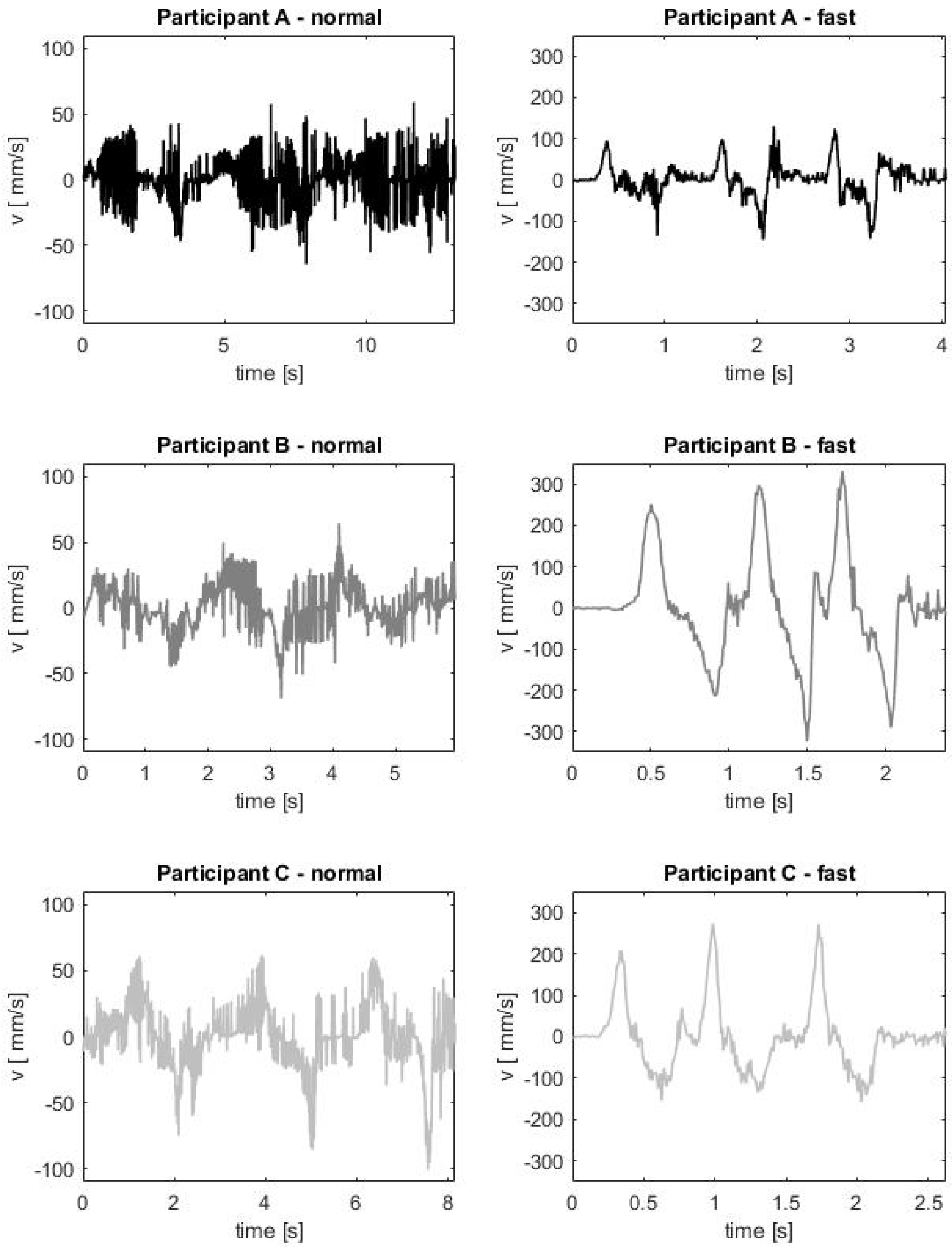


Figure E.4: Relative velocity between the two marker points for both the NORMAL and the FAST task.

E.2. Hardware Design

E.2.1. Actuator Selection

The hardware design process was initiated by searching for a suitable actuator. Actuators convert energy into motion and are the ‘muscles’ of a mechatronic system. There are various different energy sources (pneumatic, hydraulic, electric) but, following the thesis assignment, the search will be limited to electrical systems.

Initially, the focus lay on ‘robotic artificial muscles’ rather than the conventional rigid actuators. These actuators may offer many advantages, such as high power-to-weight ratio, high force-to-weight ratio, inherent compliance and no complex linkages. Several unconventional electric actuators have been considered, such as piezo-electric actuators, shape memory alloys, shape morphing polymers, di-electric polymers and electro-magnetic actuators. However, these types of actuators typically have low strains, low bandwidths, high voltage requirements and are not easily available.[4] Therefore, the choice was made to use a conventional electric motor for the design.

When selecting a motor, the flowchart from Kececi was used as a guideline.[2] As the design asks for a system with closed-loop position control, following the flowchart leads to a servo motor. Some notes on the other options:
Motors working on AC current are excluded as we would like to work with a battery. We would like a quick response of the motor to ensure a high feedback bandwidth, so brush-less DC (BLDC) motors are preferred over brushed DC motors. However, without specialized controllers, BLDC motors are difficult to control. A servo system is much easier to control, having the position-sensing unit and the control circuit already built in next to the DC motor and a gearbox. Whilst stepper motors also have excellent position accuracy, their system is open loop, they are typically slow and they constantly draw current. In a battery-powered system, the low power consumption of a servo motor is also a benefit.

I would like to note that by selecting a servo motor, an implicit decision has already been made to go for a system with force input and position feedback. Whilst it is possible to force control a servo motor based on the drawn current, this is not a precise system. If the servo has an additional spring element, and is, effectively a series elastic actuator (SEA), precise force control is possible. However, these types of actuators are not yet widely available and are thus not considered for this project.

Motor

A search was performed for servo motors on three large websites for electro-mechanical components: `rs-online.com`, `reichelt.com` and `digikey.nl`.

From all of the results on these websites, three suitable models were selected. These models were selected because they are all relatively compact servo motors with a high power density. Furthermore, the most suitable model was selected for each of the different types found, the linear actuator, the classic servo and the flat pancake model. The three models that were selected are shown in fig.E.5.

(a) Actuonix L12 (b) Robotis Dynamixel (c) Leto iBLDC

Figure E.5: Suitable servo motor options in three different styles, the linear actuator, the classic servo and the flat pancake model. Selected from the options sourced from `rs-online.com`, `reichelt.com` and `digikey.nl`

As discussed in section E.1.2, we expect maximum shoulder velocities to range from 100 mm/s to 300 mm/s, with 100 mm/s being the peak velocity for normal operation. To compare the different models, it was decided that at the peak efficiency rate, the servo must be able to reach 15 N at a linear

Table E.1: Comparison of the force/velocity specifications of the three servo motor options

Actuonix L12			Dynamixel XH-430-W350			Leto iBLDC		
			Peak Efficiency	2.51	rad/s	Peak Efficiency	6.28	rad/s
				0.75	Nm		.072	Nm
			radius	20	mm	radius	20	mm
Linear Velocity	19	mm/s	Linear Velocity	50.3	mm/s	Linear Velocity	125.7	mm/s
Force	10	N	Force	37.5	N	Force	3.6	N
1:4	76	mm/s	1:4	201	mm/s	1:4	62.8	mm/s
	2.5	N		9.38	N		7.2	N
1:2	38	mm/s	1:2	100	mm/s	1:2	41.9	mm/s
	5	N		18.75	N		10.8	N
3:4	25.33	mm/s	3:4	67	mm/s	3:4	31.4	mm/s
	7.5	N		28.13	N		14.4	N

velocity of 100 mm/s. To compare the rotational servos with the linear actuator, a radius of 20 mm was introduced to convert rotational torques to linear forces and rotational velocity to linear velocity. All the specifications are listed in table E.1. From this table it is clear that the linear actuator (Actuonix L12) is too slow and the pancake style servo (Leto iBLDC) is too weak. The Dynamixel servo has the best relative performance and meets the requirements when a 1:2 transmission ratio is added to the design. This is of course relative to the 20 mm radius that was assumed for the comparison of the servo motors.

Transmission

From the previous section it became clear that an additional transmission was desired to achieve the optimal force/velocity characteristics. Furthermore, a transmission is needed to transform the rotational motion into a linear motion. Several different concepts were considered for the transmission, see fig.E.6.

We decided to go with the simple 'winch', where a pulley is attached to the servo motor horn. The reasoning can be summarised as:

- This system has the least amount of parts. The parts are also easy to manufacture in-house.
- Winding up a cable on a pulley attached to the servo horn is a proven technique, which has been implemented before in the BioRobotics Lab.
- This system allows us to move the location of the servo motor. This way the servo motor can be positioned at hip height, where it is less obtrusive.
- This system allows for a large working stroke.

Different radii of the pulley when then compared in combination with different Robotis Dynamixel models. After looking at the performance graphs, which plot velocity, torque and efficiency, it was found that the Robotis Dynamixel XM430-W210 combined with a 30 mm pulley had the best specifications, with a linear velocity of 89.5 mm/s and a force of 33.3 N at peak efficiency. This also takes in consideration the dimensions of the servo, such that the pulley does not get so big as to compromise on the compact design of the haptic interface.

E.2.2. Force Sensor

Two main options were found for the force sensors. A commonly used option is the miniature load cell, such as the Futek LSB200, which is also used in the study by Vardy *et al.*.[3] The other option would be the Force Sensing Resistor (FSR). However, the FSR Integration guide and Evaluation Part Catalogue [1] states the following:

- 'Do be careful if applying FSR devices to curved surfaces. (...) If possible use a firm, flat and smooth mounting surface'

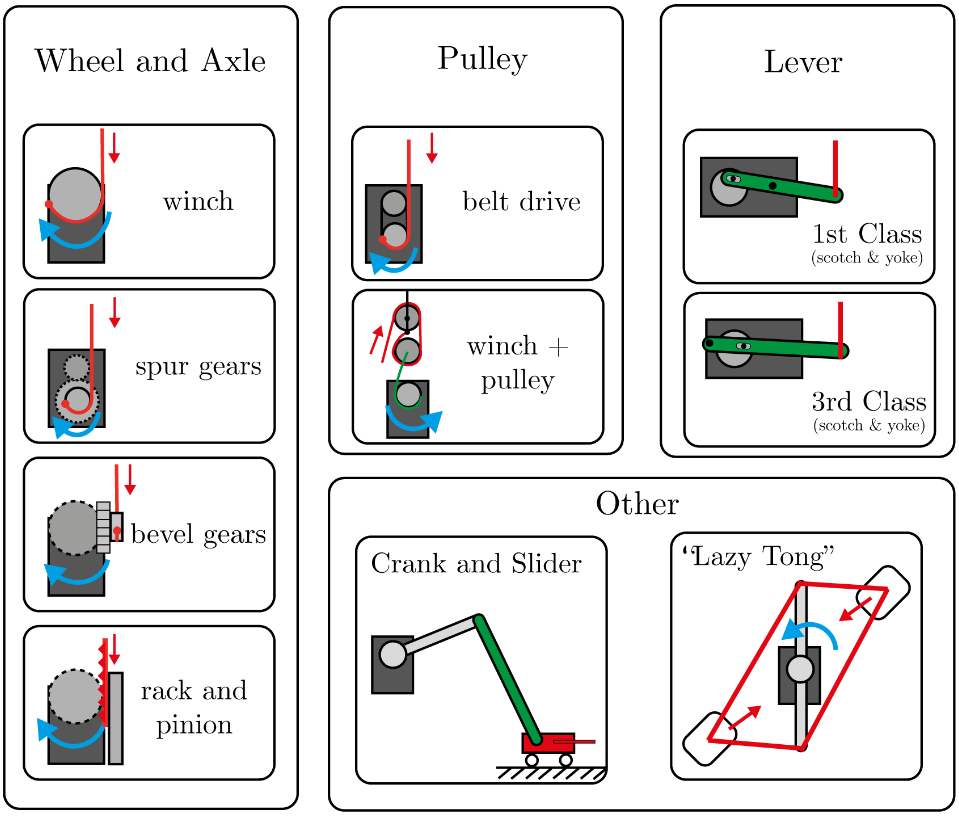


Figure E.6: An overview of the different transmission concepts considered after a design brainstorm. Where possible, the designs were grouped within the topology of the six simple machines. Not pictured: A ball/screw mechanism.

