# Feedback in voluntary closing arm prostheses

*Investigation of optimal force feedback in shoulder controlled arm prosthesis operation*

## Abstract

High rejection rates indicate that prosthetic users are not satisfied with the performance of their arm prostheses. In theory, one of the advantages of shoulder controlled prosthesis, compared to myo-electric prostheses, is that the user receives direct proprioceptive feedback about the opening width and pinch force of his prosthetic hand. However, the operating forces that commercially available voluntary closing prostheses require are too high, which leads to discomfort and disturbs the direct proprioceptive feedback.

The purpose of this study was to find an optimal operation force, at which the prosthetic user receives optimum force feedback during comfortable prosthesis operation. During experimental research, subjects were asked to reproduce a certain reference force, with and without a visual representation of the force produced. The subject's performances of blind generated forces regarding the reproducibility, stability and repeatability were evaluated to find an optimal cable force. The performances of male and female subjects, as well as the performances of subjects with and without arm defects were compared. As a result the optimal operation force level is found between 20 and 30 N for male and female subjects without arm defects. No differences in stability and repeatability performance are found between subjects with and without an arm defects. However, subjects with arm defects are found to have difficulties reproducing high force levels. In line with this, the reproducibility optimum is found between 10 and 20 N for subjects with arm defects.

It is concluded that of today's commercially available arm prostheses only one is capable of creating pinch forces at the optimal cable activation force level of 20-30 N. The created pinch forces of this prosthesis are not sufficient to handle objects in daily life. Future prosthesis design should not exceed cable forces of 30 N when realizing the desired pinch forces for daily activities. Therefore transmission ratios or servo mechanisms might be needed to optimize prosthesis design.

## Introduction

### *The use of arm prostheses in general*

Commercially available arm prostheses do not fulfil the requirements of the users. The high expectations of amputees, often triggered by media, are unrealistic. 20–40 % of arm amputees choose not to wear a prosthesis. Of those amputees who wear a prosthesis, 40-60 % do not use the full functionality it offers. Instead, they use the prosthesis for its cosmetic function (Plettenburg, 2006).

A prosthesis should look natural, should be comfortable to wear and should be easy to use (Plettenburg, 1998). Unfortunately shoulder controlled body powered prostheses require high operation forces of the user, resulting in the shoulder harness cutting into the armpits. Users find this uncomfortable. Furthermore, the use of this kind of prostheses is reported by users as tiring due to the high operating forces required (Plettenburg, 2006, Biddiss and Chau, 2006). Discomfort is leading to high rejection rates of users (Biddiss and Chau, 2007).

The ease of prosthesis control depends (among other things) on the necessity of watching the operation of the prosthetic hand or hook, also called a prehensor, to prevent slipping or crushing of the object being held. Eliminating the need for visual monitoring the operation will lead to subconscious control. The mental load of operating a prosthesis will decrease when the prosthesis is controlled subconsciously (Simpson, 1974).

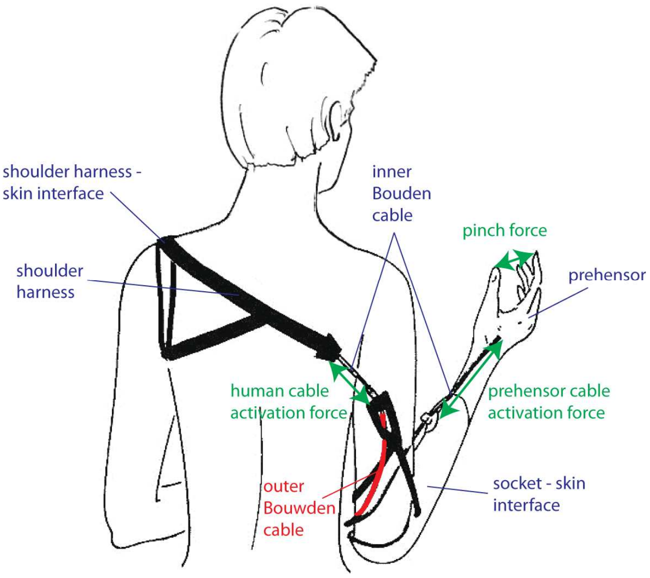

**Figure 1 Shoulder Controlled Prosthesis (Plettenburg, 2006)**

Humans know where their limbs are in space due to proprioceptive feedback cues in the human body. Visually monitoring of the limbs is not necessary to know where the limbs are in space and which forces are acting on the limbs. Compared to externally powered prostheses, body powered prostheses have the advantage of offering direct proprioceptive feedback. The user of a body powered prosthesis can feel the forces and displacements with which he is operating the prosthesis. Up to now, no commercially available arm prosthesis utilizes the full advantage of proprioceptive feedback. Mostly these prostheses require too high operating forces (Smit and Plettenburg, 2010). The high operating forces are assumed to disturb the proprioceptive feedback.

## *The use of shoulder controlled prostheses*

During World War II, Bowden cables were used in aircraft technology to transmit forces (LeBlanc, 1990). This is done by means of an inner cable, which moves with respect to an outer cable. Nowadays, many applications use Bowden cables; the shoulder controlled prosthesis is one of those. The user wears a shoulder harness on his sound side and the prosthetic hand or hook is connected to a socket covering the remaining stump. The shoulder harness and the prosthetic hand are connected via the Bowden cable mechanism, as shown in Figure 1.

The terminal device (prosthetic hand or hook) of a voluntary closing prosthesis in rest position is held open by a spring. When pulling the cable, the terminal device closes. When releasing the cable the hand opens again. For a voluntary opening prosthesis this works the other way around (Plettenburg, 2006); tensioning of the cable will open the terminal device, and relaxing the cable will close the terminal device. The grasping force is supplied by a spring. Both types of prosthesis provide the user with proprioceptive feedback. However, in case of the voluntary opening prosthesis, the force feedback is inversely related to the grasping force, and therefore very counterintuitive (Plettenburg and Herder, 2003). Therefore, this research focuses on voluntary closing prostheses only, where force and displacement feedback are directly related to the force and displacement of the terminal device.

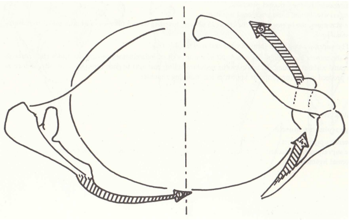

**Figure 2 Top view on thorax, left side = retraction, right side = protraction (Kapandji, 1970)**

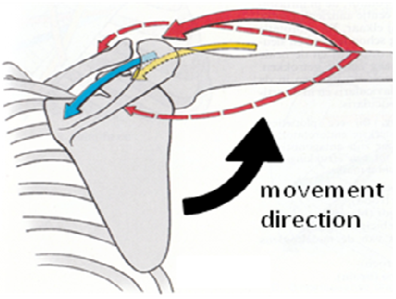

**Figure 3 Dorsal view on upper arm, shoulder and thorax showing humeral abduction (Platzer, 2005)**

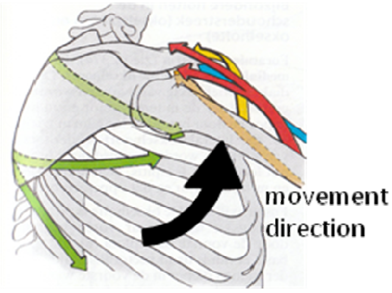

**Figure 4 Lateral view on upper arm, shoulder and thorax showing humeral anteflexion (Platzer, 2005)**

To apply tension to the cable, the user can protract his sound shoulder (Figure 2), or use humeral abduction or anteflexion of his amputated side (Figure 3 and Figure 4). Most often a combination of these body movements is used (Plettenburg, 2006). The control strategy depends on the preference of the user.

## *Prosthesis control*

When operating a prosthesis, the device is an extension of the body. The user receives feedback about the location of the prosthesis in space, in the same way a tennis player knows where his racket is in space, and with which velocity and acceleration the racket is moving (Doeringer and Hogan, 1995). The tennis player and the prosthetic user both know which forces are acting on their device. This effect is called extended physiological proprioception (EPP) (Simpson, 1974). Training improves the user’s capabilities (Doeringer and Hogan, 1995).

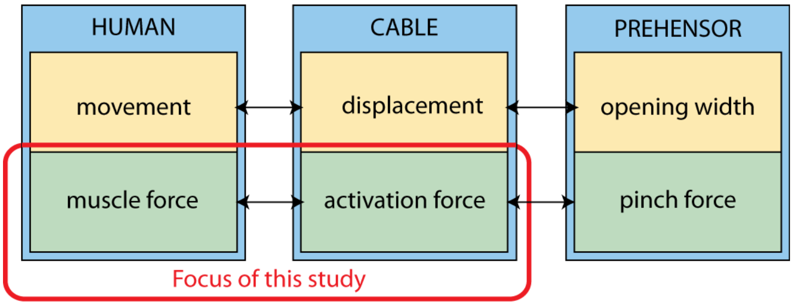

**Figure 5 Relationships in prosthesis control**

During shoulder controlled prosthesis operation, the user's body movements result in cable displacement. The cable displacement is directly related to the opening width of the terminal device. The relationships of body movement, cable displacement, and opening width of the terminal device are shown in Figure 5. Since body movements are fed back by the proprioceptive feedback cues to the central nervous system (CNS), the user is aware of his movements. Thus, in a way the user is aware of the opening width of the terminal device without looking at it.

Furthermore, Figure 5 shows that the user's muscle force results in a cable activation force, which is directly related to the pinch force of the prehensor. Smit and Plettenburg (2010) have found a linear relationship between cable activation force and pinch force of commercially available prostheses.

The focus of this study is the relationship between the user's muscle force and the cable force. More details of this relationship can be found in Figure 6, which shows an overview of the human-prosthesis control interface. Muscle activation, stimulated by the CNS, results in muscle force. Via the shoulder harness-skin interface and the socket-skin interface (Figure 1) the control cable (= the inner Bowden cable) is tensioned, which results in cable activation forces. Since the Bowden cable mechanism causes friction when the inner cable is moving with respect to the outer cable, the cable activation forces are split into cable forces before the Bowden cable, called human cable activation forces, and into cable forces after the Bowden cable, called the prehensor cable activation forces (Figure 1).

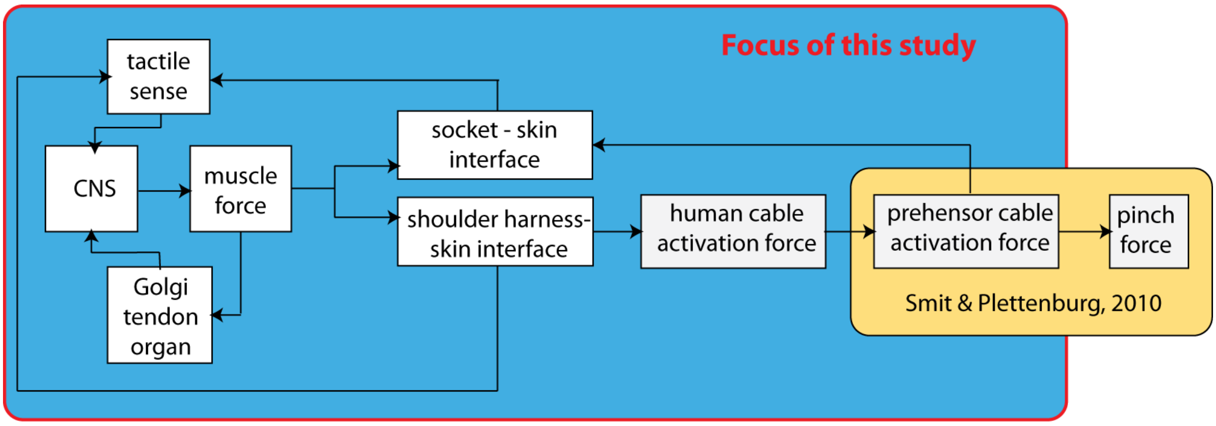

**Figure 6 Human – prosthesis control interface**

Figure 6 illustrates how the user receives force feedback via his Golgi tendon organs (proprioceptive senses) and his tactile sense. The Golgi tendon organs (GTO) sense the created muscle force and transmit this force information to the CNS. Additionally, via the shoulder harness-skin and socket-skin interfaces, the skin senses pressure and send this kind of force information to the central nervous system (CNS). Because of these feedback paths, the user is aware of his created cable forces. In normal motor control tasks, the Golgi tendon organs play an important role in force feedback, more than tactile feedback (Mugge et al., 2010).

