Data description sheet

This is the underlying data-set of the article ***"Perception and control of low cable operation forces in voluntary closing body-powered upper-limb prostheses" by Mona Hichert, David A. Abbink, Alistair N. Vardy, Corry K. van der Sluis, Wim G.M. Janssen, Michael A.H. Brouwers, and Dick H. Plettenburg.***

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Doctoral Thesis: User Capacities and Operation Forces – Requirements for Body-Powered Upper-Limb Prostheses

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Contents

1) The folder "perception data" contains the raw data of the perception experiments as described in the Methods section of the article (see Appendix). Each .xls file is named by s#p#. Thus the file name includes subject number (s#) from 1 to 25 and condition (p#). The conditions are named p10, p15, p20, p25, p30 and p40 for the no cable displacement trials, where p10 stands for 10 N target force, and p10-10, p10-20 etc. for the trials with cable excursion. Here p10-10 stands for 10 N target force with 10 mm displacement.
2) The folder "max force data" contains the data of the maximum force experiments as described in the Methods section of the article (see Appendix). Each .xls file is named by s#m#. Thus the file name includes subject number (s#) from 1 to 25 and measurement number (m#). The files m1, m2, and m3 contain the maximum measured forces before the perception experiment and the other three (m4, m5, m6) after the percerption experiment.
3) The folder "Nasa TLX" contains the raw data and the analysis Matlab file. Each .xls file is named by s#. Thus the file name includes subject number (s#) from 1 to 25. This single file per subject contains the data of all six variables examined after each condition (n=16) of the perception experiment. With the matlab file "NASATLX_METCexperiments" the .xls data sheets were analysed. See below.
4) The "Body map" folder contains the coloured body maps per participant and a summary of the hand-made analysis of all body-maps.
5) The "Matlab files" folder contains the Matlab data analysis files for the perception experiments.

Data analysis

Perception experiments

Run m-files in the "Matlab files" folder in the following order

1. Run “processRawData”
    a. Output: “rawMaxdata” and “rawMaxdata”
2. Run “processPerceptionData”
    a. Functions needed: “process_single_cond”
    b. Output: “Presults”
    c. Comments: Subject 2 did not complete the perception experiment.
3. Run “plotsNoDisplacement_Mona”
    a. Plots figures FRE and FV for perception experiments without displacement
4. Run “plotsWithDisplacement_Mona”
    a. Plots figures FRE and FV for perception experiments with displacement

NASA TLX

The m-file to analyse the outcome of the NASA TLX questionnaire is in the NASA TLX folder together with the questionnaire data. Run the “NASATLX_METCexperiments” Matlab file. The figures map contains the resulting figures. One figure with the weighted score and six with the measured categories with the 16 conditions (6 without and 10 with displacement) on the x-axis.

Appendix:

This Appendix contains the "Methods" section of ***"Perception and control of low cable operation forces in voluntary closing body-powered upper-limb prostheses" by Mona Hichert, David A. Abbink, Alistair N. Vardy, Corry K. van der Sluis, Wim G.M. Janssen, Michael A.H. Brouwers, and Dick H. Plettenburg*** in order to understand data-sets and analysing files better