- 'The FSR sensor is not a strain gauge, load cell or pressure transducer. While it can be used for dynamic measurements, only qualitative results are generally obtainable. Force accuracy ranges from approximately ± 5% to ± 25% (...)'

The choice was therefore made to stick with the commonly used load cells. The Futek LSB200, 10 lb loadcell was paired with the Burr-Brown INA125 instrumentation amplifier and calibrated for 10 bits for a 0-20N range. The measured voltage can be converted to Newton with the following formula:

$$y = 0.0225x + 0.5976 \tag{E.1}$$

E.2.3. Micro-controller

For the control of the Robotis Dynamixel servo motor, the choice was made to stay within the Robotis ecosystem, as they provide multiple libraries to control the Dynamixel servos as well as an interface to power both the motor and the micro-controller from a single power source. Due to the compact size, the Robotis OpenCM9.04 was a logical first choice. However, during the prototyping phase of the project, numerous failures occurred with the boot-loader software of the OpenCM9.04. Therefore, the choice was made to switch to the Robotis Dynamixel Shield for Arduino. The Dynamixel Shield makes use of the primary serial port on the Arduino. An additional serial port is required, which can be used for the communication with prosthetic hand, or for this project, the (virtual) slave. On the Arduino Uno, there is only serial port, so the Arduino Mega2500 was selected as it has multiple hardware serial ports. Defining a SoftwareSerial port on the Uno could theoretically be an alternative, but this was not a robust solution and raised communication issues.

E.2.4. Cabling, Enclosure and Skin Anchors

Due to the size of the servo motor and the micro-controller, the choice was made to locate the enclosure at hip height rather than directly at the shoulder. By moving the rather bulky parts to a location with more space, we can make the design appear slim and non-intrusive. This also transfers the weight to the hips, rather than the skin achors carry the full weight. The length of the cables was determined on the back length (shoulder height - hip height) of adult males according to DINED. The P10 - P90 range for the back length is 453 mm - 487 mm.

A 190 mm Bowden tube was inserted between the enclosure and the first skin anchor. This Bowden tube allows for smooth movement of the Bowden cable and also acts as a structural spacer. The first cable, with a point-to-point length of 100 mm, is inserted between the upper skin anchor on the shoulder and the load cell. The length of the load cell is 20 mm. The lower cable length was set at 360 mm. When the servo (with a 30 mm pulley) is set at 180 degrees, this results in a total 'back length' of 480 mm. The servo can then be moved to shorten or lengthen the cables. To accommodate for different back sizes a 30 mm change is required, which results in roughly 115 degrees. An additional 30 mm (1̃15 degrees) is required for the feedback range, totalling at 230 degrees, which is well below the possible range of roughly 270 degrees. Following the advice from Jan van Frankenhuyzen, the cables were soldered into the M3 screws and in the endstop (see appendix B).

E.3. Software Design

All of the code was written in Arduino and Python, which are publicly available for free.

E.3.1. Experiment Interface

In this section, a short explanation is given of all of the components of the digital experiment interface. The experiment interface was build in a PyQt-framework with a connection to one of the laptop's serial ports. The experiment interface consists of the following parts:

- **Participant Information**
  Before starting the experiment, fill in the experiment meta-data, such as the participant identifier (A, B, C, etc.), as well as their age and sex.

- **Start Experiment**
  If the system has established a serial connection with the micro-controller, the 'Start Experiment' button will be enabled. Starting the experiment will disable debug functions and will enable experiment functions such as the trial timer and saving the log at regular intervals.

- **Save Experiment**
  When a experiment is running, the 'Save Experiment' button will save the data of all recorded trials to a .csv file, coded with the participant identifier, the date and the time of the experiment. A warning will be displayed when not all trials in the experiment have been completed.

- **Force Indicator**
  Displays the force exerted by the participant on a scale of 0 - 20 N. Can be turned on/off on the participant monitor with the check-box. A permanent display of the force slider is shown to the researcher for debugging purposes.

- **Virtual Slave**
  The left bar is fixed, the right bar moves towards the left as a function of force and stiffness. When no force is applied, the virtual 'ball' is a circle, this shape is changed into a ellipse to enhance the idea of compression. The virtual slave portrays an abstract representation of a 1D voluntary closing prosthetic hand. The visualization was done with the matplotlib library.

- **# of Probes**
  During the experiment the researcher can monitor the number of probes counted by the system. Probes are counted as 0.25 probe for each pass in either direction through the two thresholds of 55mm and 50mm.

- **Serial Communication Section**
  Used to connect with the serial port of the micro-controller. One can fill in the desired COM port as well as the baudrate. With the radio buttons it is possible to monitor the force, stiffness and positions which are broadcasted by the micro-controller. The lower screen shows the commands that are send to the micro-controller. Finally, at the bottom, there are two buttons to reset and save the log of raw data points.

- **Choice Buttons**
  When the experiment is running, the researcher can start the timer by clicking on the 'Start Timer' button. When the participant has voiced their choice (either 'hard', 'medium' or 'soft') the researcher can end the timer by clicking on one of the three choice buttons. The participant's choice, as well as their completion time and number of probes are then added to the data log of the experiment. The timer button will be disabled until the system confirms that the stiffness and conditions have been updated. The system will wait with updating the stiffness until the participant has reached a resting (F < 1.5 N) position.

- **Stiffness Values**
  Before starting the experiment the researcher can change the desired numerical values corresponding to the 'hard', 'medium' and 'soft' levels in the experiment. When the experiment is not running, it is also possible to send a stiffness to the micro-controller using the radio buttons and the 'Change Stiffness' button.

- **Servo Control**
  Finally, the last section is for monitoring and control of the servo motor. The dial shows the servo motor position. The servo feedback (or the haptic feedback) can be turned on and off using the check-box. Furthermore the θ_0 position of the servo can be altered using the four buttons on the side.

E.3.2. Filter

Problem
In operation, the haptic interface showed a form of high frequency jitter. This is most likely caused by a unwanted feedback loop where the servo motor 'pulls' directly on the load cell and thus bypasses the human controller. This is depicted in figure E.7.

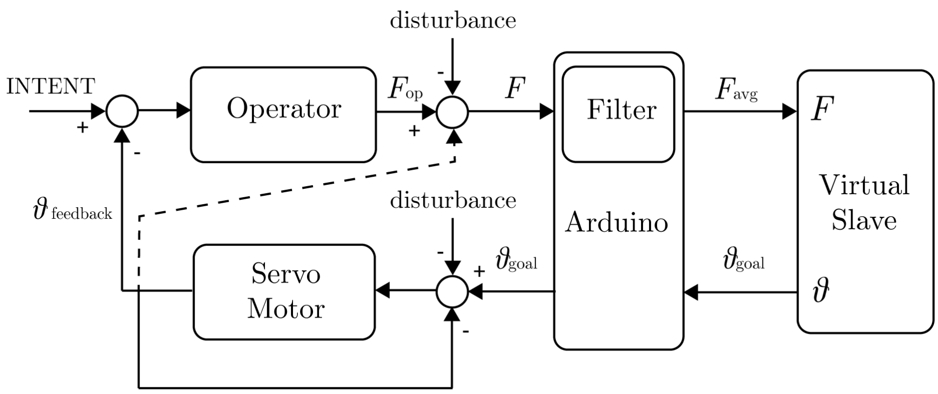


Figure E.7: Possible cause for the jitter occurring in the haptic interface (dashed line). The positional feedback from the Servo Motor directly affects the load measured by the load cell, without interference from the human controller.

We found the following:

- The jitter mostly occurred when trying to maintain a constant force level
- The jitter could be reduced by increasing the virtual stiffness k.
- The jitter could be reduced by reducing the impedance between the two skin anchors.
- The jitter had frequencies >5Hz.
- Performance improved at higher baudrates.

This problem could thus be solved by minimizing the latency and either adding a damping element or implementing a low-pass filter to the system.

Damping
For the damping element, two options were considered:

1. Physical Damper
   Adding a physical damper would solve the feedback loop whilst reducing the bandwidth. Most dampers found online would compromise the elegant, slim profile of the current design. The most promising solution would be adding a compliant element within the design of the skin anchors. This could for example be done by adding many thin pillar as a grass-like structure between the upper and bottom layer of the skin anchor. However, to test and optimize the strength and compliance of such a design quickly becomes very time-consuming, which is why the decision was made to implement a software-based solution.

2. Virtual Damper
   The virtual slave was modelled as only a spring, but could be modelled as a mass-spring-damper system to include a damping element. Modelling the system as:

$$\sum F = -kx - c\dot{x} + F_{\text{op}} = m\ddot{x}$$

   This gives an ordinary differential equation, which we tried to solve within the Arduino loop. This was implemented with a Runge-Kutta fourth order method, a custom State-Space implementation with the BasicLinearAlgebra library and finally with the simulation step from the StateSpaceControl library, but none of the methods were successful in real-time. It might be possible to find a solution within a couple of ms, but for this project the decision was made to look for a different solution.

Butterworth Filter
Looking at different low-pass filter designs (Elliptic, Chebyshev type I and II, Butterworth), it was decided that the Butterworth filter would be most suitable for this application. It does not affect the gain of the signal in the pass band and, depending on the order, it can have a steep cut-off. Two methods were investigated for the implementation of a Butterworth filter.

1. Matlab Filter Design
   Using Matlab, it is possible to design a 3rd order Butterworth filter with the following code:

```
fc = 5; % [Hz] cut-off frequency
fs = 50; % [Hz] sampling frequency
omega = fc/(fs/2);
[b,a] = butter(3, omega); % filter
H = tf(b,a); % transfer function
Hd = c2d(H, (1/fs)); % discrete
```

   Which results in the following discrete transfer function:

$$H_d(z) = \frac{0.0181z^3 - 0.05318z^2 + 0.05208z - 0.017}{z^3 - 3.035z^2 + 3.071z - 1.036} = \frac{Y(z)}{X(z)} \tag{E.2}$$

   To calculate $Y(z)$ for a given $X(z)$, this formula can be rewritten in a discrete manner as:

$$\begin{aligned} Y[k] = 0.0181X[k] - 0.05318X[k-1] + 0.05208X[k-2] - \\ 0.017X[k-3] + 3.035Y[k-1] - 3.071Y[k-2] + 1.036Y[k-3] \end{aligned} \tag{E.3}$$

   However, there were again problems with the implementation of this formula on the Arduino.

2. Arduino Filter Library
   As a alternative, the Arduino Filters library was used with Normalized Butterworth Polynomials. Six different variations were tested:

   - 2nd order, $f_c = 5$
   - 3rd order, $f_c = 5$

- 4th order, $f_c = 5$
- 2nd order, $f_c = 10$
- 3rd order, $f_c = 10$
- 4th order, $f_c = 10$

Moving Average Filter

Finally, the last filter that was implemented was a moving average filter. The averaged value $x_a vg$ can be written as:

$$x_{avg,i} = \sum_{k=0}^{n-1} \frac{1}{n} x_{(i-k)}, \quad n = 5, 10 \tag{E.4}$$

At a sample frequency of 50Hz, a moving average filter with 10 samples will pass signals up to 5 Hz. With 5 samples this is increased to 10 Hz. A downside of the moving average filter is that the pass-band is not flat, but has a sort of ripple.

Comparison of Solutions

A script was written to apply all of the filters described were applied to a unfiltered signal and logging the results. The Fourier transform of these signals are plotted in fig. E.8.