## *Disturbance of feedback and control during prosthesis operation*

The quality of the feedback, and thus the performance of the man-machine-system, depends on two components: the mechanical properties of the system, and the window of feedback perception of the human body. This window of feedback perception has a certain range and resolution. Forces and differences in forces can be too low to perceive. Furthermore, a user might notice fluctuations of forces only in a certain frequency range.

There are several reasons why the advantage of direct proprioceptive feedback as well as extended physiological proprioception (EPP) is restricted during prosthesis operation.

1) The operating forces that most shoulder controlled prostheses on the market require are too high (Smit and Plettenburg, 2010). These high required operating forces mostly result from energy losses due to friction in the mechanism, or parasite spring forces from cosmetic covering of prosthetic hands (Herder and Munneke, 1995). When the required cable operating forces are becoming too high, pain might disturb the perception of forces and thus the feedback capabilities of the human body.
2) The required cable forces might lie in a range of forces the user is not able to sustain permanently. For instance, holding an object with a voluntary closing prosthesis for a longer period is tiresome (Plettenburg and Herder, 2003). The user's created operation force might fluctuate due to fatigue.
3) The relationship of input at the shoulder harness and the output at the terminal device can be disturbed by internal friction or parasite spring forces as well (Herder and Munneke, 1995).

The literature does not state at which force levels the human perceives enough feedback to take advantage of the effect of EPP and direct proprioceptive feedback.

## *Purpose of experimental research*

The purpose of this experimental research was to find a window of optimal cable operation force, in which a human perceives the best feedback without feeling pain and getting exhausted. Once an optimal operation force window is known, the grasping forces required for daily activities need to be related to the optimal cable forces. This should result in a force transmission ratio for new prosthesis design.

In improved prosthesis design the full advantage of voluntary closing shoulder controlled prostheses should be taken by optimising the feedback. The aim is subconscious prosthesis control and thus a low mental load when operating these prostheses.

## *Approach*

When developing the measurement equipment and the measurement procedure, existing prostheses were analyzed and taken as a reference. Smit and Plettenburg (2010) investigated commercially available voluntary closing hand prostheses. Figure 7 shows the relationship between activation force (horizontal axis) and pinch force (vertical axis). The linear behaviour of different commercially available arm prostheses is illustrated in this figure. For initializing a pinch force a certain threshold activation force was needed.

The TRS hook was taken as a reference for finding requirements of measurement equipment and procedure. The TRS hook required the least activation force from the user (33 N for a pinch force of 15 N) of all tested prostheses and had the lowest activation force threshold of 10 N. Furthermore, the TRS hook had the lowest energy dissipation (=52 Nmm) of all tested prostheses. Additionally, the required operating forces lay theoretically below the critical muscle force (Smit and Plettenburg, 2010). The critical muscle force was assumed to be suitable for daily activities without exhausting the user and was estimated to be 18 % of the maximum muscle force (Monod, 1985). The maximum muscle force a prosthetic user can generate with a shoulder harness was found to be 280 N (Taylor, 1954). This altogether results in a theoretical critical muscle force of 50 N.

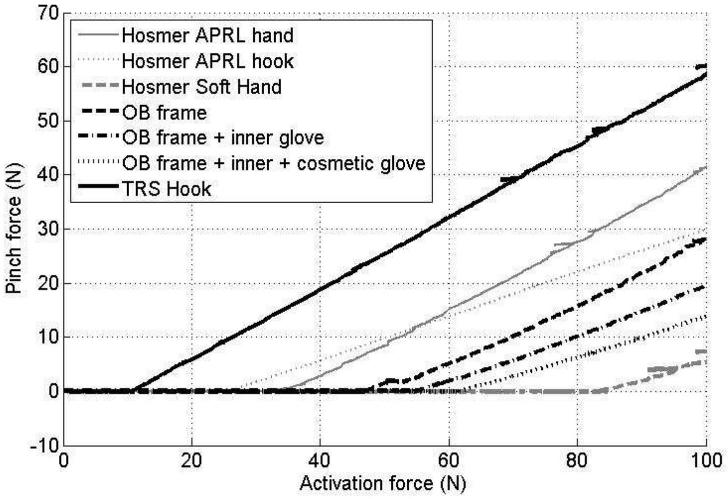

**Figure 7 Relationship of activation force and pinch force of different commercially available voluntary closing arm prostheses (Smit and Plettenburg, 2010)**

Pulling on a sock was with 34 N the highest required pinch force during daily operation found in the literature (Keller et al., 1947). Using the TRS hook and taking a pinch force of 40 N into account, this resulted in a required operation force of approximately 70 N. Thus the required cable forces for daily activities with a TRS hook lay in the range of 0-70 N.

Preliminary experiments showed that the operation force of 70 N was too high to produce constantly, which was already indicated by the calculated theoretical critical muscle force of 50 N. The highest force that subjects seemed to be able to produce on a constant level without fatigue was 40 N. **Thus, the first requirement for the measurement procedure was to evaluate cable forces up to a maximum 40 N.**

A cable activation force of 5 N was half of the force required to close the TRS hook. Preliminary experiments showed that breathing influenced the produced cable force. Depending on the subject, this breathing induced variation could vary between 1 N and 2.5 N. **Therefore it was decided not to take a lower reference force than 5 N, since the influence of breathing would be too high at lower reference forces (second requirement).**

The various prostheses showed different transmission ratios between pinch force and activation force (Figure 7). The aim of this study was to find an optimal cable activation force and relate those to the daily required pinch forces. This should result in an optimal transmission ratio. **Therefore as a third requirement only cable forces should be measured during the experiments, no pinch forces. Thus no transmission ratio should be taken into account.**

During the experiments of Smit and Plettenburg (2010) the friction effects of Bowden cables were not taken into account. Since friction between inner and outer cable depends on the curvature of the Bowden cable, it is hard to predict which friction forces might influence the measurements (Carlson et al., 1995). **The forth requirement results: The inner cable should be fixed to the prosthesis in such a way that the inner and outer cables cannot move in respect to one another. No movement means no friction.**

Even though negligible small friction between inner and outer cable could occur, unexpected interference of the used measurement equipment should still be eliminated. **Therefore, as a fifth requirement, the cable forces should be measured as closely as possible to the shoulder harness.**

**As a last requirement: The measurement equipment should offer a uniform fit for the subjects to generalize the measurement setup and procedure.**

Taking all these requirements together, the measurement equipment should simulate a prosthesis which holds and squeezes a rigid object. In this situation no movement of the terminal device occurs, thus no cable displacement occurs.

## *Summary of purpose of research and requirements for experiments*

The purpose of this study was to find an optimal operation force, at which the prosthetic user receives the best force feedback during comfortable prosthesis operation. Therefore the following requirements for measurement equipment and the measurement procedure should be taken into account:

- Only cable forces in the range between 5 N and 40 N should be investigated;
- The inner cable should be fixed to the prosthesis in such a way that the inner and outer cables cannot move in respect to one another;
- Cable forces should be measured as closely as possible to the shoulder harness;
- The measurement equipment should offer a uniform fit for the subjects to generalize the measurement setup and procedure.

# Method

The used measurement procedure was based on the psychophysical measurement method of adjustment (Gescheider, 1976). The experiments to investigate sensory weighting of force and position feedback in human motor control tasks (Mugge et al., 2009) were taken as an example.

## *Subjects*

Thirteen subjects without arm defects (7 male and 6 female) and 7 subjects with arm defects (4 male and 3 female) participated in this study. Twelve of the 13 subjects without arm defects were right-handed. The subjects of this group were on average 25±3 years old, were 178±10 cm tall, and had a body weight of 71±10 kg. All subjects without arm defects (including the left-handed subjects) wore a 'dummy' prosthesis on the right arm during the experiment. The harness was placed around the left shoulder.

On average, the seven subjects with arm defects were 42±13 years old, were 180±6 cm tall, and had a body weight of 70±7 kg. Table 1 shows an overview of the group of subject with arm defects.

**Table 1 Group of subjects with arm defects**

| **Subject No.** | **Gender** | **Arm defect** | **Arm defect since** | **Preference side (arm)** | **Age [years]** | **Height [cm]** | **Weight [kg]** | **Used prosthesis** |
|---|---|---|---|---|---|---|---|---|
| Subject 1 | female | right below elbow | birth | right | 36 | 172 | 62 | Myo-electric |
| Subject 2 | female | left below elbow | birth | right | 46 | 177 | 70 | Voluntary opening shoulder controlled |
| Subject 3 | female | left below elbow | birth | right | 47 | 178 | 75 | Voluntary opening shoulder controlled |
| Subject 4 | male | right below elbow | birth | right | 34 | 186 | 70 | Myo-electric |
| Subject 5 | male | right below elbow | birth | left | 18 | 174 | 57 | Myo-electric |
| Subject 6 | male | right above elbow | 1979 | left | 58 | 180 | 78 | Voluntary opening shoulder controlled |
| Subject 7 | male | left below elbow | 1972 | right | 55 | 190 | 76 | Myo-electric<br>till 2007: Voluntary opening shoulder controlled |

## *Measurement equipment*

The hardware used during the experiments consisted of a 'one fits all dummy prosthesis' (Figure 9), which was connected to a shoulder harness via a Bowden cable. The Bowden cable was fixated to the 'dummy' prosthesis in such a way that cable displacement was disabled. This setting simulated the grasping of non-deformable objects. An S-BEAM Junior load cell (Model FLLSB200), measuring the cable forces, was connected to the cable, and was located between the shoulder blades of the subject during the experiment. The load cell was connected through an amplifier and a data acquisition system to a laptop, which was running a LabVIEW program. The measurement setup is shown in Figure 8 and Figure 9. Specifications of the load cell, the amplifier, the data acquisition system and the used LabVIEW program can be found in Appendix A.

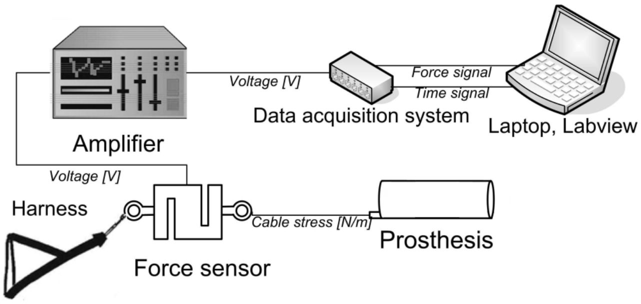

**Figure 8 Schematic overview of the measurement equipment**

## *Task*

Five experiments with five different force levels (5, 10, 20, 30 and 40 N) were carried out. In order to carry out the experiments, the subject needed to reproduce a given reference force after a beep once while seeing the reference force on the laptop screen and once without seeing the reference force, as explained in more detail in the section 'Display'. The subject was requested to reach the reference force level as fast as possible and hold his or her reproduced force as constant as possible.