Methods

Approach

Force reproduction experiments either request subjects to reproduce a force generated on the participant [17,18], or reproduce a self-generated force [19,20]. We choose the second, to let the subject first reproduce a target force which is illustrated visually on a screen (visual block), and consequentially receiving proprioceptive feedback of his body movements and tactile feedback of the exerted forces on the skin by prosthetic parts (harness and socket). Based on the perceived forces the subject reproduces the same force again without visual information (blind block). It is mainly the proprioceptive feedback perceived during the visual block, which enables the user to reproduce the same force during the blind block [16]. This simulates prosthesis use: the user estimates a force required to manipulate an object (experimental: target force) and based on his experience of former perceived forces (experimental: visual blocks), he applies the required force (experimental: blind block).
The experimental setup should be unaffected by (mechanical) properties of available prehensors and therefore either 1) a threaded rod or 2) springs of different stiffness were mounted on the end of the control cable instead of a voluntary closing prehensor. The threaded rod setting, as used in the 'no cable excursion trials', simulates holding a rigid object with a voluntary closing prehensor at a constant cable excursion. The "variable-spring-stiffness" setting, as used in the 'cable excursion trials', simulates the approach of a desired pinch force to hold an object with a voluntary closing prehensor.
Cable forces of interest were based on the examined cable force levels on TRS hook data of Smit and Plettenburg's study [3], since the TRS hook requires the lowest cable force of all tested devices. At 10 N the TRS hook starts building up a pinch force. At 40 N the TRS hook pinches approximately 20 N. A pinch force of 20 N is reported to be sufficient to complete most daily activities with an upper-limb prosthesis [7,8]. Additionally, the critical force, which is the force humans can exert without fatigue effects during continuous isometric contractions, should be considered as upper force boundary for prosthesis use. Monod determined the critical force at 15 and 20% of the maximum voluntary contraction [21]. Considering maximum cable operation forces reported by Taylor (arm flexion: 280 (24) N; shrug: 270 (106) N; arm extension: 251 (29) N) [22] and Hichert et al. (combination of shoulder protraction, humeral abduction and flexion: 267 (123) N) [23] as maximum voluntary contraction, the target forces should not exceed 40 N (251 N x 15%) to enable participants to complete all trials. Based on this, we decided to examine six force levels (10, 15, 20, 25, 30 and 40 N) for the threaded rod setting.
In contrast to the reported magnitude of maximum cable excursion of 58 (1.7) mm for arm extension [22] by Taylor, we measured maximum cable excursions of 160 to 260 mm in preliminary experiments. These experiments also showed that up to 50% of the maximum cable excursion the subjects' operation force levels were unchanged. The cable excursion should therefore not exceed 80 mm (160 mm x 50%). Based on this, we decided to examine five cable excursions (10, 20, 40, 60 and 80 mm) for the "variable-spring-stiffness" setting. The five excursions were tested at two force levels, 10 and 20 N, at which the crossover point from overestimation to underestimation of target forces for prosthesis users were found in preliminary experiments [13]. This results in ten force-excursion conditions.

Participants

Twenty-four adults (12 females, age: 49 (13) years, height: 175 (8) cm, weight: 75 (14) kg) with congenital and acquired unilateral trans-radial defects participated. All participants were free of neurological, muscle, joint or motor control problems concerning the upper extremity or the torso (exclusion criteria). A total of 16 participants had a left deficiency, 15 had a congenital defect, 13 had experience with body-powered prostheses and five are current body-powered prosthesis users.
This study was approved by the medical ethical committee of University Medical Centre Groningen (UMCG) (NL41112.042.12). The participants were recruited from University Medical Center Groningen, Erasmus Medical Center, Rotterdam, and the rehabilitation institute De Hoogstraat, Utrecht.

Materials

A custom-made prosthesis simulator (Fig 1A) was connected to the participant's prosthesis by a thermoplastic shell. For two participants, who did not own a prosthesis, the prosthesis simulator was placed on a temporary

WILMER Open Fitting socket [7]. For two other participants the prosthesis simulator was attached to the remnant arm since its length was sufficient for a firm connection. The prosthesis simulator consisted of an adjustable "figure-of-nine" harness linked to a standard 1/16'' (.159 cm) diameter stainless steel cable (C100, Hosmer Dorrance Corporation, Chattanooga, USA). The end of the control cable, which was positioned in a U-profile, was attached to either 1) a threaded rod or 2) springs of different stiffness. The steel cable was interrupted by two force sensors (FLLSB200 222 N, FUTEK , Irvine, USA), one before and one after the stainless steel cable housing for C-100HD cable (CH-100HD, Hosmer Dorrance Corporation, Chattanooga, USA). To decrease friction in the cable a Teflon liner for heavy duty cable housing (CH100-HD, Hosmer Dorrance Corporation, Chattanooga, USA) was placed in the inside of the cable housing. A U-profile was fixated to the thermoplastic shell. Within the U-profile a displacement sensor (13FLP100 A, Sakae, Zhejiang, China) was placed. The two force sensors were amplified (CPJ, Scaime, Juvigny, France) and sampled together with the displacement sensor at 50 Hz (NI USB-6008, National Instruments , Austin, USA), and finally stored using a custom LabVIEW program (LabVIEW 2012, National Instruments, Austin, USA).