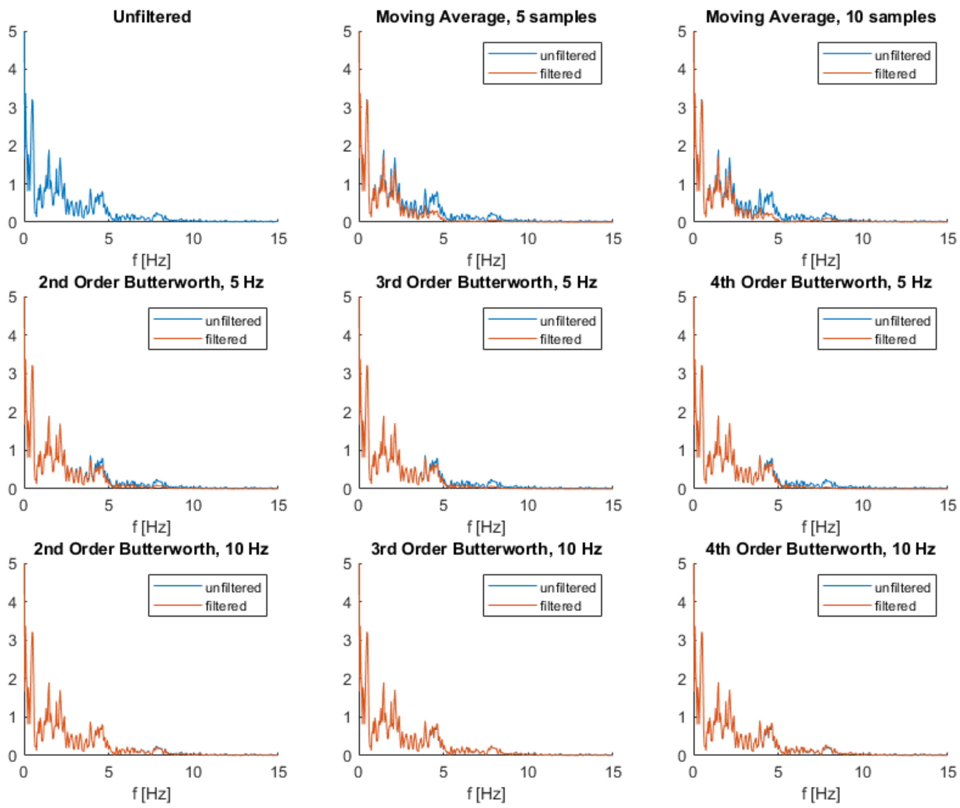


Figure E.8: Fourier transform of the different filtered signals.

A qualitative assessment of the different control signals showed that there was still jitter in all Butterworth filters. This could be indication that reducing the small peak around 4.5 Hz is essential for removing the jitter. It is hard to draw definitive conclusions, as the design of the filter changes the system and thus the frequency at which the jitter occurs. Nevertheless, the Fourier transform does give some insight on the behaviour of the different filters on the unfiltered signal. Through the qualitative assessment, best performance (meaning the least amount of jitter, smooth movement) was found for the moving average filter with 10 samples, which was used in the experiment.

F

Literature Report

Literature Study on the requirements for a wireless haptic interface suitable for E.P.P. control

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June 4, 2020

Abstract

Current prosthesis technology is often rejected due to a multitude of reasons including discomfort and ease of control. Implementation of Extended Physiological Proprioception (E.P.P.) would allow the comfort benefits of an externally powered prosthesis while maintaining the ease of control of a body-powered prosthesis. In E.P.P. the natural proprioceptive senses of the human operator are extended to the prosthesis by providing an intimate coupling between the prosthetic joint and a different healthy joint. A wireless, shoulder-worn haptic interface was suggested for such an E.P.P-controlled prosthesis, however, the requirements for this interface are still unknown.

A literature search was performed on the databases of Scopus, IEEE explore, PubMed and Web of Science. The search was broken down into three subsets: (1) existing E.P.P. systems, (2) x-by-wire systems and (3) tele-operators. The latter two are developments in other fields that are similar to the technology required for the wireless interface for an E.P.P controller.

A theoretical background was provided on the properties of an E.P.P. system, the effect of the controller architecture on the transparency of the system and the validity of the shoulder as a control location. An E.P.P-controller should make use of at least 2 communication channels, which should be complimentary. This allows for theoretically transparent behaviour with either a forward-force/position-reflection or a forward-position/force-reflecting controller architecture. Requirements were also presented concerning system bandwidth (5-8 Hz), latency (50 ms), actuator force (2-15 N) and actuator stroke (<30 mm). Additional recommendations were made where literature was inconclusive on the exact data. The presented list of requirements is not complete but provides a solid foundation for further development of the haptic interface.

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1 Introduction

Throughout history man has used prostheses and prosthetic implants to replace missing body parts that may be lost due to trauma, medical illness or congenital condition.[1] Each year about 50 children are born with a transverse upper limb reduction in the Netherlands and additionally ca. 40 people lose an upper limb or hand, providing an increasing group of clients with an arm deficiency.[2] Still many patients choose not to wear a prosthetic device with mean rejection rates reported between 23% - 26% and 20% cases of non-wear in adult populations.[3]

Biddiss *et al.*[4] ($n = 242$) found that, among other factors, dissatisfaction with the current prosthesis technology is highly associated with prosthesis rejection, with 74% of prosthesis rejecters (i.e. used a prosthetic device once a year or less) stating that they might reconsider prosthesis use if technological improvements were made at a reasonable cost.

A study by Vardy *et al.* proposed such a technological improvement: a haptic upper-limb prosthetic interface that is capable of sending proprioceptive feedback, using skin anchors instead of the traditional shoulder harness. The interface is connected wirelessly to an externally powered prosthetic hand, as shown in fig. 1.[5]

To know how and why this haptic interface is an improvement on current technology an overview will be given of the currently available prosthesis types, their strengths and their shortcomings. From there the areas of improvement can be identified and some will be highlighted because of their relevance to the proposal.

Finally, with a general understanding of the current technology available, the proposal for the new haptic interface will be explained in further detail. The exact requirements for such an interface are still unknown. The aim of this literature study will be to find these requirements so that the haptic interface can be developed in further research.

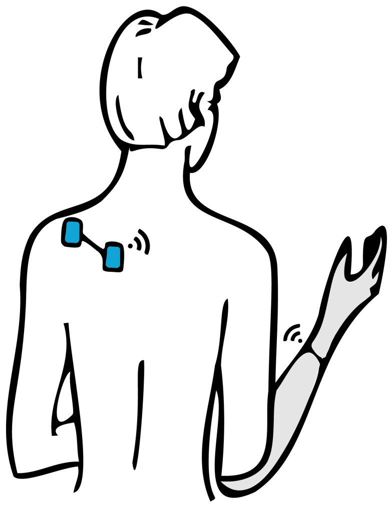


Figure 1: The proposed new prosthesis interface. The interface is attached to the user using skin anchors and has a wireless connection with the prosthetic hand. Figure adapted from Vardy.[5]

1.1 Prosthesis Types

A quick overview will be given of the current upper-limb prosthetic technologies and main reasons for rejection. Current prosthetic technology can be categorized into two main groups: passive and active prostheses. A full taxonomy of currently available prosthesis types is given in fig. 2.

1.1.1 Passive Prostheses

Passive prostheses can be further subdivided in cosmetic and functional prostheses, also known as prosthetic hands and prosthetic tools. Prosthetic hands offer a lifelike appearance and aim at the aesthetic substitution of the missing body part. Prosthetic tools (also referred to as task-specific prostheses) have a more mechanical appearance and aim to facilitate specific (two-handed) activities. These activities are often related to sports, recreation, work and vehicle driving, but some prosthetic tools (e.g prosthetic hook) are also very useful in activities of daily living (ADLs). Both passive prosthesis types can be either static or adjustable

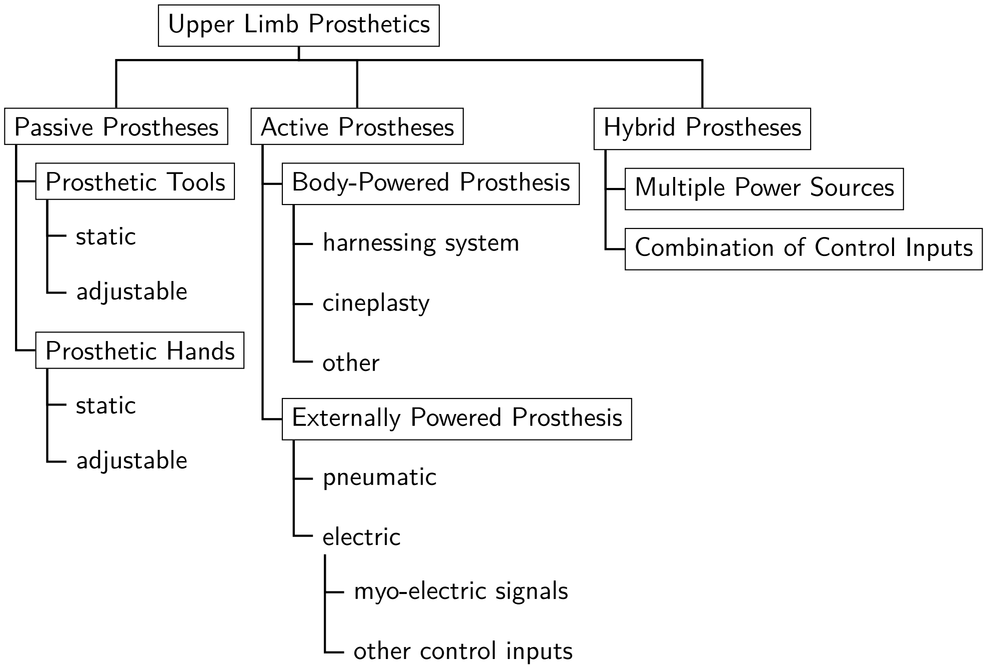


Figure 2: Taxonomy of currently available prosthesis technology

(also referred to as positional). Static prostheses cannot be moved at all whereas adjustable prostheses feature mechanisms like malleable armatures or ratcheting joints.[6–8]

While passive prostheses can provide enhanced functionality with minimal harnessing and cables this functionality is often very task-specific. These prostheses are thus not suitable for a broad range of activities.[9]

1.1.2 Active Prostheses

Active prostheses include body-powered prostheses, externally powered prostheses and the combination of the two: hybrid prostheses.

Body-Powered Prostheses

Most body-powered prostheses make use of a harness system to capture body movements, usually of the shoulder, arm or chest. These movements produce an excursion of a Bowden cable which allows for movement of a terminal device (TD) such as a hook or a hand.[8,9] The terminal devices can be either voluntary closing or voluntary opening, depending on the activity or user preference.

Other body-powered control techniques include direct muscle attachment (cineplasty)[10] and the WILMER elbow method. In the latter elbow movements are used to control the terminal device instead of movements of the shoulder or the upper arm. Extension of the elbow corresponds with opening of the terminal device and vice versa.[11]

Body-powered prostheses are typically lighter weight, durable and rugged. They have a simple and intuitive control method and provide secondary proprioceptive feedback to the user. Finally, they are generally cheaper and have lower maintenance cost than the other available options. The most common complaint is that the harnesses are restrictive and uncomfortable. Users also dislike the mechanical look of the prosthesis and the visibility of cable through the user's clothing. Poor grip force, limited functionality of the terminal devices and the energy expense for operation are also reasons for rejection of body-powered prostheses.[8,9,12,13]

Externally Powered Prostheses
Externally powered prostheses exploit an external power source to raise the energy for movement. In general, this power source will either be pneumatic or electric. Often a rechargeable battery system is used to power electric motors.[8]

There is a wide range of inputs possible for externally powered prostheses but the most common control method is through electromyographic (EMG) signals. These small electrical signals are generated when the unaffected skeletal muscles in the residual limb contract. Using electrodes on the skin or directly implanted sensors these signals are recorded and using various control schemes the user intent is deciphered.[14] Unfortunately, the EMG signal connection can be affected by the position of the electrode, movement, sweat and noise from the motors. It may also be difficult to find suitable control sites with higher amputation levels.

Other researched control inputs include a throat microphone,[15] foot controls,[16] ultrasound muscle activity[17] and Brain-Machine Interfaces.[12] Input devices can also be designed using electrical components such as potentiometers, force-resisting transducers or push-button switches.[8] With this kind of input devices a larger degree of control can be achieved by the user, but the required amount of training can be exhaustive and lead to user frustration.[12]

Externally powered prostheses have a higher grip force potential and an increased functional work envelop. The grip force is also bi-directional, meaning that they are both voluntary opening as well as voluntary closing. Disadvantages include higher initial costs, overall weight, contact temperature, maintenance costs and intolerance to wet and dirty environments. Additionally, as the visual feedback is the primary source of feedback there is an increased reliance on visual attention, which is another reason for rejection of these types of prostheses.[8,9,13]

Hybrid Prostheses
Hybrid prostheses are a combination of both body-powered and externally powered functions in one prosthetic device. The most common configuration is a body-powered elbow in combination with an electrically powered hand/wrist. Sometimes the term hybrid prostheses is also used to indicate electrically powered prostheses that acquire data from different input sources.