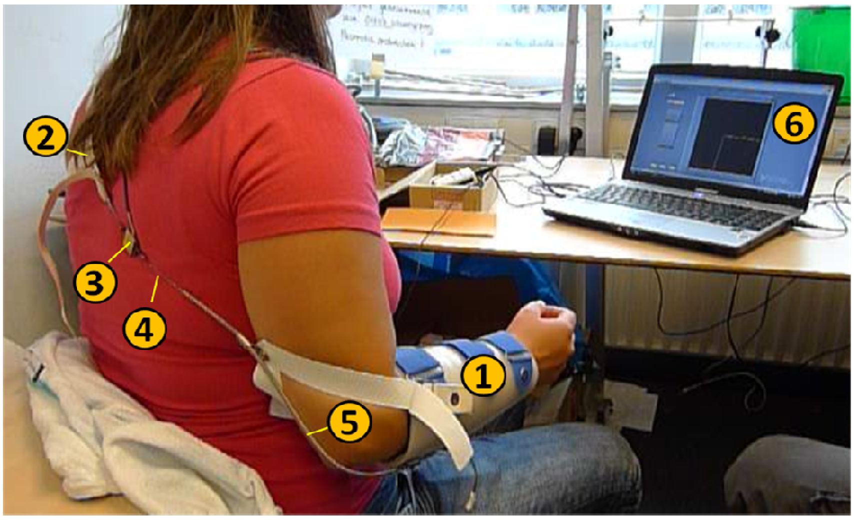

**Figure 9 Measurement setup showing the dummy prosthesis (1), shoulder harness (2), force sensor (3), inner Bowden cable (4), outer Bowden cable (5), and laptop with LabVIEW measurement program (6)**

Before the experiments started, the subject read an information letter (see Appendix B.2). Then the measurement equipment (Figure 9) was fitted to the subject. A detailed description of the correct placement of the measurement equipment can be found in Appendix B.1.

The dummy prosthesis was placed on the right arm of all subjects without arm defects, independent of their preference side. Subjects with arm defects wore their own prosthesis on their arm defect side. The ‘dummy’ prosthesis was placed on the prosthesis to establish a better connection with the measurement equipment to the stump. In every other respect, the task was the same for both groups.

Once the test equipment was fitted to the subject, the subject was given a short introduction to the experimental task, followed by a brief training session with one of the 5 reference force levels, in a random order. The force level used for training purpose was also the first experimentally recorded force level. The duration of the training depended on the operation skills of the subject. Once the subject understood the task, and was able to operate the test equipment in the right manner, the first experiment commenced.

During the experiments the subject wore only a T-shirt, sat on a chair without armrests and looked at the front panel of the LabVIEW program on a computer screen (Figure 10), which is explained in the section ‘Display’. The subject was instructed to deliver forces by abduction and adduction of the arm wearing the ‘dummy’ prosthesis and by protraction of the opposite arm/shoulder (Figure 2, Figure 3, and Figure 4) or a combination of those three. The subject had to determine the optimal strategy. The subject was not allowed to place his arm wearing the ‘dummy’ prosthesis on his lap or thorax; instead he was asked to hold and move this arm freely in space. The subject was allowed to place his other hand in his lap. Furthermore the subject was asked to sit as relaxed and as comfortably upright as possible.

After completing all 5 experiments, the subject was asked to fill out a questionnaire (see Appendix B.3). The goal of the questionnaire was to collect subjective data about the subject’s experiences during the experiments.

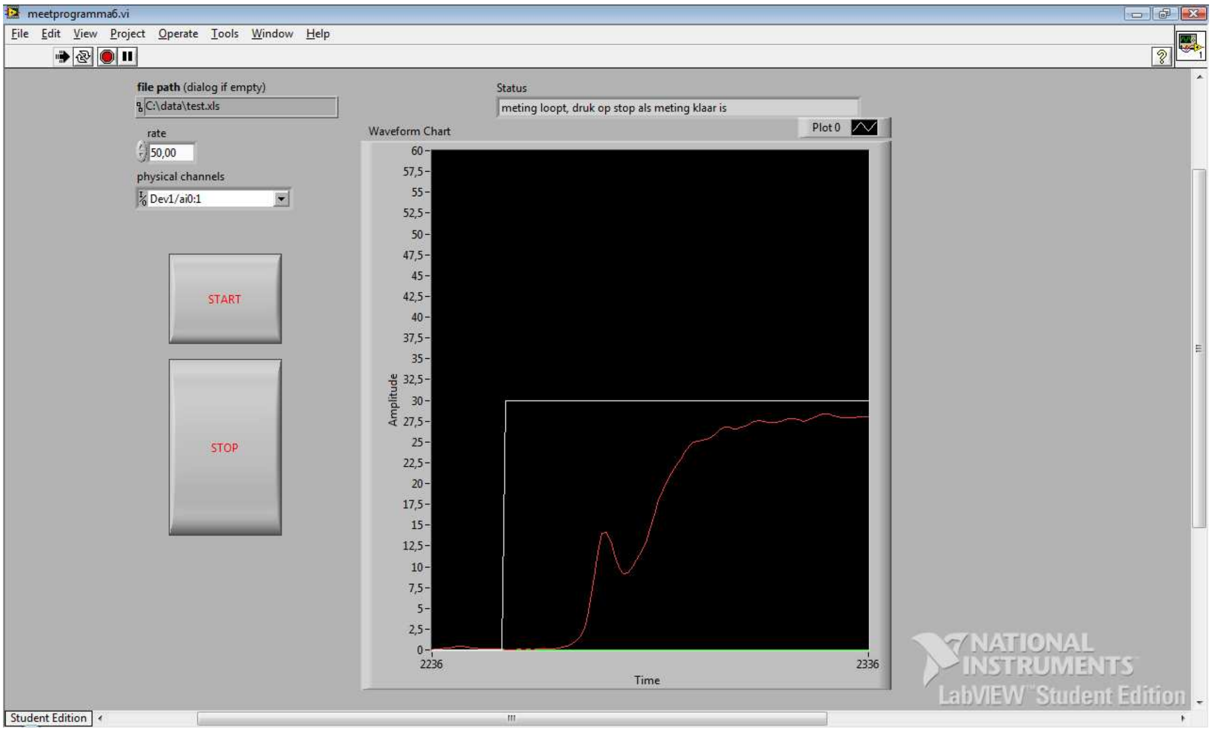

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**Figure 10 Front panel of the LabVIEW measurement program**

## *Display*

The display the subjects saw during the experiment was the front panel of the LabVIEW program (Figure 10). The coordinate plane (waveform chart), with the time on the horizontal axis and the force in Newton on the vertical axis, contained a red and a white line. The white line was the reference force which had to be tracked, shown as a block wave. The red line was the produced force of the subject. The waveform chart moved horizontally with time, thus on the right side of the waveform chart the actual delivered force was shown, whereas the delivered forces in the past could be seen for a few seconds before they disappeared on the left side of the waveform chart.

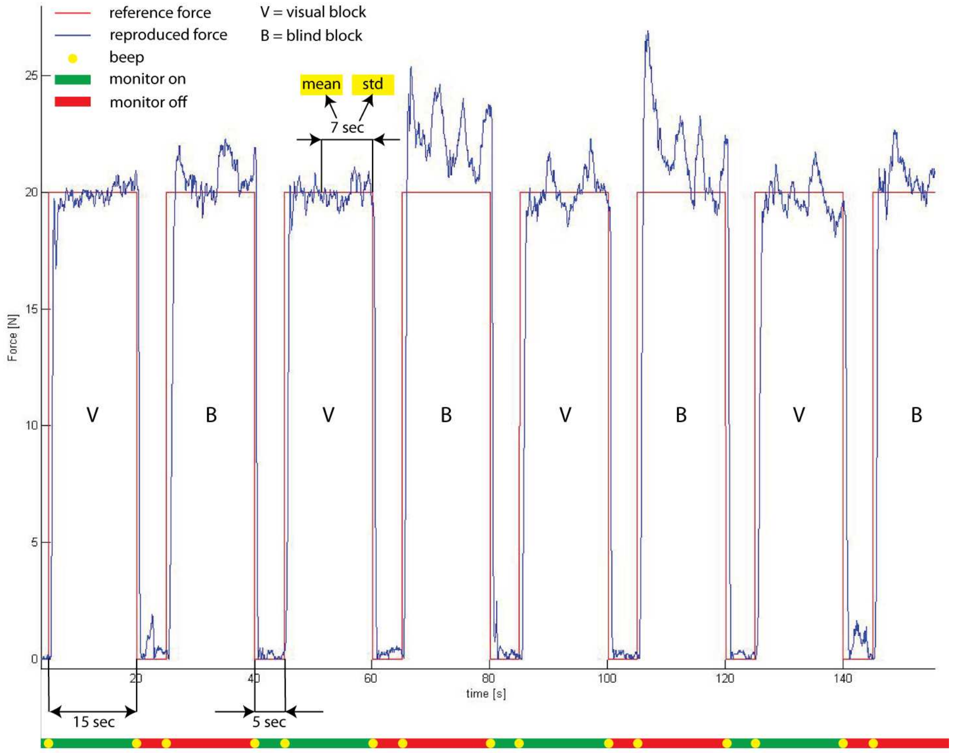

**Figure 11 Illustration of the beginning of one experiment at reference force level 20 N. The red lines indicate the reference force, the blue lines the reproduced force. The length of each block is 15 seconds with a break between the blocks of 5 seconds; means and standard deviations (std) are taken from the last 7 seconds of each block.**

Figure 11 shows the beginning of one experiment at one reference force level. The red line indicates the reference force, the blue line the reproduced force. The duration of one block was 15 seconds followed by a break of 5 seconds. A beep identified the beginning and the end of each reference force block wave (Figure 11). Furthermore at every second reference force block wave, the waveform chat was switched off. This means that the subject could see the reference force (white line in LabVIEW program - Figure 10) and the reproduced force (red line in LabVIEW program - Figure 10) at the first reference force block wave (= block with visual feedback) and could not see the reference force and produced force at the following reference force block wave (= block without visual feedback). Because of the beeps the subject knew during the block without visual feedback when to start and stop reproducing the reference force. Another block with visual feedback followed, continued by a block without visual feedback, and so on (Figure 11). One experiment contained 15 blocks with visual feedback (henceforth referred to as visual blocks) and 15 blocks without visual feedback (henceforth referred to as blind blocks).

One experiment at one reference force level took 10 minutes. Five reference force levels (5 N, 10 N, 20 N, 30 N, and 40 N) were measured. The reference force levels were offered to the subject in a randomized order. The test matrix can be found in Appendix B.4. The vertical axis settings in LabVIEW were chosen in a way that the reference force was always shown in the middle of the vertical axis of the waveform chart (Figure 10).

## *Data analysis*

LabVIEW wrote the parameters time, reference force and measured produced force with a sample frequency of 50Hz to a data file.

Visual blocks were analysed separately from blind blocks. The data was analysed in both absolute and relative sense. The relative force levels were expressed as a percentage of the reference force by dividing the absolute value by the reference force. For the data of one subject at one reference force level the following steps were made:

It was assumed that the steady state was reached after 8 seconds. The last 7 seconds of each block were used for analysis, to eliminate the fluctuations caused by the initial response. The means and standard deviations of these last 7 seconds of each block were calculated. This resulted in 15 means and 15 standard deviations per condition (visual and blind) per reference force.

When a new experiment with a different force level started, the subject needed to get used to the force. To eliminate learning effects, the data of the first 3 visual and first 3 blind blocks were not taken into account. In a few cases false data blocks were discovered, e.g. where the subject did not hear the beep and as a result did not reproduce the force. In these cases the related blocks of both conditions were eliminated.

To establish a reference, subjects without arm defects were tested first. Thereafter experiments with subjects with arm defects were carried out and their results were compared with the data of subjects without arm defects.

For the group of subjects with arm defects, only the results of the subjects who succeeded in completing the respective experiment were taken into account for calculating the mean and standard deviation. Thus, for example the average and standard deviation across the group of subjects with arm defects was calculated from only 3 subjects in the 40 N experiment, whereas for the 5 N experiments the results of 7 subjects were taken into account for the mean and standard deviation value.