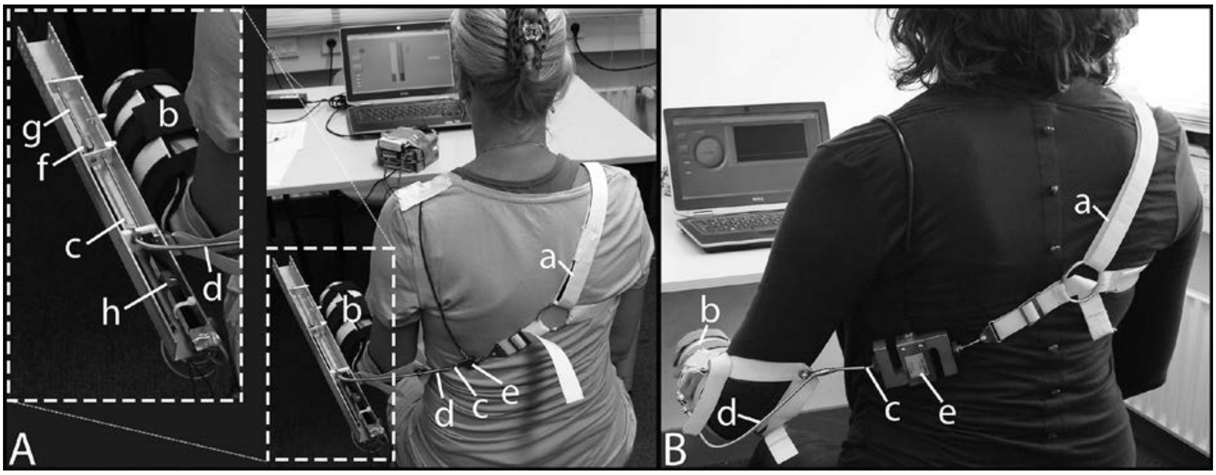

Fig 1. Measurement set-up. The measurement set-up for the force reproduction task (A) and maximum force measurements (B) consisted of a "figure-of –nine" harness (a) and thermoplastic shell (b) which are connected through a Bowden cable (c) running through a cable housing (d). In the maximum force measurements setup (B) the cable excursion is disabled. Here the cable (c) is interrupted by a force sensor at the subject's back (e). In the force reproduction task setup the cable is interrupted by two force sensors (e & f), which measure the cable forces before (F_{back}) and after (F_{arm}) the cable housing respectively. In this figure a threaded rod (g) is illustrated leading to disabled cable excursions. The threaded rod is interchangeable with springs of different stiffness, which resulted in different cable force-excursion characteristics. A displacement sensor is recording cable excursions (h).

To investigate ten different force-excursion conditions, ten interchangeable springs with varying spring stiffness and pretensions were utilized as shown in Table 1. The spring's characteristics (stiffness and pretension) were chosen to match the predefined force-excursion parameters.

Table 1. Stiffness and pretension of the utilized springs in each condition

Condition	Spring stiffness [N/mm]	Spring pretension [N]
10 N – 10 mm	0.44 (0.06)	5.5 (0.6)
10 N – 20 mm	0.19 (0.04)	6.3 (0.8)
10 N – 40 mm	0.20 (0.01)	2.0 (0.3)
10 N – 60 mm	0.08 (0.00)	5.6 (0.1)
10 N – 80 mm	0.08 (0.00)	4.0 (0.1)
20 N – 10 mm	1.50 (0.18)	5.3 (1.6)
20 N – 20 mm	0.57 (0.01)	8.9 (0.2)
20 N – 40 mm	0.26 (0.01)	10.0 (0.1)
20 N – 60 mm	0.22 (0.00)	7.2 (0.1)
20 N – 80 mm	0.21 (0.04)	5.2 (1.1)

Maximum force measurements

Another similar custom-made prosthesis simulator (Fig 1B) was utilized to measure the participants' pre and post experimental maximum forces. Cable excursions were disabled in this setup. The Bowden cable was interrupted by a force sensor (S-Beam load cell ZFA 100kg, Scaime, Juvigny, France). The measured forces were amplified (CPJ, Scaime, Juvigny, France), sampled at 1 kHz (NI USB-6008, National Instruments , Austin, USA), and finally stored using a custom LabVIEW program (LabVIEW 2012, National Instruments, Austin, USA).