Hybrid prostheses are lighter than their fully electric counterparts and generally provide more grip strength as compared to their fully body-powered counterparts. The combination of actuation techniques or control inputs also allows the user to (simultaneously) control more degrees of freedom. A disadvantage is the sustained need for a shoulder harness.[8,9,12]

1.2 Improvements

Collectively, studies disagree as to whether body-powered or (myo-)electric prostheses are ultimately superior to one another. Users may reject an upper-limb prosthesis for a multitude of reasons, including lack of functional need, discomfort (weight, temperature, energy expense), ease of control and impediment to sensory feedback.[4,13] Because of the broad range of possibilities within the field of upper extremity prosthetics it would be difficult to discuss every reason for rejection. Vardy *et al.*[5] note two specific drawbacks in their paper:

- discomfort and compensatory movements due to high operation forces in body-powered prostheses
- high mental load due to lack of proper feedback in myo-electric prostheses

In the following section both these drawbacks will be investigated.

1.2.1 Discomfort

Operation Forces
A common complaint about body-powered pros-

theses is the physical load it imposes on the user. The activation cable forces required to achieve a 15 N pinch force at the terminal device range from 33 to 131 N in the evaluated prostheses.[18] Comparing this to the maximum operation forces for fatigue-free operation, a study from Hichert *et al.* showed that 8 of the 10 of the evaluated prostheses could not be operated fatigue-free by over 50% of the subjects.[19]

Optimal operation forces would lie between 10 and 20 N for subjects with arm defects, a range that none of the evaluated prostheses operate in.[18,20] Next to the discomfort or even pain, the high operation forces may disturb the user's perception of proprioceptive feedback.[20] Lower cable operation forces would lead to better control of the prosthesis.[20,21] Finally, the high operation forces limit the maximum grip strength of the user, which is also commonly reported as an area of improvement for prosthetic design.[6] Several solutions are suggested to tackle this problem, such as lowering the overall hysteresis of the system,[18] implementing transmission ratios or servo mechanisms,[20] or the use of an external power source.

Harness

Another source of discomfort in body-powered prostheses is the shoulder harness. The most commonly used 'figure-of-8' or 'figure-of-9' harnessing systems consist of an axilla loop around the contra-lateral shoulder and a control strap that is attached to the prosthesis.[8] An example is presented in fig. 3.

When performing (maximal) force tasks users reported pain in the neck, upper back, shoulder and armpit as well as irritation and touchiness.[22] Frequent wearers of prostheses are also likely to experience skin irritation and/or blisters as consequences of prosthesis use.[4] There is also the cosmetic aspect of the shoulder harness: the suspension system and cables can be visible through and damage the user's clothing.[13] Some users also dislike the appearance of the cable and harness, although it is not mentioned as a design priority.[6,8]

There have been several attempts to improve the comfort and cosmetic value of body-powered prosthesis. Many different harness pattens exist and research has been done into alternative body-power sources without the need for a shoulder harness were explored, such as the earlier mentioned cineplasty and the WILMER elbow method.

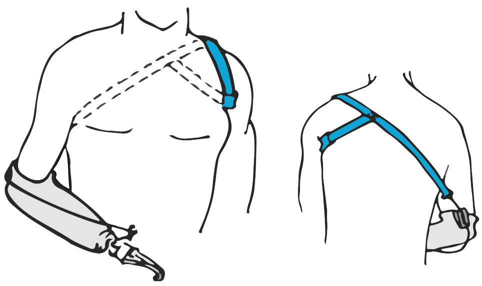


Figure 3: Schematic representation of the 'figure-of-9' shoulder harness for a body-powered prosthesis with a prosthetic hook. Figure adapted from 'Upper Limb Prosthetics'[23]

Other research focused on alternatives for the harness, one of which is the Ipsilateral Scapular Cutaneous Anchor System of Debra Latour.[24] In this Anchor system the Bowden cable is attached to a flat plastic patch that is directly adhered to the skin at the scapula, as can be seen in fig. 4. With this system the contralateral side of the body is not restricted in the motion and free for other tasks. The straps are eliminated altogether which reduces the discomfort around the armpit and shoulder and increases the cosmetic value.[25]

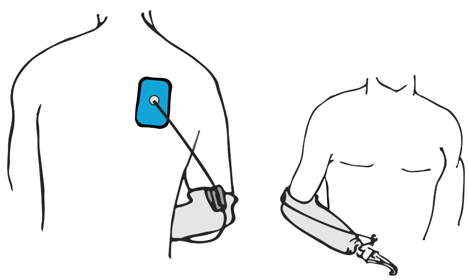


Figure 4: Schematic representation of the Ipsilateral Scapular Cutaneous Anchor System, designed by Debra Latour.[24]

1.2.2 Sensory Feedback

The basis of hand movement is closed-loop motor control as it is highly dependent both on efferent motor control and afferent sensory feedback. Consequently, a common thought is that prostheses would function better if they used closed-loop control as well. The current absence of sensory feedback systems impedes the efficient use of prosthesis systems. Ideally, a prosthesis should be able to convey both exteroceptive (i.e. physical interactions with the environment) and proprioceptive (i.e. state of the prosthesis, joint angles) information to the user in a perceivable and possibly effortless manner.[26,27]

Sensory Feedback Techniques
Sensory feedback systems use sensors to detect external stimuli. The information is sent to a haptic feedback device that conveys this information to the prosthetic user. Childress *et al.* originally divided sensory feedback signals into three different pathways, shown in fig. 5.[26,28]

Currently, most prosthetic devices lack haptic feedback systems by design and as a result prosthetic users adopted alternative strategies to close the control loop, they rely heavily on visual feedback as well as other indirect feedback mechanisms.[27] In these cases sensory substitution methods are applied and the state of the prosthesis is communicated through feedback signals that are not representative of what the missing limb would experience. In current myoelectric prostheses the grip strength (touch or pressure) is for example estimated by the user using auditory cues like the motor sound.[26,27] This is referred to as pathway A. (See fig.5)

The need to process the modality and/or the location of the perceived feedback signal applies an extra cognitive demand on the user and operation of the prosthesis requires high and continuous attention. The extra cognitive load may negate on one of the potential benefits of sensory feedback, reduced conscious attention.[27]

In pathway B, haptic feedback systems are applied to sense external stimuli and translate these to somatic sensory signals (e.g. tactile, proprioception, temperature, vibration) directed to the skin or directly to the central nervous system (CNS).

The final pathway, pathway C consists of feedback signals intrinsic to the prosthetic control system. In this pathway the control-loop is closed without having the user in the loop. Moving the control loop from the user to the prosthetic device could reduce the cognitive load but does not allow the user to manipulate the prosthesis according to what is sensed. Thus, for optimal control it makes sense that the control loop needs to be closed through pathway B: the sensory motor system.[26]

Within Pathway B there still several different possible techniques to close the loop.

1. Sensory Substitution
   The information from the prosthesis is communicated to the user through a different sensory channel or through the same channel but with a different modality. The user has to interpret the type and location of the stimulus and be able to associate it with the information from the prosthesis. The sensory substitution here differs from the feedback in pathway A in the sense that the feedback systems are purposefully designed to communicate information to the user (e.g. grasp force through vibrations pads). Commonly used techniques are vibrotactile stimulation, electrotactile stimulation and auditory feedback, all of which have studies reporting improvement in grasping tasks as compared to visual feedback alone.[26,27]

2. Modality-matched Feedback
   Feedback is said to be modality-matched when the user senses the feedback signal in the same way it would sense the original information from the prosthesis. One could have modality-matched exteroceptive feedback, where electromechanical and thermoelectric devices are set up such that for example touch on the prosthesis is experienced as touch by the prosthetic user.[26]

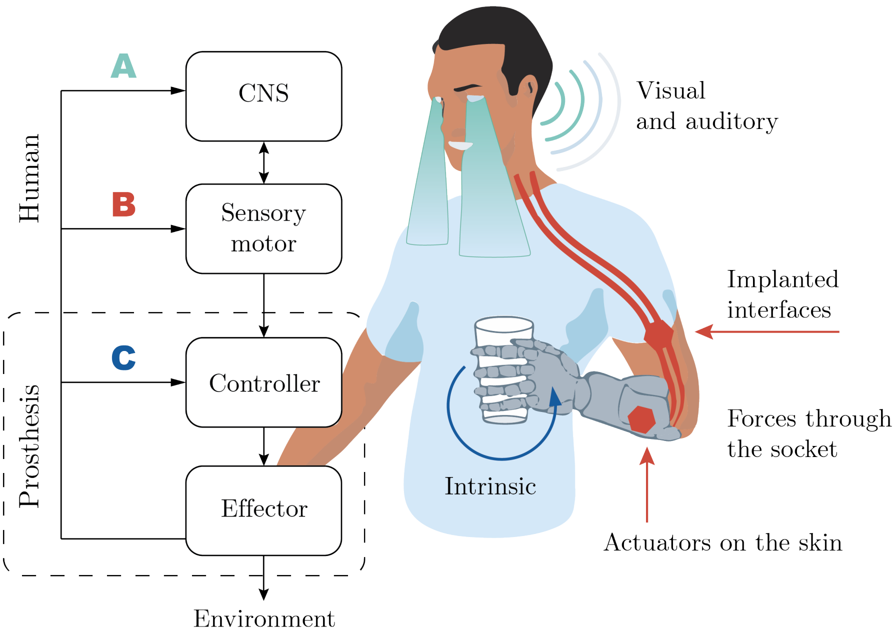


Figure 5: Overview of the three different feedback pathways. Figure adapted from Antfolk.[26]

3. Somatotopically Matched Feedback
   Even with modality-matched feedback the user must still process the difference in location of the perceived feedback signal as compared to the 'natural physiological feedback' that one would get from a sound limb. Schofield *et al.* discuss a final method where the feedback signal is also somatotopically matched, meaning that, using direct neural stimulation techniques, the prosthetic user will sense the feedback signal at the same physiological location as feedback from a sound limb. Using somatotopically matched feedback may further reduce the cognitive load on the user and require less training.[27]

As mentioned before, the need to process modality and/or location is undesired. By adding haptic feedback systems purposefully designed for closed-loop control it might be possible to reduce the cognitive load and thus increase the ease of control for the prosthetic user.

A good baseline to work towards it that of body-powered prostheses where it is shown to be possible to achieve sub-conscious control. The strength of body-powered prostheses lies in the sensory feedback that is inherent to the 'Bowden cable'-design. This cable couples the dynamics of the body of the prosthetic user to the dynamics of the world encountered by the prosthesis. This coupling allows for both proprioceptive and exteroceptive feedback from the prosthesis.[29] Essentially, the design of the body-powered prosthesis provides modality-matched proprioceptive feedback through the concept of extended physiological proprioception.

Extended Physiological Proprioception
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 movement of the prosthesis is (proportionally) linked to the movement of one of the natural joints, for example the shoulder.[30] Because of this linkage the user can sense the state of the prosthesis through his natural joint, the proprioceptive senses of the user are 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.[31]

Because the feedback is sensed through the naturally arising proprioceptive sensations of the sound joint the signal is inherently modality-matched.

Next to the commonly available body-powered Bowden-cable prosthesis[32] several other methods for applying the concept of E.P.P to prosthetic control have been investigated. Researchers have looked at different types of body-powered actuation such as (pseudo-)cineplasty[10,33] and exteriorized tendons as well as externally powered prostheses using pneumatics[30] or electric motors[34] as a power source.

These techniques all require some form of harnessing and cables, which is aesthetically unpleasing and can be uncomfortable. Koukoulas *et al.* did design a bio-mechatronic controller without the need for a mechanical linkage, but this design requires surgery to directly attach DC motors to the muscles.[35] A final method of implementation is with the EMG of a shoulder muscle as input while using functional electrical stimulation to limit the shoulder position.[36]

1.3 Haptic Interface Proposal

The proposal by Vardy *et al.* is the development a new haptic interface for an electrically powered prosthesis that can provide proprioceptive feedback to the user. The interface will make use of skin anchors and wireless communication instead of a shoulder harness, removing a source of discomfort while at the same time making the design more aesthetically pleasing, as can be seen in fig.6. By using an externally powered controller the control forces can be kept in a comfortable range. Proprioceptive feedback is fed back to the user by pulling the two skin anchors together.[5]

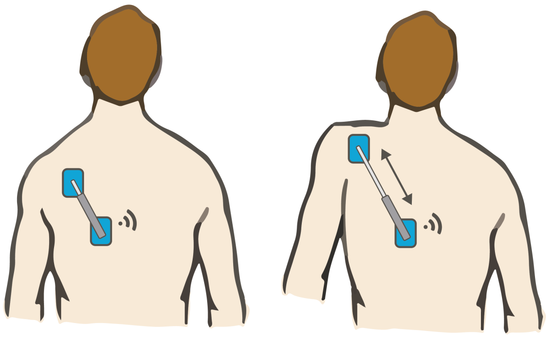


Figure 6: The proposed new prosthesis interface. The control input is exerted by the same movement as a body-powered prosthesis. Figure adapted from ACE Fitness.[5,37]

The proposed prosthetic 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.[11]

One of the key elements of this interface is the actuation between the skin anchors that will allow for the proprioceptive feedback. With no mechanical linkage available, there needs to be an intimate virtual coupling between the haptic interface and the prosthetic hand to allow E.P.P control. Next to that the timing aspect of the feedback is crucial. Short latencies are important for the brain to develop a sense of embodiment of the prosthesis.[26] The exact requirements for a 'wireless' E.P.P actuation system are currently unclear, which leads us to the research question of this literature study:

- What are the requirements for a wireless, shoulder-based, haptic interface suitable for E.P.P control?