### Performance criteria

The performance of a subject depended first of all on how well a subject was able to estimate and reproduce the given reference force, henceforth referred to as reproducibility. In daily activities we estimate the pinch force our hand creates, which is needed to grasp and hold an object. In an ideal world the pinch force of a prosthesis is directly related to the cable activation force of the prosthesis. A prosthetic user needs to estimate the cable force he is creating using the shoulder harness of the prosthesis. Herewith the estimation of the pinch force of the prosthetic hand is made. A bad estimation of the pinch force might result in the slipping or crushing of a held object.

The mean of the reproduced force of each block was averaged across the last 12 blocks (mean of means). **A measure of reproducibility was the deviation of the reproduced force (mean of means) and the reference force.**

A second performance criterion was the ability of a subject to hold the reproduced force at a constant level, henceforth referred to as stability. When grasping and holding a vulnerable object, the boundaries of tolerable pinch forces might be narrow. Therefore it is important to be aware of deviating the pinch forces and thus the cable activation force. **The standard deviation of the reproduced force of each block was averaged over the last 12 blocks (mean of noise) and was taken as a measure of stability.**

Last but not least, a measure of performance was the ability to reproduce the same force several times, henceforth referred to as repeatability. Once a prosthetic user learned the required cable force to grasp and hold a certain object, he needed to be able to recreate this cable force each time he wanted to handle this specific object. **Over the last 12 blocks the standard deviation was taken from the mean values of the reproduced force at each block (noise of means). This was taken as a measure of reproducibility.**

## Statistical analysis

SPSS was used to investigate the statistical significance of the effects of force level, condition (visual or blind blocks) and sex. A significance level of 0.05 was maintained for all statistical tests. ANOVA repeated measures, one-sample and paired T-test were performed. In order to analyse the significance of differences within performance data sets and evaluate the significance of differences between performances of different groups (male vs female subjects and subjects with arm defects vs subjects without arm defects), ANOVA repeated measures was consulted for all three performance factors (reproducibility, stability and repeatability). The performance results (mean of means, mean of noise and noise of means) were taken as the dependent variables.

One sample T-test was performed to evaluate the significance of differences between the reproduced force and the value representing no deviation between reproduced force and reference force in terms of reproducibility.

The paired T-test was performed to investigate the significance of differences between visual and blind block performance at the same force level for all three performance factors (reproducibility, stability, and repeatability). Additionally, this test was used to look into the significance of differences between two different reference forces during blind block performance for reproducibility, stability, or repeatability.

# Results

First the results of subjects without arm defects are described, followed by the results of subjects with arm defects compared with the results of subjects without arm defects. Since visual blocks are the reference for blind blocks, the results of visual blocks are shown in the figures below next to the results of blind blocks. However, this research focuses on the results of blind blocks. The results are evaluated in absolute and relative sense.

As described in ‘Method’, three performance factors are being investigated in this study: reproducibility, stability and repeatability. The subjects’ performance is analysed based on the average values and the standard deviations across the entire group of subjects.

## *Subjects without arm defects*

The results of subjects without arm defects are illustrated in terms of reproducibility, stability and repeatability in absolute and relative sense in Figure 12 to Figure 17. The standard deviations across the results of the group of subjects are indicated by the error bars in the figures. The ‘o’ shows the average values across the results of the group of subjects. First the results of the group of all subjects are described (left plot in figures). Then the difference between female subjects (mid plot of figures) and male subjects (right plot of figures) are explained.

ANOVA repeated measures reveal significant differences within the data sets for the analyzed data of reproducibility, stability and repeatability, as shown in Table 2. Accordingly, optima can be found within these data sets.

**Table 2 Significance of reproducibility, stability and repeatability data sets in absolute and relative sense**

| | **Absolute** | **Significant** | **Relative** | **Significant** |
|---|---|---|---|---|
| **Reproducibility** | F(4,8)=4.677, p=0.031 | Yes | F(4,8)=25.992, p<0.001 | Yes |
| **Stability** | F(4,8)=92.713, p<0.001 | Yes | F(4,8)=14.871, p=0.001 | Yes |
| **Repeatability** | F(4,8)=15.721, p=0.001 | Yes | F(4,8)=6.920, p=0.010) | Yes |

### Reproducibility (mean of means)

The absolute reproducibility is shown in Figure 12 and the relative reproducibility in Figure 13. The measure of reproducibility is the deviation of the reproduced force (mean of means) and the reference force. The dashed black lines in both figures show where the reference and reproduced force are equal. A reproducibility value below this dashed black line indicates that the reproduced force is smaller than the reference force; if the reproduced force is higher than the reference force then the reproducibility value lies above this dashed black line.

#### *Group of all subjects*

Figure 12 and Figure 13 display the point at which the reproduced force equals the reference force, thus where the red line crosses the black line, between 20 and 30 N. Overall the smallest deviation between reference force and reproduced force is found in the 20 N experiment for absolute reproducibility (Figure 12) and in the 30 N experiment for relative reproducibility (Figure 13).

Comparing the absolute and relative reproducibility results between visual and blind blocks during the same experiment, no significant differences between visual and blind results are found for 20, 30 and 40 N. However, a significant difference is found for the reproducibility results between visual and blind blocks of 5 and 10 N experiments. Corresponding T- and p- values are shown in Table 3.

**Table 3 Significance in differences of absolute and relative reproducibility results between visual and blind blocks**

| Reference force level of experiment | T- and p- values | Significant |
|---|---|---|
| 5 N | T(12)=-3.838, p=0.002 | Yes |
| 10 N | T(12)=-3.474, p=0.005 | Yes |
| 20 N | T(12)=-2.048, p=0.063 | No |
| 30 N | T(12)=-0.010, p=0.992 | No |
| 40 N | T(12)=-0.082, p=0.936 | No |

The smallest deviation between the results of different subjects is found during the 5 N experiments for the absolute reproducibility (Figure 12). With increasing reference force per experiment, the deviation between the subject's results increases, resulting in the highest deviation between the subject's results in the absolute sense found during 40 N experiments. For relative reproducibility (Figure 13), the lowest deviation between the subject's results is found during 30 N experiments, whereas the highest deviation between the subject's results in the relative sense is found during the 5 N experiments. For relative reproducibility, the deviation between the subject's results decreases with increasing reference force up to the 30 N experiment. The deviation between the subject's results then increases slightly during the 40 N experiment.

For the absolute reproducibility, the reproduced force is not significantly different from the reference force (zero line) for the 20, 30 and 40 N experiments. However, 5 and 10 N experiments show significant differences. Corresponding T- and p- values are shown in Table 4.

**Table 4 Significance in differences between the reproduced and reference force in terms of absolute reproducibility**

| Reference force level of experiment | T- and p- values | Significant |
|---|---|---|
| 5 N | T(12)=3.923, p=0.002 | Yes |
| 10 N | T(12)=3.558, p=0.004 | Yes |
| 20 N | T(12)=1.385, p=0.191 | No |
| 30 N | T(12)=-1.440, p=0.176 | No |
| 40 N | T(12)=-1.651, p=0.125 | No |

For relative reproducibility, the 20, 30 and 40 N experiments show small deviations between the reproduced force and reference force (Figure 13). Furthermore, the whiskers of the error bars are short, thus there are a small deviation between the results of subjects. Noticeably high deviations between the subject's results during the 5 and 10 N experiments are illustrated in Figure 13. The deviations between the reference and reproduced force are also noticeably higher during the 5 and 10 N experiments than those of the 20, 30 and 40 N experiments.

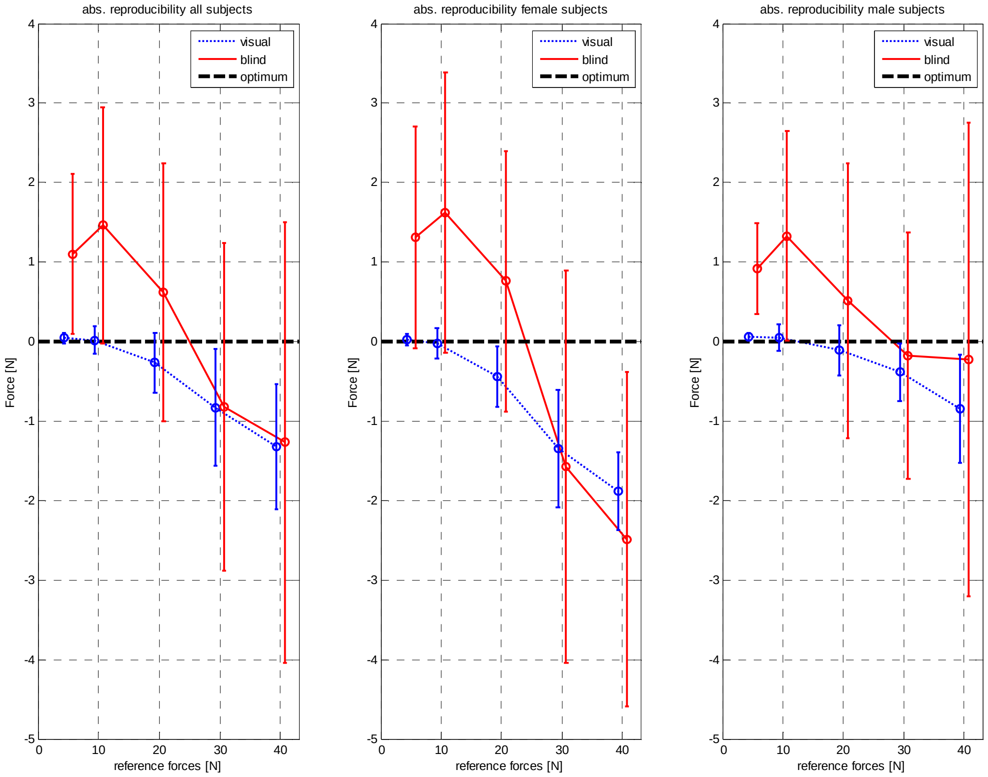

**Figure 12 Absolute reproducibility (absolute mean of means minus reference forces). Averages (o) and standard deviations (error bars) across the group of subjects are shown for all subjects (left), female subjects (mid), male subjects (right).**

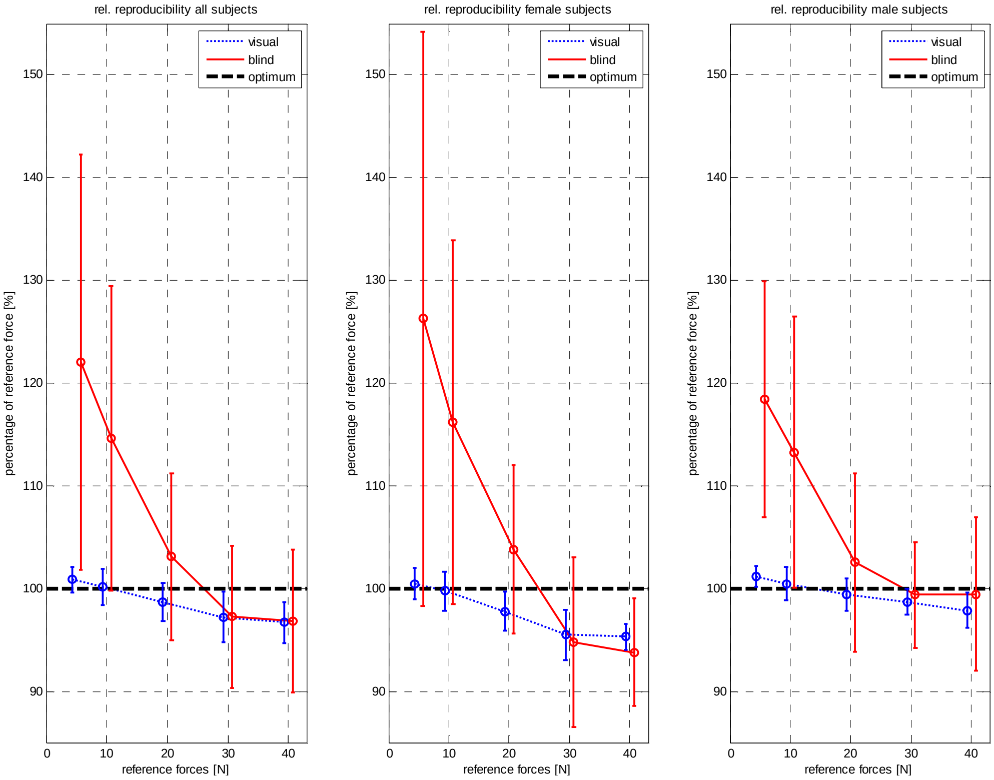

**Figure 13 Relative reproducibility (relative mean of means). Averages (o) and standard deviations (error bars) across the group of subjects are shown for all subjects (left), female subjects (mid), male subjects (right).**

### *Female versus male group*

Splitting the group by gender, the reproduced force equals the reference force between 20 and 30 N for both, male and female subjects. This is found for absolute and relative reproducibility. The smallest deviation between the reproduced and reference force for the group of females is found in the 20 N experiments and for males in the 30 N experiments for both, absolute and relative reproducibility.