Questionnaires

To analyze the given task and the used system with its force –excursion combinations and the differences between the different conditions, subjective data of perceived workload were gathered via the Nasa Task Load Index (NASA-TLX) questionnaire (Desktop Version 2.1.2, developed by David Sharek, NASA Ames Research Center, Moffett Field, USA). A Dutch translation of the questionnaire was provided. The questionnaire assesses the total workload divided into six subscales: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration.

Furthermore, subjects were requested to indicate regions of no, mild or severe discomfort on a map of the body (Body-Map) by coloring the respective body parts green (touchiness), orange (irritation), or red (pain) (Fig 2).

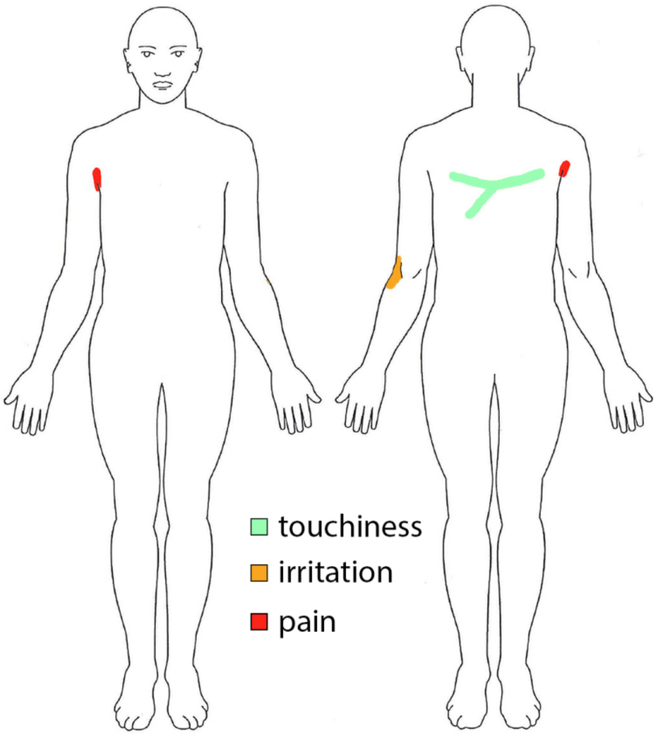

Fig 2. Body-Map. The Body-Map was coloured by one subject indicating pain (red) at the back of the left elbow, irritation (orange) in the right arm pit and touchiness (green) on a stripe of his back.

To monitor post experimental pain and fatigue effects, a few days after the experiment each participant was asked in an email whether he/she had experienced any post-experimental pain the day of the measurement or the following days, and if so in which part of the body.

Procedure

The chronological experimental procedure is shown in Fig 3. First, subjects were requested to exert their maximum force on the cable utilizing the equipment shown in Fig 1B. Three measurements were taken with a duration of three seconds each. This procedure was repeated at the end of the experimental procedure to monitor physical fatigue caused by the experiment. Then the subjects conducted the force reproduction experiments equipped with the measurement setup shown in Fig 1A, consisting of two parts: six trials with cable excursion disabled, followed by ten trials with cable excursion. After completing each of these 16 trials the subject was requested to fill in a Nasa-TLX questionnaire. The individual relevance of each of the six subscales to the total workload was supplemented by a paired comparison of the six subscales, ascertained during the first and last questionnaire. The Body-Map questionnaire was provided four times: after the pre and post maximum force measurements as well as after the force reproduction experiments without and with cable excursion.