2 Method

The literature study is performed following the guidelines of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analysis) statement. The PRISMA statement consists of a 27-item checklist and a four-phase flow diagram and was set up to help authors improve the reporting of systematic review and meta-analyses.[38]

2.1 Search Strategy

Three database searches were performed to gather background information on the research question. An initial database search was performed using the Scopus, IEEE XPlore, PubMed and Web Of Science search engines using the terms ((*"extended physiological proprioception"* OR *E.P.P* OR *EPP*) AND *prosthe**) in the meta-data of the articles. This search yielded a total of 59 unique articles. All types of articles and publications of all years were included.

This first search aims to find the theoretical requirements of a wireless E.P.P. control system as well as listing what devices currently exist and find the design requirements for those devices. Because of the limited amount of research in the field of E.P.P. the search was extended to related fields.

The control system of an E.P.P.-controlled hybrid prosthesis using Bowden cables and an externally powered terminal device can be compared to a type of power assist system such as power-steering system for a car.[10,31,32] In these systems there is still a mechanical connection between the input and the output.

When the mechanical link is removed and is replaced entirely by electro-mechanical components you enter the field of x-by-wire systems. The system-inherent haptic feedback is lost with the removal of the mechanical link but x-by-wire systems have developed systems that preserve the operator's proprioceptive feedback ('feel') with the vehicle.[39] The field of force-reflecting tele-operators is also very relevant, as removing the direct (mechanical) link between the anatomical and prosthetic joint makes the prosthetic device, in essence, a tele-operator.

Additional searches into these fields were performed on the Scopus and IEEE XPlore databases. To explore the field of *-by-wire systems the following search terms were used: (*"haptic feedback"* OR *"force feedback"*) AND **by-wire*). For the IEEE XPLORE engine this last term was adapted to *"by wire"*. The search terms related to the field of haptic feedback in tele-operation were: ((*"tele operat*"* OR *tele manipulat** OR *teleoperat** OR *telemanipulat**) AND (*"haptic feedback"* OR *"force feedback"*) AND (*proprioceptive* OR *kinesthetic*) NOT "*shared control*"). All database searches were performed latest in January 2020.

Finally some additional studies were identified through external sources, which include references from studies included in the qualitative set as well as relevant (unpublished) work from my supervisor and/or his colleagues.

2.2 Selection Criteria

Following the PRISMA method flow diagram, duplicate entries were removed from the set of identified studies. Afterwards an initial screening was performed based on the title and abstract. Reasons for exclusion may include irrelevant topics or the topic being to specific too the field, thus not relevant for the analogy to prosthetic control.

Articles concerning shared compliant control (SCC) were excluded because SCC allows the force/torque feedback loop to reside entirely in the robot side, whereas standard force reflection allows the operator to feel forces and torques sensed at the robot.[40] Similarly, articles regarding extended physiological taction, cutaneous feedback (specifically skin-stretch devices), simulation environments and virtual feedback are excluded from the qualitative set. Studies were also excluded when the full-text was not available or not available in English.

Studies are included for the full-text eligibility phase when they provide either high-level information about the system schematic, when

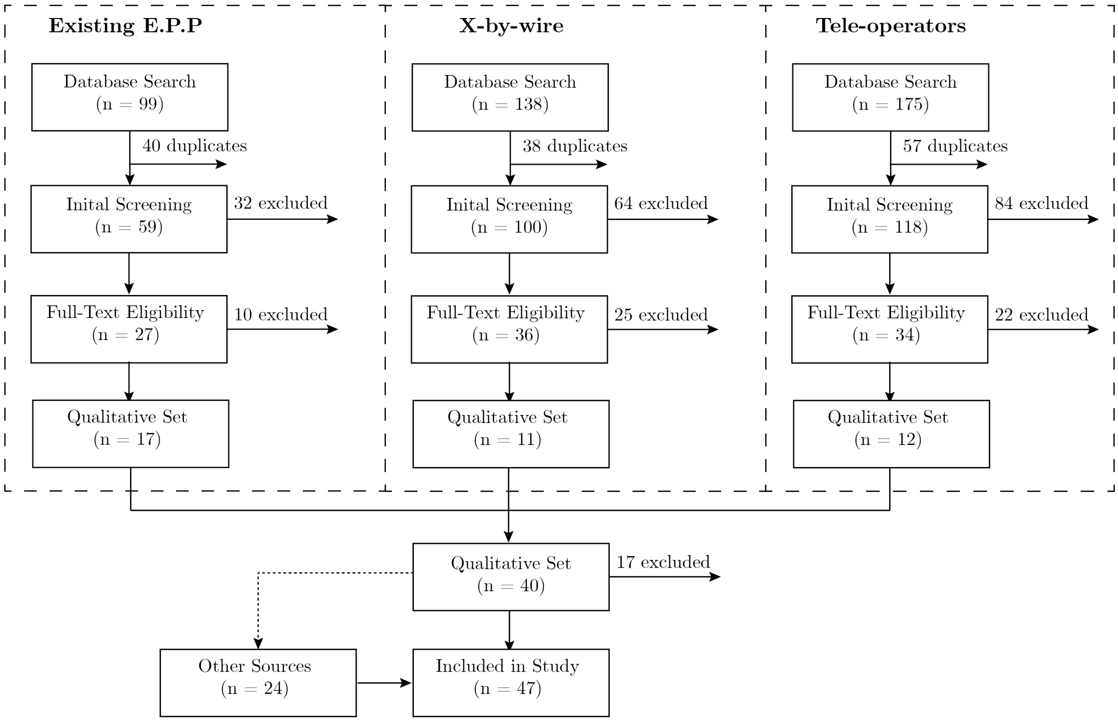


Figure 7: Flow of information through the different stages of the literature study. A total of 47 sources were included.

they describe the design of a haptic interface or when they describe the characteristics of the ideal feedback loop.

The full flow of information through the different processes is depicted in fig.7.

3 System Requirements

The requirements for the haptic interface will be divided into two categories: *functional* and *constructional* requirements, a division previously used by Shimoga in his research into force and touch feedback in tele-manipulation.[41] The functional requirements will cover the key functionalities of an E.P.P. system as well as the proprioceptive and bandwidth compatibilities of a feedback device for a prosthetic hand. The constructional requirements relate more to the specific placement of the haptic interface and will discuss the desired range of motion, operating forces as well as requirements related to 'wearable' aspect of the system.

3.1 Functional Requirements

3.1.1 Key Functionalities of an E.P.P. system

The concept of extended physiological proprioception is first coined by Simpson in the early seventies. Simpson concluded that it is unlikely to find a satisfactory substitute for an actual joint as a receptor for proprioceptive information. He instead suggests an approach where the movement of the prosthetic movement is linked proportionally to the movement of another, natural joint. By linking the movements you effectively extend the natural physiological proprioception to the prosthetic joint.[30] From this theory Childress has developed a set of fundamental rules for E.P.P. systems:[42]

- The user should be able to make all joints of the prosthesis rigid so that it can be used as a rigid extension of the body.
- The user should be able to make all of the joints of the prosthesis 'free' so that the prosthesis may be positioned into new positions for possible locking (make rigid).
- The movement of a free joint should be connected to the body so that body position corresponds to joint position, body velocity corresponds to joint velocity and body force corresponds to joint torque.

The first two are fairly straightforward, the user must be able to move the prosthetic joint and hold it in any desired position. The latter might not be as trivial, especially without a mechanical connection between input and output. There are many different 'connections' possible with different characteristics which affect the transmission of information between environment and human operator.

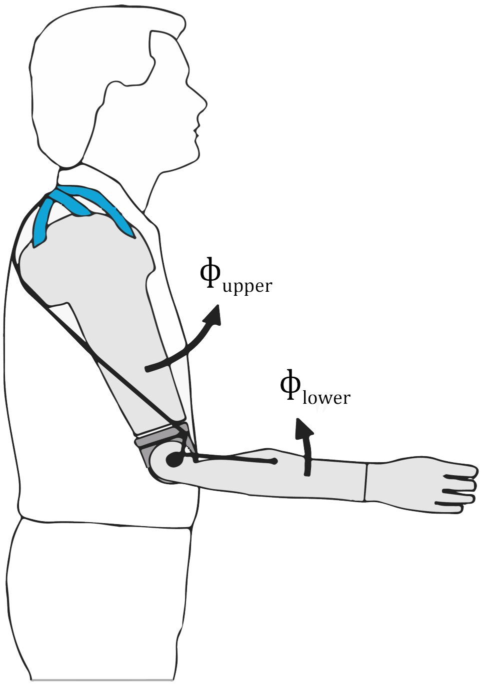
In the design of tele-operators there is a similar "desire to provide a faithful transmission of signals (positions, velocities, forces) between master and slave to couple the operator as closely as possible to the remote task."[43] Here, the master is analogous to the haptic interface and the slave corresponds to the prosthetic device. In the ideal case, the users would feel as if they are interacting directly with the remote task (i.e. the environment), the system would then be completely *transparent*.

In practice, perfect transparency will not be possible, as it requires infinite-gain feedback loops. However, the concept can still be used as a measure of performance during system design, for example in the selection of a suitable system architecture.[43,44] This will be further explored in section 3.1.2.

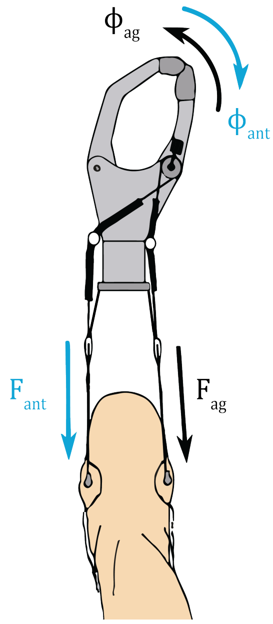
Unbeatable Position-Servo-Mechanism

Another feature of the direct relationship between the anatomical and prosthetic joints is the 'unbeatable' relationship between input and output. The input (anatomical joint movement) must be constrained by the output (prosthesis joint movement) such that the input cannot get ahead or fall behind the output.[45] This 'unbeatable' position-servo mechanism is what differentiates E.P.P. controlled devices from a typical position-servo mechanism.[31]

In the research of Doubler *et al.* the users were able to violate the E.P.P-linkage relationship by quickly depressing or retracting the shoulder, but there was no indication that this aspect affected the controllability of the system. The authors hypothesize that in normal use, the user would adapt to the capabilities of the system components and would not often feel a



(a) Uni-directional E.P.P. control using the forward flexion of the upper residual limb to control the elbow position. When there is tension on the control cable there is a direct relationship between ϕ_{upper} and ϕ_{lower}. This relationship may not hold during extension of the residual limb, depending on the movement speed and the response of the mechanism.



(b) Bi-directional EPP control using cineplastized forearm muscles as an agonist/antagonist pair. The length of the muscles, and thus the force pulling on the prosthesis, is directly proportional to the angle of opening.

Figure 8: Examples of uni- and bi-directional E.P.P. control. Figures adapted from Al-Angari.[31]

need to exceed those capabilities.[32]

This is actually an example of how the classical cable-driven E.P.P. controller is an *uni-directional* E.P.P. controller. The physiological joint is only mechanically constraint to the output in one direction: elevation/protraction of the shoulder. The range of this single input is divided into different bands for flexion, extension and 'parking'. When depressing/retracting the shoulder, the input is not constrained and there is thus no E.P.P. control in this direction, as can be seen in fig. 8a. This is often an issue in E.P.P controllers relying on some sort of cable tension.