In Figure 12 (absolute reproducibility) and Figure 13 (relative reproducibility), it appears that the reproduced force of females deviates more from the reference force than the reproduced force of the males at all reference force levels for both conditions. However, the differences between the results of male and female subjects are not statistically significant (absolute: F(4,8)=1.241, p=0.367; relative: F(4,8)=2.019, p=0.185).

The deviation of reproduced force and reference force in the absolute sense for the 40 N experiments is not significantly different from the optimum (zero line) for male subjects (T(6)=-0.199, p=0.849), whereas the difference for females is significantly different (T(5)=-2.894, p=0.034).

It should be mentioned that for the absolute and relative reproducibility, the highest deviation between the reproduced and reference force with visual feedback is found during 40 N experiments. Females have an offset of approximately 5 % and males of 2 % of the reference force.

## Stability (mean of noise)

The absolute and relative stability are illustrated in Figure 14 and Figure 15. The measure of stability is the standard deviation of the reproduced force of each block averaged over the last 12 blocks (mean of noise).

### *Group of all subjects*

For absolute stability the minimum mean of noise is found in the 5 N experiments (Figure 14). Not only is the average value of all subjects the smallest, but also the deviation between subjects is found to be the smallest. The higher the experiment's reference forces, the higher the mean of noise and its deviation over the group of subjects. The results of all experiments at different reference forces are found to be significantly different from each other.

For relative stability, the minimum mean of noise is found in 30 N experiments (Figure 15). Here the smallest deviation across the group of subjects is also found. However, no significant differences between the trials of 20 and 30 N, between 30 and 40 N, and between 20 and 40 N are found. Corresponding T- and p- values are shown in Table 5.

The highest relative mean of noise is found at reference forces of 5 and 10 N. The stability results of these two experiments (5 and 10 N) are found to be not significantly different from each other. The results of 5 N experiments are found to be significantly different from the rest of the experiments at different reference forces. The relative stability results of 10 N experiments are found to be different from the results of 20 and 30 N experiments. Whereas no difference between the 10and 40 N are found. Corresponding T- and p- values are shown in Table 5.

**Table 5 Significance in differences between experiments with different reference force levels in terms of relative stability**

| Reference force levels of experiments | Relative stability | Significant |
|---|---|---|
| 5 N & 10 N | T(12)=1.982, p=0.071 | No |
| 5 N & 20 N | T(12)=3.734, p=0.003 | Yes |
| 5 N & 30 N | T(12)=6.516, p<0.001 | Yes |
| 5 N & 40 N | T(12)=3.997, p=0.002 | Yes |
| 10 N & 20 N | T(12)=2.473, p=0.029 | Yes |
| 10 N & 30 N | T(12)=2.919, p=0.013 | Yes |
| 10 N & 40 N | T(12)=1.419, p=0.181 | No |
| 20 N & 30 N | T(12)=0.935, p=0.368 | No |
| 30 N & 40 N | T(12)=-1.748, p=0.106 | No |
| 20 N & 40 N | T(12)=-0.603, p=0.558 | No |

Overall the mean of noise of visual blocks is lower than the mean of noise of blind blocks. For all force levels, significant differences between the two conditions are found for absolute and relative stability. Corresponding T- and p- values are shown in Table 6.

**Table 6 Significance in differences between visual and blind blocks in terms of absolute and relative stability**

| Reference force levels of experiments | Absolute and relative stability | Significant |
|---|---|---|
| 5 N | T(12)=-4.095, p=0.001 | Yes |
| 10 N | T(12)=-4.557, p=0.001 | Yes |
| 20 N | T(12)=-7.194, p<0.001 | Yes |
| 30 N | T(12)=-4.487, p=0.001 | Yes |
| 40 N | T(12)=-7.050, p<0.001 | Yes |

### *Female versus male subjects*

The above described minima for absolute (5 N) and relative stability (30 N) are found for both male and female subject groups. In the absolute and in the relative sense, the average values of the mean of noise and the deviation of the mean of noise across the subject groups is smaller for males than for females for the experiments at all reference forces in Figure 14 and Figure 15. For the absolute stability, a significant difference is found between male and female stability performance (F(4,8) = 7,267, p = 0,009). However, the differences between males and females in terms of relative stability are not found to be different (F(4,8) = 0,770, p = 0,574).

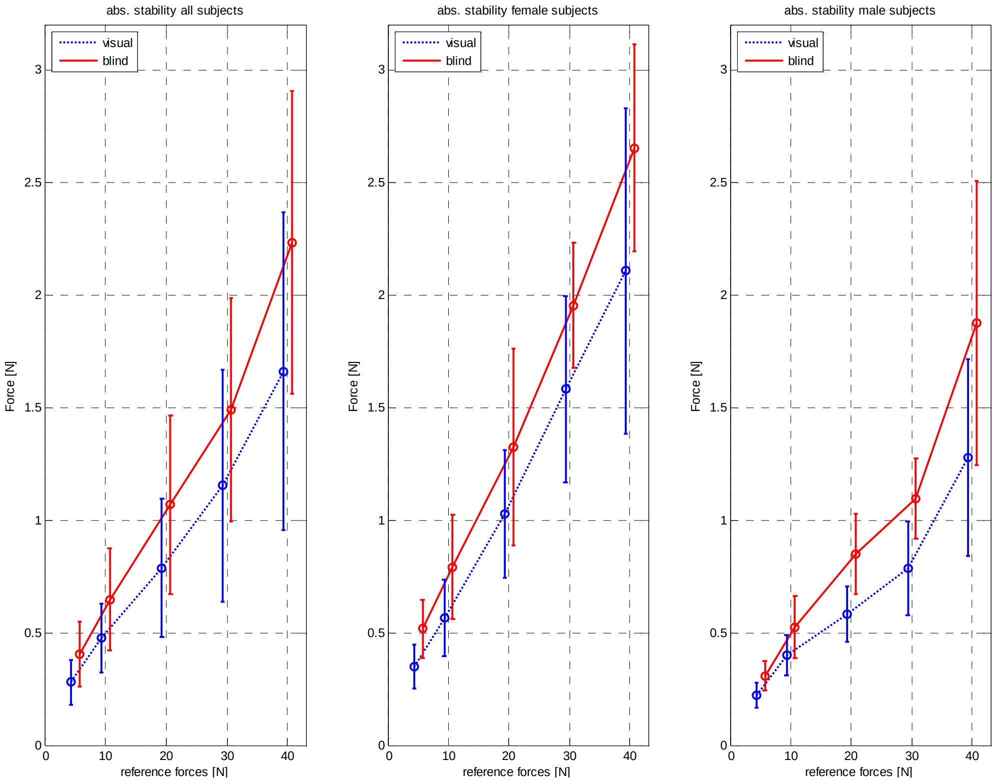

Figure 14 Absolute stability (absolute mean of noise). Averages (o) and standard deviations (error bars) across the group of subjects are shown for all subjects (left), female subjects (mid), male subjects (right).

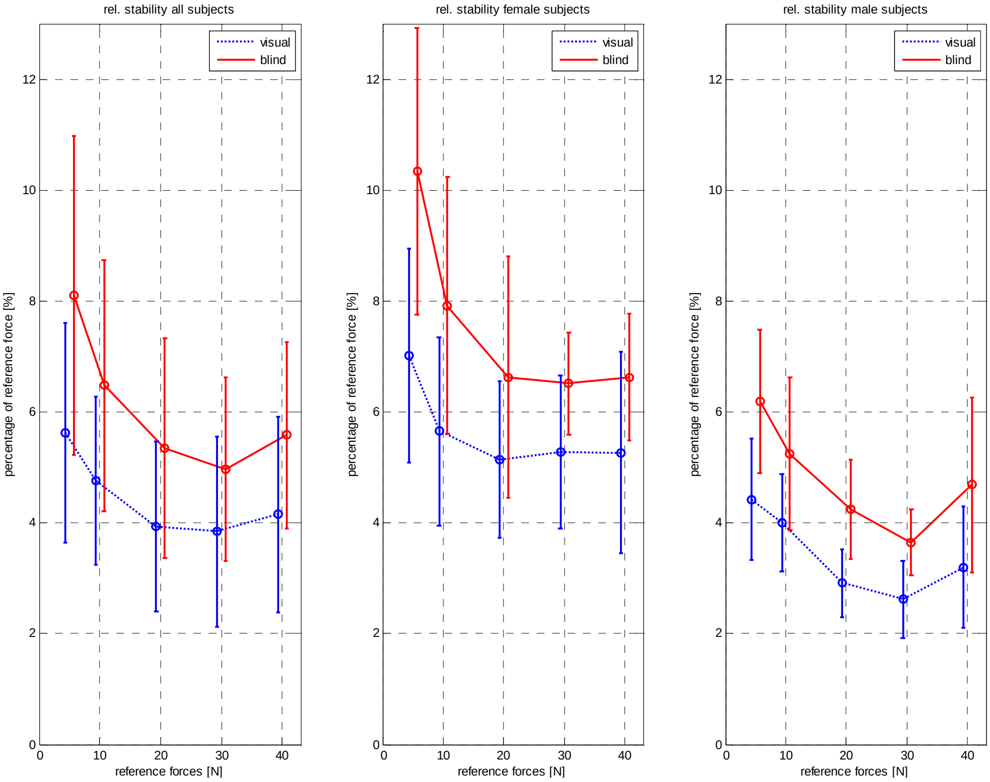

Figure 15 Relative stability (relative mean of noise). Averages (o) and standard deviations (error bars) across the group of subjects are shown for all subjects (left), female subjects (mid), male subjects (right).

## Repeatability (noise of mean)

The absolute and relative repeatability is shown in Figure 16 and Figure 17. The measure of reproducibility is the standard deviation from the mean values of the reproduced force at each block (noise of means).

### *Group of all subjects*

For absolute repeatability the minimum is found for the 5 N experiments (Figure 16). The deviation of data across the group of subjects is the lowest in 10 N experiments. No significant difference in noise of means is found between the 5 and 10 N experiments (T(12)=-1.849, p=0.089). The higher the reference force level during the experiments, the higher the average absolute noise of mean value becomes.

For relative repeatability the minimum is found during the 30 N experiments (Figure 17). Here also the deviation across the group of subjects is the smallest. However, no significant differences between the 20 and 30 N experiments (T(12)=0.851, p=0.412), between 30 and 40 N experiments (T(12)=-0.655, p=0.525), and between 20 and 40 N experiments (T(12)=0.081, p=0.937) are found. The spread of the results across the group of all subjects during the 40 N experiments is recognizably higher than the spread of the 20 and 30 N experiments. The highest averaged noise of means and the highest deviation between the subjects' results are found during the 5 and 10 N experiments. The repeatability values of 5 and 10 N experiments are not significantly different from each other (T(12)=1.785, p=0.099).