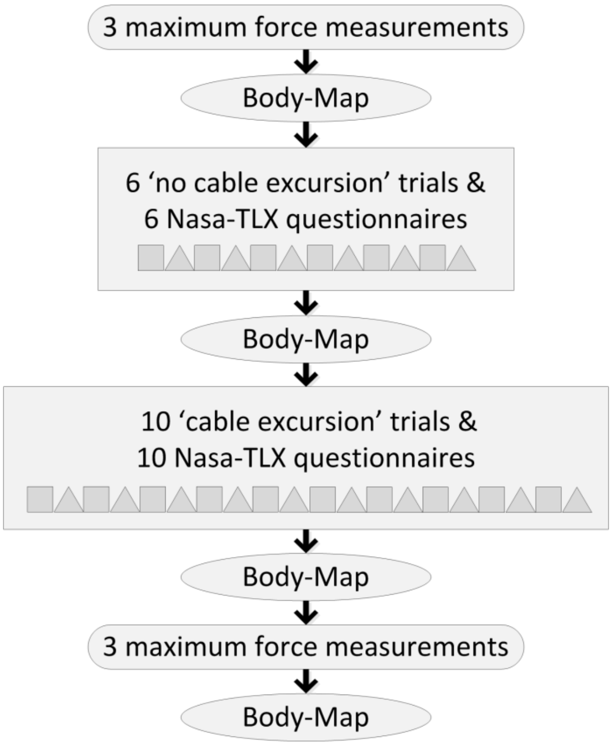

Fig 3. Experimental procedure. The flowchart of the experimental procedure illustrates the chronologic order of maximum force measurements (rounded rectangles), body-map questionnaires (circles), force reproduction experiments with and without cable excursion (rectangles) with alternating force reproduction trials (squares) and Nasa-TLX questionnaires (triangles).

For the force reproduction trials the measurement set-up of Fig 1A was fitted to the subject. During the ‘no cable excursion’ trials a threaded rod was placed in the U-profile disabling cable excursion. For the ‘cable excursion’ trials, the threaded rod was replaced by linear springs of different stiffnesses. Six force levels (10, 15, 20, 25, 30 and 40 N) for the ‘no cable excursion’ trials and ten force-excursion combinations (10, 20, 40, 60 and 80 mm each at 10 and 20 N) for the ‘cable excursion’ trials were examined resulting in 16 test conditions. Before each trial, the subject was allowed one training run at 22 N to familiarize himself with the task. Fig 4 shows the experimental procedure of the six ‘no cable excursion’ trials. The order of the six force levels (part 1 - ‘no cable excursion’ trials) and the ten force-excursion conditions (part 2 - ‘cable excursion’ trials) were counterbalanced over participants. One trial consisted of eleven alternating visual and blind alternating blocks, all at the same constant reference force level. So for example, the target force was 0 than 20 than 0 than 20-0-20 etc. One block lasted 5 seconds followed by a 2 second break, resulting in a duration of 152 seconds per trial. During a visual block the constant reference force and the produced force measured on the arm of the subject (F_{arm}) was shown on the laptop screen, whereas during a blind block only the constant target force was displayed. In other words, during the visual blocks subjects reproduced the target force based on the visual information on the screen, whereas during the blind blocks subjects based the magnitude of the reproduced force on the perceived force during a visual block. Participants were instructed to produce the force as stable as possible. During the ‘cable excursion’ trials visual feedback to the subjects’ arm was disabled with a hairdressers cloth tightened to the walls, as the arm position would have given information about the cable excursion. Subjects had the opportunity to practice the given task for 120 seconds. For the ‘cable excursion’ trials subjects were given 60 seconds to become accustomed to the new condition. In the event that a subject experienced (concentration) difficulties in one block, another visual and blind block was added to the condition to complete the measurement.