It is possible to implement E.P.P. in both movement directions, which is known as *'bi-directional'* or full E.P.P. control. An example using a cineplastized muscle-pair is depicted in fig. 8b.[31,46] While bi-directional E.P.P. control provides a more intimate human-machine interface, and thus in theory better control, it also has its downsides. It requires often requires two control sites and it is not possible for the user to 'park' the prosthesis.[31]

Another example of a violation of the 'unbeatable principle' is the design of Gibbons and O'Riain, which attempts to enhance the classic E.P.P. model by allowing for more than one input-output relationship. By removing the fixed linkage the users can choose between different input-output relationships and thus perform a greater number of movements. A change in the input/output-linkage can be seen as putting a car in the reverse gear. By removing the fixed (mechanical) linkage, the relationship between in- and output is lost and the system no longer prevents the input from exceeding or 'beating' the output. Instead, a warning system was implemented. The system warns the user by a vibration on the shoulder whenever the input exceeds the output capabilities of the system. When the user feels this vibration, he or she can halt and wait for the output to catch up or backtrack his movements until the input is no longer ahead of the output.[47]

3.1.2 System Architecture and Controllers

The complete system connecting the sound joint of the operator to the environment through the prosthetic joint consists of five elements.

- Human Operator
- Haptic Interface (Master)
- Communication Layer
- Prosthetic Hand (Slave)
- Environment

As shown in fig. 9, the prosthesis system consists of the haptic interface, a communication layer and the prosthetic hand and is what connects the human operator with the environment. To comply with the original literature, this system will be referred to as the tele-operator. The tele-operator system is depicted as two-port network, a model often used in the field of tele-operation.

Each element between the human operator and the environment can affect the interaction with the environment, for example due to disturbances such as hysteresis or friction.[48] When it seems as if there are no elements between the human operator and the environment, the tele-operator is transparent. Mechanically speaking, a perfectly transparent tele-operator can be modelled as a rod with an infinitely small weight and an infinitely high stiffness.[49] The feedback signal is not 'cluttered' by the inertial or other dynamical effects of the tele-operator.

Perfect transparency is impossible and it is not yet clear what degree of transparency is required to allow for (subconscious) E.P.P. control. Nevertheless, it is thought that transparency is a good criterion for evaluating suitable control architectures.

To examine how practical limitations affect the ability of the system to transmit the environment impedance, Lawrence introduced a general tele-operator architecture. His proposal included the master and slave impedances (Z_m,Z_s), local position feedback gains on both master and slave side and four communication channels (c_{1-4}) for sending force and velocity in both directions. This architecture was later extended to the 'Extended Lawrence Architecture' (ELA) to include local force feedback gains.[43,44] The full architecture is shown in fig. 10. The local force controllers are represented by c_5 and c_6, whereas c_7 and c_8 are the local position controllers.

Depending on what is sent through the communication layer, different forms of control can be used. Using the ELA, Nearum *et al.* evaluated 16 (2^4) different controller configurations, 12 of which are of practical interest.

While energy in the two-port network model is described by the force-velocity pair, the non-recoverable position deviation after a disturbance is a major drawback of a velocity-force type architecture. This can be improved by using the integral of the velocity, position as a control input.[50] An experimental study by Mora *et al.* showed that better results were obtained with position control in terms of completion time, the sum of squared forces and tracking error.[51] Because of these reasons position-control is preferred over velocity-control in the controller configurations. The 12 possible controllers can be grouped into 4 categories:

- *Uni-lateral Operation*
  When using only communication channels towards the slave side (c_1 and/or c_3), basic position and/or force-control can be used to control the slave in an open

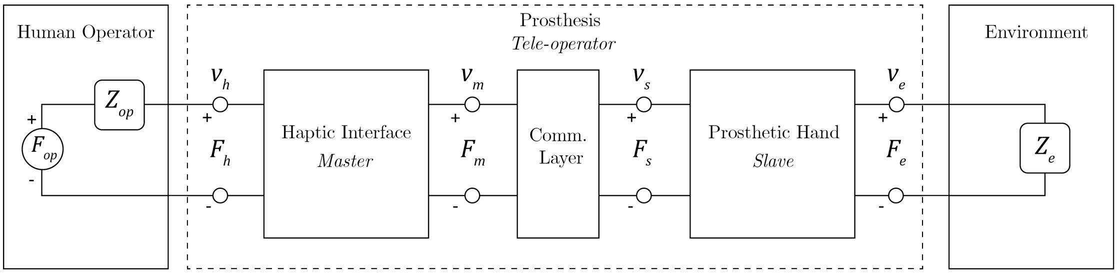


Figure 9: System architecture of the complete prosthesis system, depicted as a two-port network. The prosthesis system can be viewed as a tele-operator with a master, a slave and a communication layer.

Two-Port Network

To analyse the transparency of a system, the tele-operator is often modelled by a two-port network. The two-port network is a concept borrowed from electrical engineering, where the impedance Z is defined by the relation between current and voltage. When translated to mechanical properties, the impedance describes the relation between velocity (v) and force (F).

$$F_e = Z_e(v_e) \tag{1}$$

The operator can be viewed as a power source when giving force inputs, or a current source for velocity inputs. To translate the concept of transparency to the two-port network model: if the human operator is to feel as if he or she is interacting with the environment directly, the operator's force on the master (F_h) and the master's motion (v_h) should have the same relationship as the force and the motion on the slave side. Having the same relationship between force and velocity on both sides requires that the impedance Z_h transmitted by the human operator, defined by $F_h = Z_h(v_h)$ equals the impedance of the environment. The transparency condition is thus: $Z_h = Z_e$.[43]

A more popular way of denoting the transparency condition is using the hybrid matrix, where master velocity and slave force are designated as independent variables.

$$\begin{bmatrix} F_m \\ -v_s \end{bmatrix} = \boldsymbol{H} \begin{bmatrix} v_m \\ F_s \end{bmatrix}, \qquad \boldsymbol{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \tag{2}$$

When the forces and velocities on the master and slave side are equal, and the tele-operator is thus transparent, the hybrid matrix representation will be given by:

$$\boldsymbol{H} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \tag{3}$$

While practically not desirable (with respect to scaling the forces) or even possible, this hybrid matrix representation can be used as a standard for evaluating the transparency of tele-operator control schemes.[44]

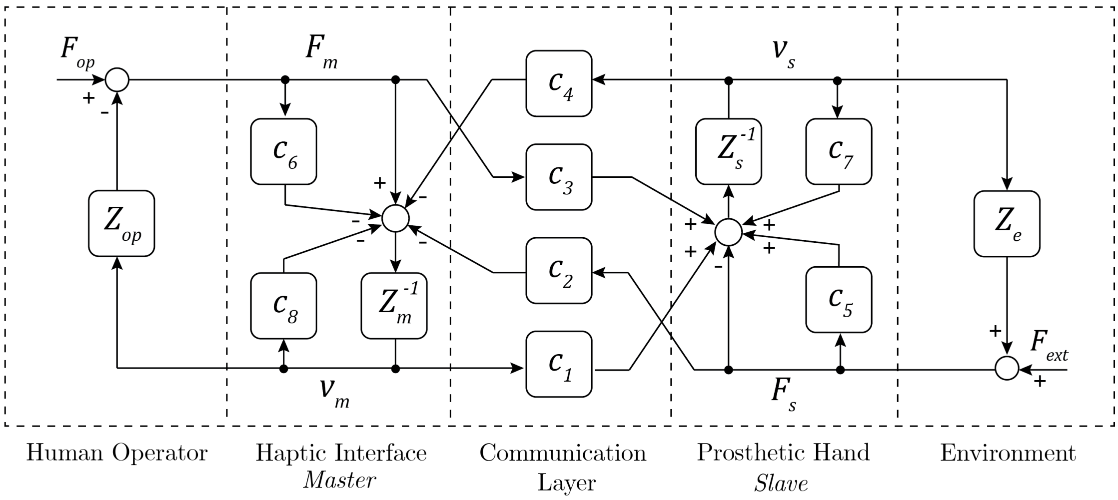


Figure 10: The Extended Lawrence Architecture (ELA). Figure adapted from Nearum.[44]

loop. This is referred to as uni-lateral control, as communication only goes into one direction. Some systems still provide feedback without any measurements at the slave side. They model the prosthetic device and the environment and compute a virtual feedback to send to the user.[52,53] This is not a true representation of the environment and is thus not an option for transparent control.

- *Error-based Operation*
  In error-based operation two communication channels of the same type are used, either c_1 and c_4 for position-error based tele-operation or c_2 and c_3 for force-error based tele-operation. Nearum *et al.* were able to show that it is not possible to achieve transparency using error-based tele-operation using the hybrid matrix notation of the two-port network.[44]
  A more intuitive approach of Doubler and Childress showed the same. When using the same variable for both input and feedback, the system must be designed in such a manner that a difference (or error) ϵ can exist. This error is the control input. Due to the desired one-to-one relationship the input must be constrained by the current output, and the input is thus restricted within the range of $\pm\epsilon$. The smaller the value of ϵ, the more intimate the coupling between input and output. However, the range of proportional control is better with a larger ϵ.[32] The size of the error is a problem inherent to error-based operation, it is not possible to achieve an error of 0 and this is thus not a suitable architecture.
- *Compliant Operation*
  In compliant control two complementary control channels are used. Either the position is used as a control input, and force is fed back to the user (c_1,c_2) or force is used as an input and position is fed back (c_3,c_4). These architectures are also known as position-forward and force-forward control, forward-flow and forward-effort control or impedance and admittance control. It is possible to achieve transparency with both options,[44] and their specifics will be discussed more extensively in the next paragraph.

- *Union of Controllers*
  The final option is the combination of a compliant controller with another communication channel. All these combinations of 3 or 4 communication channels can achieve transparency. Although

transparency can be achieved with just two channels, more channels may prove better and more robust overall performance when dealing with the transparency/stability trade-off.[44]

Admittance vs. Impedance

Mechanical impedance is a measure of how much an object resists motion when subjected to a force, much like how stiffness is a measure of how much an object resists deformation when subjected to a force. Mechanical admittance is the inverse of the impedance.

Impedance and admittance control are ways to control the relationship between force and velocity. Instead of controlling either a position or a force, you control the power transferred to the environment through the force-velocity pair. The admittance control scheme has an outer force control loop and an inner position loop that is controlled at a faster rate such that the dynamics can be neglected. Impedance control has it the other way round, with an outer position loop and an inner force loop. Each method has its pros and cons: admittance control generally leads to higher robustness while impedance control leads to higher accuracy.[54] A comparative study on tele-operation of aerial robots showed that an admittance control strategy was better suited for rendering vehicle dynamics forces while the impedance control architecture rendered the environmental forces more effectively.[55]

The choice between the two depends on the available hardware as well. Some manipulators lack the ability to do direct servo control of torque. In the standard Lawrence architecture the operator is shown as an effort (force) source, but the system can be altered to include the operator as a dependent flow (velocity/position) source.[56] Stiff actuators are preferred for inner position loops, while inner force loops can benefit of some mechanical compliance in the actuators.[54]

Multiple examples have been found of force-forward/position-reflecting E.P.P. control schemes.[31,32,35,57] The generalised E.P.P. control scheme of Weir also showed the force as a controlling variable while feeding back position to the input.[58] Koukoulas *et al.* presented a bilateral control scheme for a bio-mechatronic E.P.P. controller, as shown in fig. 11a. This system clearly shows the outer position-reflecting loop and the inner position loop of admittance control. As an example, this control scheme was translated to the Extended Lawrence Architecture, as shown in fig. 11b.[35]

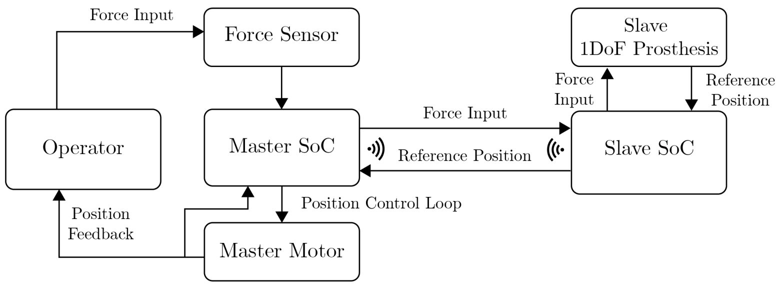
You can see that c_6 can be used to cancel out the control force, such that the master follows only the reference position from the slave. Furthermore, this comparison shows that the ELA is not sufficient for all control types, as the inner position loop was moved to the master side, utilizing c_8 rather than c_7, which would be suggested by Nearum *et al.*.[44] The location of the summation and master impedance in the positional may differ as well.