Overall the noise of means of visual blocks is lower than the noise of means of blind blocks. For all force levels, significant differences between the two conditions are found. Corresponding T- and p-values are shown inTable 7.

**Table 7 Significance in differences between visual and blind blocks in terms of absolute and relative repeatability**

| Reference force levels of experiments | Absolute and relative repeatability | Significant |
|---|---|---|
| 5 N | T(12)=-5.852, p<0.001 | Yes |
| 10 N | T(12)=-8.192, p<0.001 | Yes |
| 20 N | T(12)=-9.361, p<0.001 | Yes |
| 30 N | T(12)=-10.162, p<0.001 | Yes |
| 40 N | T(12)=-6.534, p<0.001 | Yes |

### *Female versus male subjects*

The above described absolute repeatability minima are also found for the separate groups of male and female subjects. The relative repeatability minimum for females is found in the 40 N experiments, whereas males show their minimum noise of mean value during 30 N experiments. Although in Figure 16 and Figure 17 the repeatability results of male subjects seem overall to be lower than those of females, no significant differences in repeatability performances are found between the male and female subjects in the absolute (F(4,8)=0.355, p=0.834) and relative sense (F(4,8)=0.662, p=0.636).

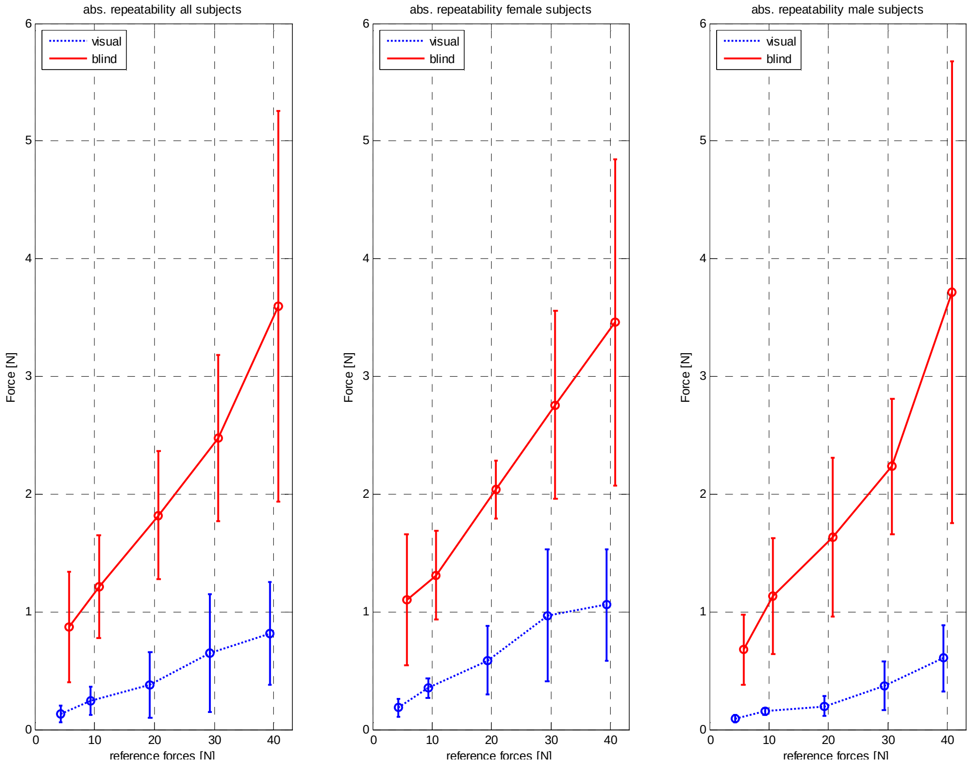

**Figure 16 Absolute repeatability (absolute noise of means). Averages (o) and standard deviations (error bars) across the group of subjects are shown for all subjects (left), female subjects (mid), male subjects (right).**

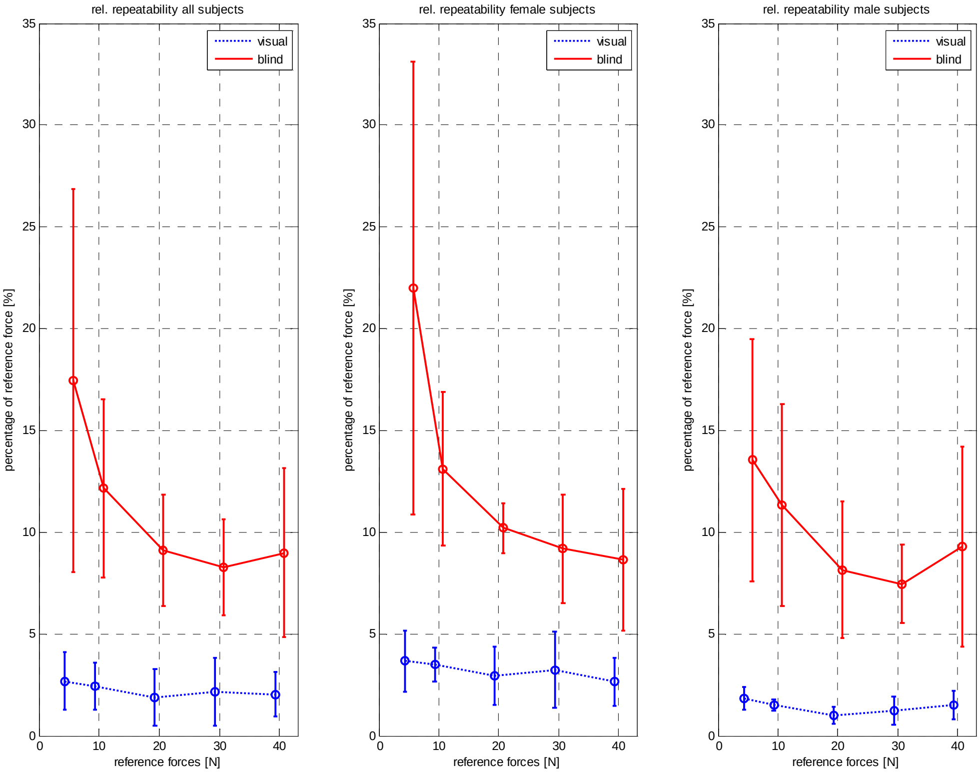

**Figure 17 Relative repeatability (relative noise of means). Averages (o) and standard deviations (error bars) across the group of subjects are shown for all subjects (left), female subjects (mid), male subjects (right).**

### Summary of results of subjects without arm defects

Between the 20 and 30 N experiments, the deviation between the reproduced and reference force becomes the smallest in terms of absolute and relative reproducibility (Figure 12 and Figure 13). The absolute stability and repeatability minima are found at 5 N (Figure 14 and Figure 16), whereas the minima for relative stability and repeatability are found during the 30 N experiments (Figure 15 and Figure 17).

The higher the reference force level becomes during the experiments, the higher the average values of absolute stability and repeatability become. Additionally, the higher the reference force level becomes during the experiments, the higher the deviation across the group of subjects becomes for reproducibility and repeatability.

During the 5 and 10 N experiments, the highest deviation between the reproduced and reference force result in terms of relative reproducibility. Additionally, the highest values in terms of relative stability and repeatability are found during these experiments. Furthermore, the deviations between the subjects' results are the highest for the 5 and 10 N experiments in terms of relative reproducibility, stability and repeatability.

### Questionnaire and comments during measurements

The subjective impressions resulting from the questionnaires (Figure 18) re-emphasise the findings as summarized in the section 'Summary of results of subjects without arm defects'. Subjects found 20 N the easiest force to reproduce blind (7 of 13 subjects), followed by 30 N with 5 votes. According to these subjects, the hardest force to reproduce blind was 5 N (8 votes) and 40 N (4 votes). Furthermore 40 N was found to be the most uncomfortable/tiring force (7 votes).

Females complained during the 40 N experiments about discomfort and trembling when reproducing the reference force. One subject did not even manage to finish the experiment. Another female subject found this force easy to reproduce, since this was the maximum force she could create. Furthermore subjects commented that the 5 and 10 N reference forces were difficult to feel.

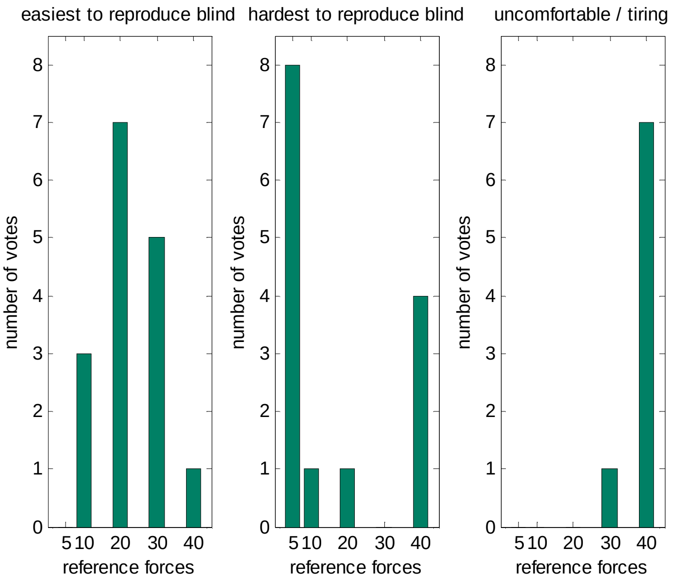

**Figure 18 Outcome questionnaires of subjects without arm defects**

## *Subjects with arm defects*

In this section, the results of the subjects with arm defects are compared to the results of subjects without arm defects in terms of reproducibility, stability and repeatability in the absolute and relative sense in Figure 19 to Figure 24. In these figures the results of both groups are illustrated as a hatched area, which indicates the standard deviation across the groups of subjects. A dotted line illustrates the average value across the group of subjects. Only the results of blind blocks are compared.

All seven subjects with arm defects succeeded in finishing the 5 N experiment, whereas only six of the 7 subjects were able to complete the 10 and 20 N experiments. The 30 N experiment was carried out by four of the seven subjects with arm defects and three of the tested seven subjects succeeded in carrying out the 40 N experiment.