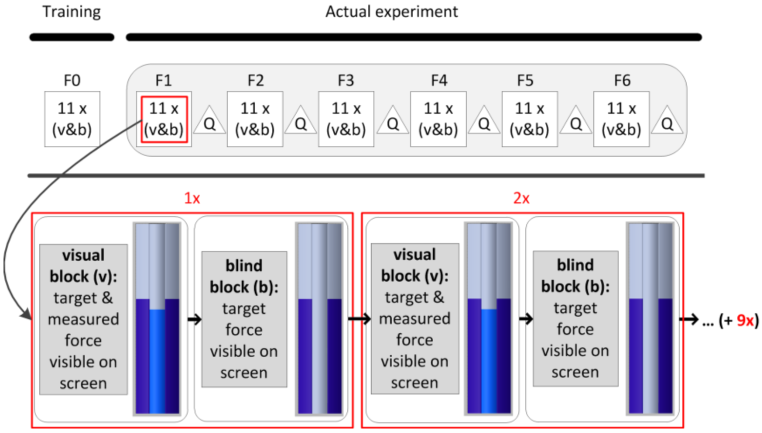

Fig 4. Experimental procedure of 'no cable excursion' trials. Flowchart illustrating the experimental procedure of the six 'no cable excursion' trials as shown in Fig 3. After practicing the force reproduction task at 22 N (F0), six force levels (10, 15, 20, 25, 30 and 40 N) were examined during 11 alternating visual and blind blocks. The force reproduction task at each force level (squares) was followed by a Nasa-TLX questionnaire (triangle). The order of force levels (F1 to F6) was counterbalanced over the subjects. The outer (purple) bars indicate the target force; the inner (blue) bar indicates the measured force.

Data analysis

Metrics

Participants' performance was assessed by the force reproduction error, which is the difference between target and reproduced force, and the force variability, which is the noise of the reproduced force. These metrics were determined from the cable forces measured at the back of the subject.

The last 2.5 seconds of measured force (Fig 5) were analyzed by calculating the mean and standard deviation. Because the perceived force during the visual block must be reproduced during the blind block, the force reproduction error (FRE) per block was calculated as the average force of a blind block minus the average force of the foregoing visual block (S1 Equation). The results per block were then averaged over all blocks of the trial to obtain the overall force reproduction error (per subject, per force level) (S2 Equation). The first visual and blind blocks of each trial were eliminated from data analysis.

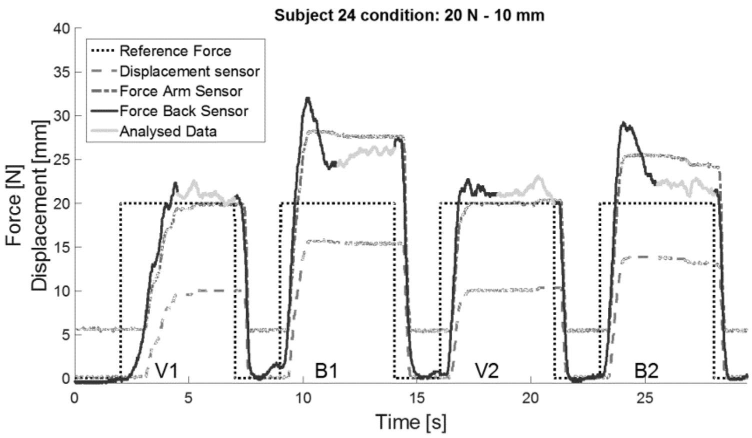

Fig 5. Raw data 'cable excursion' trials. The raw data of the first 30 seconds of a typical trial, condition 20 N – 10 mm, represents the target force of 20 N, the approximate 10 mm cable excursion measured by the displacement sensor and the two cable forces measured at the arm (F_{arm}) and the back (F_{back}) of the subject. Visual blocks (V1, V2) are alternating with blind blocks (B1, B2).

The force variability (FV) results from the standard deviation of the blind blocks (S3 Equation) averaged over all analyzed blocks (S4 Equation).

The force reproduction error and force variability were determined for each condition (six force levels for 'no cable excursion' and ten force-excursion combinations for 'cable excursion' trials).

Maximum force measurements

The highest values of the three pre and three post maximum force measurements were determined. Only trials where the maximum force was attained within the predetermined 3 seconds were included (114 of 150 trials). In those cases where the measured cable force was still increasing at the 3 second mark, it was concluded that the maximum force had not yet been reached and the trial was excluded from the analyses. The maxima of the three pre and post measurements were taken to analyze for fatigue effects.

Statistics

For statistical analysis SPSS version 20 was used. Pre and post experiment maximal force levels were compared using a paired Student t-test. Repeated measures ANOVAs were used to determine the experimental effects ('no cable excursion' trials: target force; 'cable excursion' trials: target force × excursion) for force reproduction error and force variability. A significance level of α=0.05 was maintained.