One implementation has been found of an impedance control scheme for E.P.P. control, where a force-reflecting head-stick was used for manipulations. However, the paper does state that there may be fundamental transparency limitations with the design, which may be addressed by using alternative bilateral architectures.[56]

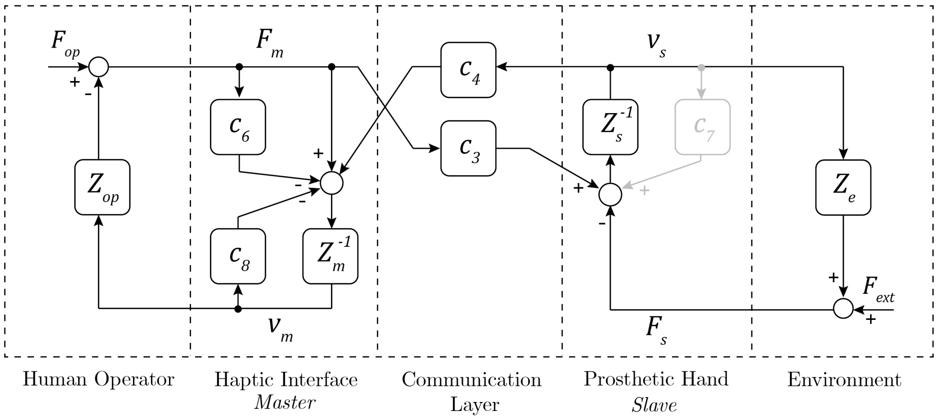
Stability

Up until now only the transparency of a system was discussed, but stability is an equally important topic. Transparency and robust stability are conflicting design goals in tele-operation systems and a trade-off must be made in practical applications.[43] Stability is often evaluated with the passivity argument, meaning, a passive system is a stable system. A (two-port) network of only passive elements is passive itself and thereby implicitly stable.[50] The human operator can technically exhibit non-passive behaviour, but it is known from everyday experience that the interaction of humans with passive objects is stable.[59]

Position-forward/force-reflecting architectures are not necessarily passive and stability is often an issue. It can be improved by reducing delays or attenuating the force feedback,



(a) Architecture diagram of the implementation of the Biomechatronic E.P.P. prosthesis controller using wireless technology. Figure adapted from Koukoulas.[35]



(b) A possible representation of the bio-mechatronic architecture in the Extended Lawrence Architecture diagram. Following Naerum, forward-effort suggest using controller c_7 for the inner position loop,[44] however in this architecture the position loop is implemented on the master side with c_8.

Figure 11: Architecture diagram of the bio-mechatronic E.P.P. prosthesis controller as presented in its original form (above) and a possible representation in the Extended Lawrence Architecture (below).

at the cost of reduced sensitivity.[43,50] However, in the specific case of a prosthetic system force attenuation may actually be desirable to reduce operating forces at the shoulder site. Mechanical compliance or appropriately designed impedance matching filters may also solve stability issues in force control.[50,54]

3.1.3 Bandwidth

The bandwidth of a system describes the range of frequencies that can pass through the closed-loop system without being reduced. Frequencies higher than the 'cut-off frequency' will be filtered and are less present in the output signal. The higher the bandwidth and thus the larger the range of frequencies in which accurate transparency can be achieved, the larger the degree of tele-presence.[43]

As pointed out by Gibbons and O'Riain, one needs to balance the need for a fast response of the prosthesis to the user input and the necessity to allow the hardware sufficient time to react to the drive signals.[47,60] When the bandwidth of the prosthetic components is too slow, the movement of the controlling joints will be restricted. These limitations will be brought to the user's awareness and the subconscious aspect of E.P.P-control is lost, there is thus a minimum required bandwidth for E.P.P systems.[58]

There is also an upper-bound on the required bandwidth of the system, as the human operator cannot utilize data beyond his or her capacity. It is therefore useful to estimate the human capabilities. The input/output capabilities of human operators are asymmetric.

On the control *input side*, it has been shown that for typical pursuit tracking tasks, humans are capable of tracking signals with cut-off frequencies up to 1 Hz.[45,58] This is for unexpected signals, the bandwidth increases for periodic signals (2-5 Hz), internally-generated or learned trajectories ($\sim$5 Hz) and reflexive actions ($\sim$10 Hz).[61] The human wrist reflexes can for example easily exceed 12 Hz and can be 25 Hz for the fingers.[62] The bandwidth requirements of the system are thus dependent on the desired tasks.

Motion commands to the fingers are generally slower, humans can typically transmit commands at 5 - 10 Hz. Goertz found that bandwidths of 10 Hz for the master to slave direction approximately match motor capabilities of the human arm and found it adequate for teleoperation.[63]

The estimated bandwidth for limbs is smaller, at 2-5 Hz.[41,61] The shoulder, which will be the control source for the haptic interface, has at least 99% of its power spectrum below 5 Hz.[64] The haptic interface will be limited by the capacities of the shoulder, so a bandwidth of 5 Hz seems sufficient for the control inputs.

On the *feedback side*, the human operator can process different types of feedback at different speeds. It is estimated that the bandwidths of proprioceptive/kinesthetic feedback signals are in the range of 20-30 Hz. When tactile sensing of low-amplitude vibrations is desired the feedback must be provided at about 320 Hz.[41,61]

Based on the high frequency reflexive movements of wrists and fingers Ellis *et al.* suggest a force bandwidth of 40 Hz to 80 Hz.[62] In the combined kinesthetic and tactile interface of Thiem *et al.* the kinesthetic part of the device was used for feedback up to 50 Hz.[65] A bandwidth of 100 Hz is mentioned as required for force stability control and force feedback in steer-by-wire systems.[66]

Much higher feedback bandwidths were suggested by Sharpe, reporting that much of the necessary sensory information was in the 5 - 10 kHz range. However, subsequent work has shown that while there is improvement in task completion time with increased force reflection bandwidths, this improvement saturates at lower frequencies. Little to no improvement is seen at bandwidths higher than $\sim$8-9 Hz.[67]

This is supported by Wildenbeest *et al.*, who found that while overall task performance is substantially improved by providing low-frequency (7 Hz) haptic feedback, further increasing the haptic feedback quality only yields marginal improvements, even when the full natural spectrum of haptic feedback is provided.[68]

3.1.4 Latency

The latency time of the haptic interface is the delay between stimulus and response. For example the time between what is felt at the prosthesis and what is felt by the prosthesis user, but also the delay between moving the sound joint and movement of the prosthetic joint. Low latencies are needed to achieve transparency, the delay of the bi-directional (wireless) communication must be minimal to avoid 'sluggish' behaviour.[35] Too long delays may also destabilize the system.

Brain-to-hand delays have been measured to be in the order of 300-500 ms, which gives an estimation of allowable delays including the sensory-motor system.

Koukoulas *et al.* achieved cumulative latencies in the order of 40-50 ms and have adequate evidence pointing to a high degree of transparency. This is similar to Kontogiannopoulos *et al.* who proved transparency of their controller with delays of approximately 78 ms.[35,69] Other research showed that subjects were able to perceive E.P.P. feedback from a pressure bag system with a time delay of about 100 ms.[70] Farrell *et al.* found that a delay of 100 ms does not cause a significant decrease in performance, but users noted that with controller delays greater than 50-100 ms it felt as if they were operating the prosthesis 'in molasses'.[71] No significant improvements (in completion time) were found for delay times smaller than 48 ms.[67]

With delays greater than 1 second it was not possible to perform peg-in-hole tasks with just kinesthetic force feedback. By implementation of advanced control schemes such as shared compliant control it was possible to complete these tasks with relatively large delays, however this probably not relevant for the haptic interface, as typical delays for general computer-based short-distance designs lie between 10 and 50 ms.[40]

3.2 Constructional Requirements

3.2.1 Shoulder Input

The haptic interface of Vardy *et al.* has a shoulder-worn master system that can be placed on both the affected and the healthy side of the body. There are several reasons to choose the shoulder as the input location for the haptic interface.

Shoulder movements do not affect the orientation of the terminal device (gripper) during operation and it is thus possible to control grip force and aperture of the terminal device independently from the prosthesis' position and orientation.[5,72]

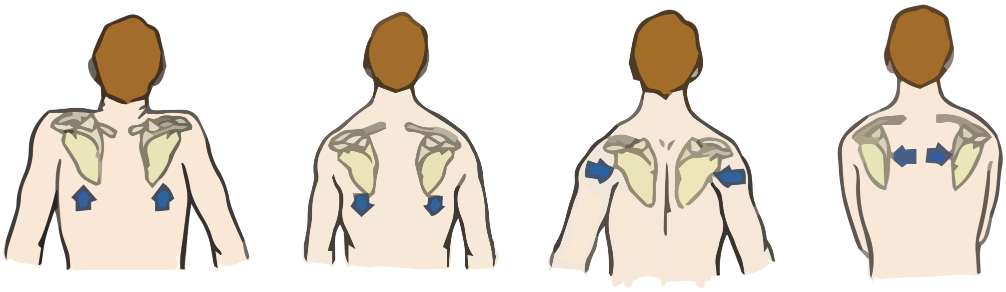
It was noted by Bernstein *et al.* that control of body positions is not achieved by specific muscle-joint combinations, but rather through a spatial sense. Coordinate movements exist as topologically oriented 'engrams' (units of cognitive information in the brain) that can be translated into different joint-muscle sets.[42,45,73] This supports the belief that control of (prosthetic) hand motions can be achieved by using the shoulder joint-muscle set. Using the shoulder position to control the 'finger and thumb' of the terminal device is also a natural and intuitive coding and it thus follows the concept of extended physiological proprioception.[30,64]

Furthermore, it was shown in the research of Doubler *et al.* that the results shoulder-effected position-controlled and velocity-controlled tracking tasks were similar to tracking tasks performed with the physiological elbow and wrist. This would indicate, assuming non-limiting dynamics of the haptic interface, that a E.P.P-controlled prosthesis with shoulder inputs could exhibit similar characteristics to the physiological counterparts.[45] Finally, it is already known that body-powered prostheses using shoulder movements as input are suitable for prosthesis control with proprioceptive feedback.

Given the shoulder as a control input, a distinction can still be made between position, velocity and force control inputs. It has been shown shoulder-effected position control has more potential for providing effective control than similar velocity control, with a 36 to 107% increase in information transmission rates.[45] No research was found on the information transmission rates using force inputs from the shoulder.

3.2.2 Actuator Force and Stroke

Displacement
To determine the maximum displacement between the two anchor points on the shoulder Vardy and Plettenburg performed an experiment to uncover which movements yield the largest displacements. Four different scapular motions were considered: elevation, depression, protraction and retraction, which are depicted in fig.12. The fifth motion included in the study is the combination of elevation and protraction.[72] Other combinations of movements, such as simultaneous depression and protraction or elevation and retraction are more difficult to achieve.[32]



(a) elevation (b) depression (c) retraction (d) protraction

Figure 12: Four different scapular shoulder movements. Figure adapted from ACE Fitness.[37]

The combination of elevation and protraction proved to yield the largest change in distance for a single direction in the study of Vardy *et al.* with a maximum of 40.1 mm. For this movement the median lies around 34 mm with a standard deviation of roughly 3 mm.

The maximum absolute displacement for a combination of both neutral to shoulder elevation (26.6 mm) and neutral to depression (12.4 mm) would be 39 mm. Similarly, a range of 50.2 mm can be achieved for protraction-retraction.

However, considering the smoothness of the shoulder motions, Vardy *et al.* ($n = 20$) showed that depression and/or retraction showed erratic behaviour in 10 subjects, compared to only 3 for shoulder elevation. Combining movements to include depression or retraction is therefore not desired.[72]

In the research of Doubler elbow and wrist movements were mapped to shoulder displacements of 44.5 mm and 59.7 respectively, which shows a similar order of magnitude. However, Doubler also mentions that it was difficult for the subjects to reach the full range of protraction/retraction in their experiments.[32]

With a larger displacement (larger cable excursions) one can achieve a better resolution and relate the output more accurately to the input.[22] However, it appeared that one could achieve better dynamic control by using less than the full range. Using the full available range of motion may also be uncomfortable and require unnatural movements from the prosthetic user, thus it may also be desirable to use less than the full range of motion for both comfort and cosmetic reasons.[32]

Aside from the range of the shoulder motion, the ability of the subject to make fine incremental movements is important, as it gives the number of discrete steps that can fit within the operation range. The research from Johnson *et al.* showed that roughly 43.2 ± 18.8 command levels could be achieved over the full range in the vertical movement. For the horizontal movement direction this was 42.7 ± 36.8.[64] It is clear from the large standard deviations that this is highly dependent on the subject. It can give an idea of the required sensitivity, taking the means of both the displacement for elevation-protraction and the number of command levels, this gives us an estimated step size of ca. 0.8 mm.