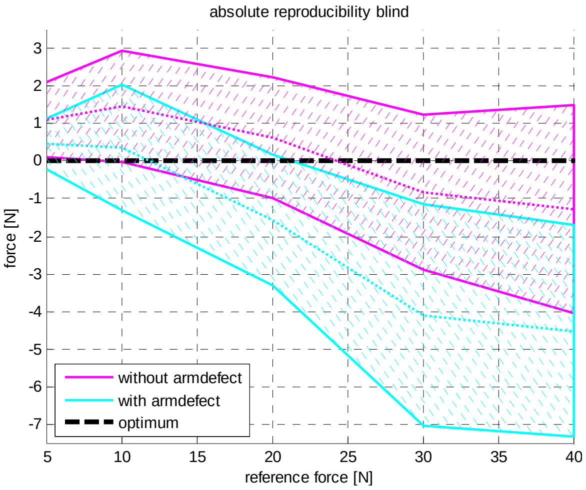

**Figure 19 Absolute reproducibility results comparison of subjects with and without arm defects. Averages (dotted lines) and standard deviations (upper and lower border of area) across the group of subjects are shown for blind blocks.**

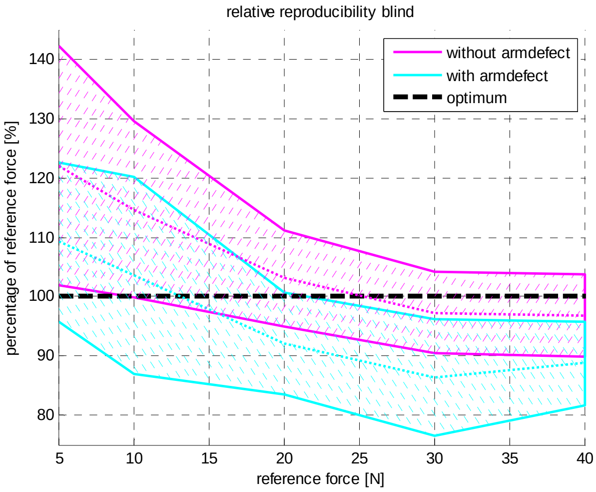

**Figure 20 Relative reproducibility results comparison of subjects with and without arm defects. Averages (dotted lines) and standard deviations (upper and lower border of area) across the group of subjects are shown for blind blocks.**

### Reproducibility (mean of means)

The results of absolute and relative reproducibility are shown in Figure 19 and Figure 20. The figures illustrate that both subject groups have a certain overlap of reproducibility results. The average reproducibility result across the group of subjects with arm defects lies inside the area of results of subjects without arm defects for the 5 and 10 N experiments, whereas this average value lies outside this area for the 20, 30 and 40 N experiments. The lower standard deviation borders of subjects with arm defects for all five experiments lie outside the area of subjects with arm defects for absolute and relative reproducibility. The upper standard deviation borders lie within this area.

The force where the reproduced force equals the reference force is found between 20 and 30 N for subjects without arm defects in absolute and relative sense. For subjects with arm defects the reproduced force equals the reference force between 10 and 20 N, as illustrated in Figure 19 and Figure 20.

### Stability (mean of noise)

Figure 21 and Figure 22 illustrate the absolute and relative stability results. Overall the stability results of both groups overlap in absolute and relative sense. The average mean of noise value of the group of subjects with arm defects lie in the standard deviation area of subjects without arm defects for all five experiments. The lower standard deviations borders of subjects with arm defects are found outside the standard deviation area of subjects without arm defects. The upper standard deviations borders of subjects with arm defects lie within the standard deviation area of subjects without arm defects, with the exception of the upper standard deviation of the 30 N experiment.

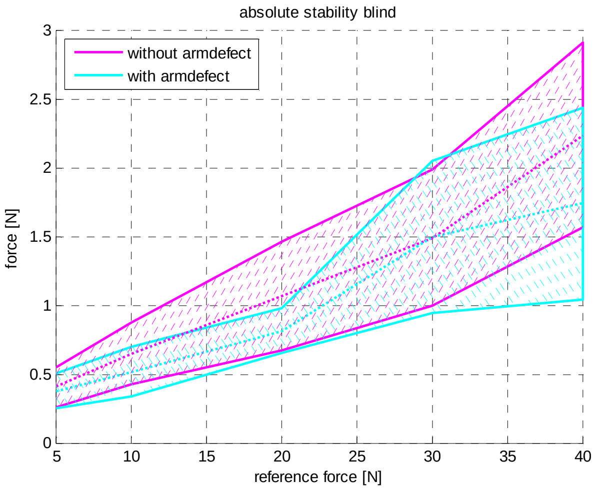

**Figure 21 Absolute stability results comparison of subjects with and without arm defects. Averages (dotted lines) and standard deviations (upper and lower border of area) across the group of subjects are shown for blind blocks.**

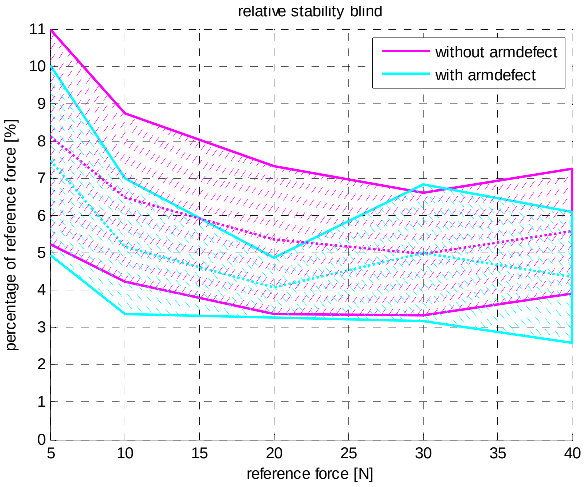

**Figure 22 Relative stability results comparison of subjects with and without arm defects. Averages (dotted lines) and standard deviations (upper and lower border of area) across the group of subjects are shown for blind blocks.**

### Repeatability (noise of mean)

The absolute and relative repeatability of both groups of subjects are illustrated in Figure 23 and Figure 24. Overall the repeatability results of both groups overlap in absolute and relative sense. Both figures show that the deviation of repeatability of subjects with arm defects are found within the borders of the standard deviation of subjects without arm defects during the 5 and 10 N experiments. The upper standard deviation border for the 20 and 30N experiments and the lower standard deviation border for the 40 N experiments of the subjects with arm defects lie outside the area of results of subjects without arm defects. Remarkable is the low deviation across the group of subjects with arm defects. The low number of subjects able to perform this 40 N experiment has to be considered.

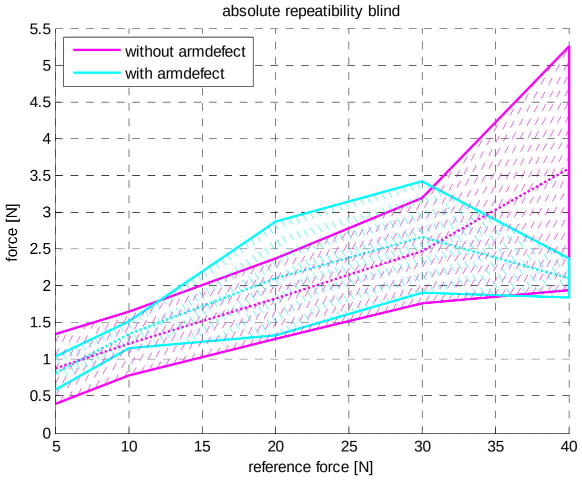

**Figure 23 Absolute repeatability results comparison of subjects with and without arm defects. Averages (dotted lines) and standard deviations (upper and lower border of area) across the group of subjects are shown for blind blocks.**

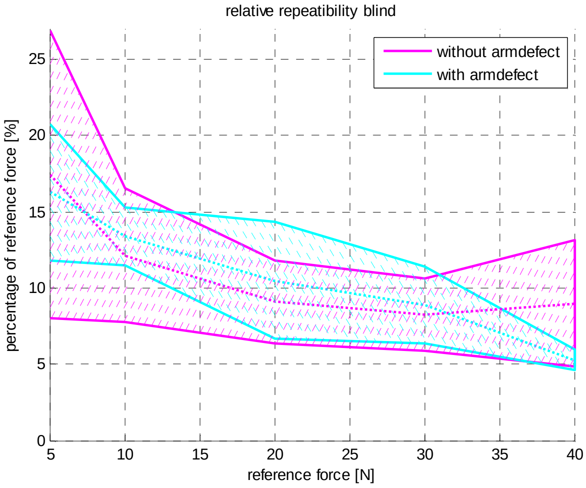

**Figure 24 Relative repeatability results comparison of subjects with and without arm defects. Averages (dotted lines) and standard deviations (upper and lower border of area) across the group of subjects are shown for blind blocks.**

# Discussion & Conclusion

The displayed reference force (Fref) is reproduced by the subject, which results in the reproduced force during visual blocks (Frep_visual). During blind blocks, the subjects reproduced the force they felt during the visual blocks (Frep_visual), which resulted in the reproduced force during blind blocks (Frep_blind). This is shown schematically in Figure 25. This figure also illustrates that, when comparing the visual performance with the reference force, conclusions can be drawn about the quality of visual feedback and the subject's capabilities, such as strength and reflexes. When comparing the blind performance with the visual performance, conclusions about the quality of tactile and proprioceptive feedback can be drawn. Comparing the blind block performance with the reference force provides information about tactile and proprioceptive feedback as well as about the subject's capacities.

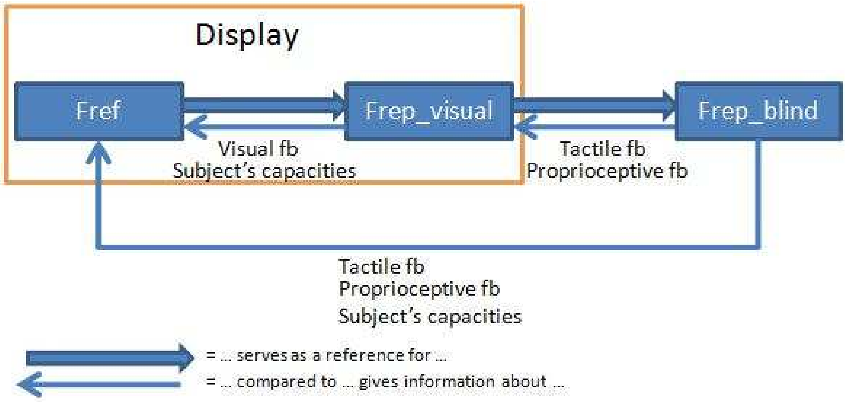

**Figure 25 Block diagram showing the relationships between the different forces and feedback mechanism (Legend: Fref = reference force, Frep_visual = reproduced force during visual block, Frep_blind = reproduced force during blind block, fb = feedback)**

In some cases the reference force cannot be reproduced due to a lack of physical strength. In this case, the subject cannot feel how it should feel to reproduce a certain reference force correctly. As a result, the subject receives an incorrect reference and not only the lack of tactile and proprioceptive feedback influences the subject's performance, but also his capacities. The purpose of this study is to find operating forces to control a prosthesis efficiently and comfortably. A prosthetic user operates a prosthesis comfortably, when he does not feel pain or suffer fatigue. Therefore the capacities of humans must be considered alongside the tactile and proprioceptive feedback capabilities. This is why, for reproducibility, the difference between blind reproduced force and reference force is taken. For stability and repeatability, the lowest possible noise (zero noise) is taken as a reference.

## *Optimal operation force level*

The purpose of this study is to find an optimal operation force, at which the prosthetic user receives the best force feedback during comfortable prosthesis operation. To find the optimal operation force, three performance factors are introduced in the section 'Method – Performance criteria'. The optima of these performance factors are defined as follows:

- The optimum for **reproducibility** is the force level at which the reproduced force (mean of means) equals the reference force. In Figure 12 (absolute reproducibility) and Figure 13 (relative reproducibility), the dashed black lines illustrate the optimum. The closer the reproduced force to the reference force –thus the closer the red line is to the dashed black line – the better the subject's performance.
- The optimum value for **stability** is the force level where the mean of the noise is minimal. Here, noise is defined as the average value of the standard deviation of the reproduced force. The lower the value of mean of noise, the better the subject's performance.
- The optimum of the **repeatability** is the minimum value of the noise of means (the standard deviation across the average produced force of each block). The lower the noise of means, the better the subject's performance.

In chapter 'Results', the results of the three performance factors are described. By combining the found results with the definitions of optima for the three performance factors, the following conclusions can be made about the subjects without arm defects:

- An optimum is found between the 20 and 30 N experiments for absolute & relative reproducibility.
- The optimum for relative stability and repeatability is found during the 30 N experiment.
- The optimum for absolute stability and repeatability is found during the 5 N experiment.

Although the optima for absolute stability and repeatability are found for the 5 and 10 N experiments, these operation forces cannot be called the optimum for several reasons.

- These experiments show the worst performance and highest deviation across a group of subjects in terms of relative reproducibility, stability and repeatability.
- A significant difference is found between visual and blind blocks in terms of absolute and relative reproducibility.
- The questionnaires show that 5 N is subjectively considered the hardest force to reproduce blind.
- During the 5 and 10 N experiments, the subjects commented that the force is hard to feel.