Forces

The magnitude of the feedback forces must be selected in such a way that they are low enough to be in the comfortable range of the operator but high enough to be detected and used for control.

Comfortable forces are different for every person. Following the fact that humans can conduct isometric contractions at 15%-20% of their maximum voluntary contractions, Hichert *et al.* found that forces up to 38 N for the average female and up to 66 N for the average male will lead to fatigue-free operation.[41,74] A range of

10 to 40 N was suggested as the desired range for future prosthesis design, with 10 N being the lowest level at which pinch forces start to build up using a body-powered TRS hook. Within this range, force reproducibility is roughly the same for all force levels, but force variability increases with increasing force levels.[22] The upper bound restricted by comfort is thus 40 N, but lower control forces will lead to lower force variability.

However, when a true unbeatable system is desired the shoulder-worn actuator must be able to resist the maximum exertable forces. Maximum cable forces have been reported to be 257 N on average, but with a very large variability. Individual maximum cable forces from the study ranged from 86 N to 538 N.[74]

There is also a lower bound to the operation forces, defined by the force reproduction capabilities of the user, stiction levels at the shoulder joint and arm configuration. This lower bound was reported to be 2 N by Vardy *et al.*[5] Other sources state force thresholds of 0.3 - 0.7 N and 1N was mentioned as a design goal.[63]

Force errors ranged from ∼0.5 for a 2 N reference force to ∼1.3 N for an 8 N reference force. These errors are for blind reproduction, with visual feedback these errors are reduced to less than 0.3 N. The biggest force variability was measured at a reference force of 8 N with a mean variability of about 0.2 N.[5]

From a perceptual point of view, the just notable difference values ranged from 0.11 to 0.17 N, corresponding to Weber fractions between 2% and 5%.[5] As to the scaling of the feedback forces, Wildenbeest *et al.* found that subjects were able to gain enough information from partial feedback (25% of full feedback). Other feedback gains other than 0 and 1 were not tested, so a definitive conclusion the necessary level can not be made.[75] As a reference, the Delft Cylinder hand can produce pinch forces of 30 - 60 N.[76] Scaling this back to 25% would result in feedback forces between 7.5 and 15 N. Considering the comfort of low operation forces, a maximum of 15 N seems reasonable. This complies with earlier findings of Plettenburg *et al.* that found optimal cable operating forces between 10 and 20 N for subjects with arm defects. Cable forces between 5 and 10 N were deemed too low.[20]

3.2.3 Other System Requirements

Friction The exact effects of friction depend on the type of E.P.P. system that is implemented and the source of the friction. In the work of both Doering and Farrell it was found that static friction can cause limit-cycle behaviour. Static friction was considered to be a worst-case scenario because it's coefficient is much larger than that of kinetic friction. Static friction also introduces the stick-slip phenomenon, which is detrimental to E.P.P control. Besides the effect on limit-cycle behaviour, removing static friction would also be better for the proportional relationship between the input of the user and the input measured. It would also provide a better information exchange through an improved resolution.[57]

Backlash Backlash, or play, is lost motion through space between different parts of the mechanism. When the system moves through the backlash zone, the change in input is effectively lost. Reducing the amount of backlash will thus improve E.P.P control, and the reduced backlash system of Farrell did indeed eliminate limit cycle behaviour.[57] Measures to reduce backlash tend to increase friction levels, so a trade-off has to be made here.[63] While the amount of allowable backlash is entirely dependent on the design, Garlick specified a number of 2 mm for his proposed tele-operator design whilst Fisher mentions 0.1 mm and 0.1 degree.[63]

Backdrivability When it is possible to deliver environmental power to the actuator to drive it's motion, this is referred to as backdrivability. It is a mechanical property of the actuator system and describes whether it is easy to invert the motion. It may also be possible to implement a virtual backdrivability by control with a force loop, therefore backdrivability is not necessary with an admittance control or explicit impedance schema.[54]

When implementing a control scheme without an closed force control loop, such as implicit impedance control or a position-error loop, backdrivability is necessary.[54, 63]

Power Consumption Power consumption is an important factor in the design of externally powered prostheses as it's battery life is often limited. Several components of the system use energy, such as the sensors and actuators at the slave and master side, the controller and the wireless communication.

Al-Angari *et al.* mention a design goal that the controller should use no more than 5% of the source power. Whilst an arbitrary rule of thumb, it was developed using previous experience developing electrically powered prosthesis. Their micro-controller has a quiescent current of 0.48 mA.[31]

For wireless communication options lie in the range of 4.9 - 29 mA, with Bluetooth Smart Modules having the lowest power consumption.[77] This gives an idea of the order of magnitude, but no specific design goals are given.

No specifics were mentioned on the power consumption of the other components.

3.2.4 User Requirements

And finally there are of course general user requirements for the system. According to Johnson,[64] the complete prosthesis system must be:

- cosmetically acceptable
- easy to don and doff
- provide repeatable proportional command signals that do not drift or change over time
- provide reliable logical command signals that the user can consistently produce
- not interfere with other activities of the user, such as eating or talking
- provide a natural extension to the user's intact motor system
- provide subconscious control, requiring little attention from the user
- be durable
- be readily available or fabricated
- be reasonably priced

The specific example of a shoulder-worn haptic interface has not yet been developed before, so the literature search into existing E.P.P controlled prostheses and tele-operators did not yield any specific requirements, as these requirements generally do not transfer well when a different physiological location or application is used. As a general remark, it was found that for both the haptic interface and the complete system there is a general desire to minimize the inertia. Larger inertias affect the transparency of the system and systems with large dynamics are characterized by large control lags.[75, 78]

The size of the haptic interface is restricted by that of a human shoulder and from a cosmetic perspective it would be desirable that the system can not be seen through the clothing of the operator.

These user requirements and wishes can be further specified into system requirements in the follow-up of this literature study.

4 Discussion

‘ The purpose of this study is to find out what are the criteria for a wireless haptic interface suitable for control utilizing the concept of extended physiological proprioception. To answer this question a search was performed on existing E.P.P systems and similar systems from different fields, namely x-by-wire systems and tele-operators.

It was found that in order for a system to be E.P.P-controlled there must exist an intimate coupling between the physiological joint and the prosthetic joint. What differentiates an E.P.P-system from a regular position-servo mechanism is the ‘unbeatable’ relationship between input and output. Whilst this is a key concept, two examples were found where this principle can be violated without effect on the controllability of the system. This is solved either by adaptability of the human operator or by communicating the violation of the relationship through a different sensory channel.

The complete prosthesis system can be defined following the definition of a tele-operator, with the system consisting of a haptic interface, a prosthetic and a communication layer. Several requirements were found concerning the functionality of both the entire system and just the haptic interface.

- **The prosthesis system should use at least two complimentary communication channels.**
  Transparent operation is possible when at least two complimentary communication channels are used. A trade-off should be made between the transparency and the stability of the system. Whilst there is no definitive reason to select a position-forward or a force-forward type of control system, existing E.P.P-systems tend to point towards the latter.

- **The prosthesis system should be able to send controls with a bandwidth of at least 5 Hz.**
  This is in line with the estimated upper bandwidth of physiological shoulder motions.

- **The prosthesis system should be able to receive feedback with a bandwidth of at least 8 Hz.**
  Multiple studies showed little improvement in task performance when the bandwidth was increased above $\sim$8 Hz.

- **The prosthesis system should have a latency of at most 50 ms.**
  With delays greater than 50-100 ms the delay was perceivable as sluggish behaviour to the user. Below 50 ms there was no improvement in task performance.

- **The prosthesis system should utilize position signals rather than velocity signals.**
  The shoulder has higher information transmission rates using position signals rather than velocity signals.

- **The haptic interface should utilize the combined movement of elevation/protraction.**
  This movement yields the largest absolute displacements, which should allow for more accurate control.

- **The haptic interface should work within a working stroke of 30 mm**
  This is below the 25th percentile for the marker-pairs for the movement of combined elevation-protraction. As it uses less than the full range of motion it should be comfortable, yet the displacement is still large, allowing for better control.

- **The haptic interface should work with forces over 2 N**
  Forces below 2 N were deemed to low for useful control.

- **The haptic interface should work with forces up to max. 15 N**
  This is low enough to be in a comfortable range, but high enough to be controlled with optimal force feedback. When scaled up to force levels at the slave side it also falls within the range of desired pinch forces.

Where the literature was inconclusive on exact figures, some recommendations can still be made concerning the selection of components:

- When using a force-transducer, the accuracy must be under 0.1 N to be below the 'just notable difference' of a human operator.

- When using a position-transducer, the accuracy must be under 0.5 mm. Based on the number of control levels in the full range, an estimated step size per control level of 0.8 mm was found.

- The components of the prosthetic system should be selected such that both backlash and static friction are minimized. This is a trade-off and the amount of backlash and friction is very dependent on the mechanical design, so no hard requirements can be given.

- The need for a compliant controller with two complementary control channels implies the use of a force control loop, this eliminates the explicit need of a backdrivable actuator.

- Power consumption of the components should be minimized, as a rule of thumb the controller should use no more than 5% of the power source.

Finally, in section 3.2.4, some user requirements were found that can provide a base to further define specific system requirements when a design will be made for the haptic interface.

Several limitations of this literature study can be noted.

Unbeatable Relationship The maximum forces that can be exerted by the human operator will almost definitely exceed the capabilities of a wearable haptic device. A fully unbeatable relationship is therefore impossible, it will only be unbeatable to a certain extent. Whilst there have been examples of violating the unbeatable relationship of an E.P.P-system it is not yet clear to what extent the user can adapt this and how the violation should be communicated to the human operator. This should be investigated further when moving forward with a design for the haptic interface.

Position-Position Control It might be possible to apply a transparent position-position control law by using force sensors to make both the master and slave 'virtually' transparent. However, it would be easier and perhaps cheaper to use an intrinsically transparent device and the bandwidth of the system would be theoretically larger.[79]

Position-position control was also preferred by Pierce *et al.*. Under position-force control, the human was prone to close their at a rate faster than the capabilities of their gripper. A resistive force is applied when the human operator exceeds the capabilities of the gripper, providing a connection between both grip apertures. The was still the issue of poor transparency, which was solved by using a gain-switching PD-loop.[80]

These examples show that whilst not inherently transparent, there are solutions to apply position-position control schemes that provide a good sense of transparency to the user.

Maximum Force Levels The effect of scaling down feedback forces has only been tested for one level, it is thus hard to say if the feedback forces can be scaled down even further without affecting task performance. Furthermore, the assumption has been made that research on cable operation forces can be translated to the shoulder-worn device, something that has not necessarily been proven. To provide a more substantiated estimate of the desired maximum forces more research should be done.

Demographic and Actuator Stroke In the research regarding the maximum shoulder displacements the subjects were 20 healthy male subjects with a mean age of 26.7 years old.[72] This is a limited subject group and the requirement for the actuator stroke is thus not representative for younger and/or female operators.

Furthermore, it is unclear if the data shown is for the set of best performing marker points or if it is averaged over the participants. Finally, the resolution of positional control of the shoulder is estimated using results from a different study,[64] but further research could provide exact data on the just noticeable difference for the position.

Further Requirements Finally, to complete the set of requirements the user requirements must be translated to specific system requirements. Also, additional requirements must be found concerning user safety, such as information on the maximum voltages, temperature and safe operating frequencies for the wireless signals.

5 Conclusion

In the discussion in section 4 the results of the literature study were translated into a set of nine requirements for an E.P.P-controlled system, specifically one using the wireless haptic interface as proposed by Vardy *et al.*

The prosthesis system should ..

- use at least two complimentary channels.
- be able to send controls with a bandwidth of at least 5 Hz.
- be able to receive feedback with a bandwidth of at least 8 Hz.
- have a latency of at most 50 ms.
- utilize position signals rather than velocity signals.

Furthermore, the haptic interface should ..

- utilize the combined movement of elevation/protraction.
- work within a working stroke of 30 mm.
- work with forces over 2 N.
- work with forces up to max. 15 N.

Whilst not a complete set, these requirements can form the base for the design of a haptic interface that may be capable of E.P.P-control. The concept of extended physiological proprioception may alleviate the operator of the mental load that comes with the lack of feedback in externally powered prostheses while maintaining comfort due to low operation forces and a harness-free set-up.

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