The 40 N experiments show no significant differences to the 30 N experiments, where the optimum operation force is found, in terms of absolute and relative reproducibility as well as for relative stability and repeatability. Still, an operation force of 40 N cannot be called an optimum because:

- The highest deviation between the subjects is found in terms of absolute reproducibility at this force level. Thus, subjects are not always equally capable of reproducing a certain force.
- The results of the 40 N experiments show the worst performance and highest deviation between subjects in terms of absolute stability and repeatability. This means that subjects are not capable holding a force at a constant level during one block and have difficulty reproducing the same force at different moments in time. Additionally, the performance of different subjects regarding absolute stability and repeatability differ the most during the 40 N experiments.
- A recognizably higher deviation within the group of subjects in terms of relative repeatability is found for the 40 N experiments than for the 20 and 30 N experiments.

- The highest offset of visual blocks in terms of absolute and relative reproducibility is found during the 40 N experiments. Thus, the subjects' capacities appear to reach their boundaries at this operation force.
- This is confirmed by the outcome of the questionnaires, where 7 out of the 13 subjects (54 %) agreed that 40 N was the most uncomfortable / most tiring force to reproduce (which was also mentioned several times during the course of this experiment). Furthermore, 4 subjects (31 %) found 40 N the hardest to reproduce blind.
- One female subject mentioned that this force is the highest force she was able to reproduce, while another female subject was not even able to finish the 40 N experiment.

## *Comparability of experimental data*

Another objective of this research is based on the question: Can the performance of a person with arm defect be predicted using the experimental results of subjects without arm defects? The results of subjects with and without arm defects are compared in terms of reproducibility, stability and repeatability in the absolute and relative sense in the section 'Results – Subjects with arm defects'. The average stability and repeatability results across the group of subjects with arm defects are found in the deviation area of the results of subjects without arm defects. Therefore it can be concluded that the stability and repeatability performance of subjects with arm defects does not differ to the performance of subjects without arm defects.

The same is found for the absolute and relative reproducibility of the 5 and 10 N experiments. However, for the 20, 30 and 40 N experiments, the average results across the group of subjects with arm defects are lower than the lower standard deviation border of subjects without arm defects for absolute and relative reproducibility. Therefore, a difference in reproducibility performance is found for the three higher forces between subjects with and without arm defects. Furthermore, the reproduced force equals the reference force between 10 and 20 N for the subjects with arm defects, whereas this optimum is found between 20 and 30 N for subjects without arm defects. Thus, another difference in reproducibility performance is found between subjects with and subjects without arm defects.

The fact that subjects with arm defects did not succeed in performing experiments with the higher reference forces –mainly the 30 and 40 N experiments (see test matrix in Appendix B.4) – implies that those cable forces are too high to operate during daily activities for subjects with arm defects. Indeed, the lower optimal force level for reproducibility performance emphasizes this conclusion.

## *Secondary findings*

An interesting effect that the results show is that in the blind blocks, subjects without arm defects produce more force than necessary at the three lowest force levels (positive error), whereas they produce less than required force at 30 and 40 N (negative error). In studies using similar measurement protocols to this study, such as the research of Mugge at al. (2010), the blind produced force is always higher than the reference force. When the blind produced forces become lower than the reference forces, it is assumed that these force levels are not easily reproduced because of a lack of the subject's strength. So far, this is only a hypothesis and further research needs to be conducted in order to investigate this effect in more detail.

## *Study limitations*

In this research, cable displacement and the prehensor's opening width were not taken into account. As mentioned in the section 'Approach', cable force and cable displacement come together in prosthesis operation when grasping an object. In this study, only a simulation of holding and pinching a rigid object is analysed. Does the cable force which provides the best feedback change when holding and squeezing a soft object for example? This needs to be investigated in follow up research.

Penalties and rewards were not utilized during the experiments. It is unknown how penalties or rewards will influence the performance of subjects participating in these experiments. Additionally, the experiments conducted do not give an indication as to whether subjects perform better after training. The results do not show any extended physiological proprioception learn effect. In order to investigate whether subjects perform better after training, more tests will need to be performed at defined time intervals.

At this point, it is necessary to mention that, when reproducing the reference force during visual blocks of the experiments, the visual feedback might have been influenced by the scaling of the vertical axis of the waveform chart in the LabVIEW program. The vertical axis was scaled for 5 N experiments from 0 to 10 N, whereas during 40 N experiments the vertical axis was scaled from 0 to 80 N. Thus, a higher resolution for the reproduced force and its deviation was given at small forces compared to high forces. This might have influenced the performance at higher forces negatively compared to the performance at smaller force levels. However, the performance is certainly also influenced by the subject's capabilities, such as strength and reflexes. The results of the questionnaires support this further, as is discussed previously in section 'Discussion - Optimal operation force level'. Additionally, the reproduced forces of visual blocks are lower than the reference force at the higher force levels. When the offset is only due to the resolution, the reproduced forces in visual blocks then can also have been higher than the reference force.

When comparing the group of subjects with arm defects with the group of subjects without arm defects, a group of subjects of 25±3 years is compared to a group of subjects of 42±13 years. This also raises the question whether the same similarities and differences between the groups will be found if two groups of approximately the same age are compared. Further research should be conducted to answer this question.

## *Prosthesis design*

### Uniform design

It is economically advantageous to develop a uniform prosthesis design for male and female users. But is uniform design comfortably controllable for both male and female users? Thus, is uniform design feasible? The performance of males compared to the performance of females is not found to be significantly different in terms of absolute and relative reproducibility, relative stability, as well as absolute and relative repeatability. Still, the stability and repeatability performance of males appear better than that of females. In other words, female subjects experience more difficultly holding a certain force stable than males, and also experience more difficultly creating the same force at different moments in time (repeatability). Additionally, females appear incapable of reproducing the higher forces as easily as the male subjects. This is shown for a reference force of 40 N by a significant offset between zero line and deviation of the reproduced and reference force for absolute reproducibility. Additionally, the highest offset of visual blocks in terms of absolute and relative reproducibility is found for females. The fact that one female subject was not able to finish the experiment, and the comment of another female subject that 40 N is the highest force she could probably reproduce, emphasise this.

Thus, it seems to be more important for female than for male users to maintain the required operating forces in the range of the optimal cable force. However, male users will also benefit from lower operation forces in terms of comfort and control. The optimal force feedback of males might lie at a slightly higher force level than that of females, but male subjects are still also less capable of operating a prosthesis with an operation force of 40 N continuously. This can be concluded based on the fact that the deviation across the group of male subjects increases, compared to the 30 N experiments in terms of all performance factors in the absolute and relative sense.

Additionally, the force that females maintain is less constant than that of the males (stability), and females also have a higher deviation between reproduced forces (repeatability) than males. Males will also benefit from a prosthesis design that lowers the noise of the produced force (increasing the stability) and lowers the deviation between produced forces at different points in time. Therefore it can be concluded that a uniform prosthesis design is feasible.

### Commercially available prostheses

During this study, an optimal cable activation force is found between 20 and 30 N, where comfortable prosthesis operation is possible with cable force feedback. The cable operation force of 40 N causes discomfort, in terms of pain and fatigue. Higher operation forces will most likely cause even more discomfort and should therefore be avoided during daily activities.

The behaviour of voluntary closing prosthesis, as investigated by Smit and Plettenburg (2010), and as illustrated in Figure 7, is taken together with the found optimum between 20 and 30 N. As a result, the only prosthesis that can be operated in this optimum force range is the TRS hook. The other examined prostheses require cable forces that are too high, which will lead to discomfort during operation. However, assuming operation with cable forces up to 40 N, the TRS hook can only be operated with maximum pinch forces of 20 N. Considering that during the experiments of Smit and Plettenburg the Bowden cable mechanism was eliminated, it can be assumed that the produced pinch force of 20 with a 40 N cable force is even lower in practice. As a result, the required grasping force of 34.3 N for pulling on a sock (Keller et al., 1947) cannot be reached within the investigated optimal cable operation force range using the TRS hook or other commercially available prehensors.

The absolute stability and repeatability performances investigated during the 40 N experiments should be considered when investigating the performance of the TRS hook. Taking for absolute repeatability the average value of the 40 N experiment in Figure 16, the offset of the estimated force is approximately 3.6 N. On top of this 3.6 N offset comes an offset of 2.2 N due to the average value of stability performance during the 40 N experiment (Figure 14). Thus, operating a voluntary closing prosthesis will lead to an offset of 5.8 N from the cable force of 40 N, which is an offset of 15 % cable force. Note that in the worst case this offset will be even larger as actual fluctuations can be higher. Again, follow up research should be conducted into which cable force offsets are most tolerable during daily activities.

## New prosthesis design

However, in order to improve prosthesis design, daily required pinch forces should be related to the found optimum of 20 and 30 N cable force. Pinch forces higher than 20 N will most likely be required in daily activities as well. A lower offset than 15 % at 40 N cable forces is preferable. Therefore follow up research should be conducted in order to investigate possible technical solutions. One might consider implementing transmission radios with either a constant or a variable gain or implementing servo mechanisms.

A transmission gain can be constant or variable. This raises the question of whether a human can easily adapt to a non-linear relationship between muscle force and cable activation force as well as between cable activation force and pinch force. An additional question to be answered is: Do subjects feel small differences (e.g. 1 or 2 N) in the optimal operation force area? The appropriate transmission gain can be chosen based on the answers to these questions.

Further research needs to be conducted on the required pinch forces of daily life activities, in order to find the right force transmission ratio of pinch forces versus cable forces. The pinch forces obviously also depend on the size and the friction coefficient of the contact surface of the object and prosthetic hand /hook (also referred to as prehensor). Objects that humans handle on a daily basis differ in surface area and shape as well as surfaces friction coefficient. They can also be hard and soft.

Controlling a body-powered prosthesis requires controlling the prehensor's opening width as well as the pinch force. In this research, cable, displacement and the prehensor's opening width are not taken into account. Still, this is an important factor in prosthesis design and should not be overlooked. It is uncertain whether prehensor opening width and pinch force can be analysed separately in terms of prosthesis control. However, follow up experimental research including cable displacement should investigate whether:

1. there is also an optimal cable displacement, where the user receives the best feedback of the displacement;
2. the found cable force is still the optimal force when cable displacement is taken into account.

Once these questions are answered, a transmission ratio for cable displacement and the prehensor's opening width can also be included in a new prosthesis design.

The Southampton Hand Assessment Procedure (SHAP) materializes a kit, containing objects that are necessary to handle during daily activities (Light et al., 2002). Experimental research should be conducted in order to investigate pinch forces of different prehensors and the related cable forces to grasp these objects. Using this kit, it may become possible to develop a standardized test method for all commercial available prostheses, in order to check the performance of the prosthesis before launching it. Additionally, the effect of sensory weighting between cable force and cable displacement when grasping a soft object, for example, might be studied using this kit.

## *Summary of conclusions*

In summary, the following points can be concluded from this research:

- The optimal operation force, at which the user receives optimal feedback and is able to control the prosthesis comfortably, is found between 20 and 30 N for subjects without arm defects.
- A lower optimal operation force between 10 and 20 N is found for subjects with arm defects. Stability and repeatability performances of subjects with and without arm defects are comparable.
- Cable forces between 5 and 10 N are too low to be controlled with optimal force feedback.
- The border of comfortable operation is found around the cable activation force of 40 N. At this boundary, the proprioceptive feedback is disturbed.
- A uniform prosthesis design can be used for female and male prosthetic users.
- Only one commercially available voluntary closing prosthesis, the TRS hook, is capable of creating pinch forces with the found optimal cable activation forces. However, pinch forces of the TRS hook created with the optimal cable activation forces are too low for daily activities.
- New prosthesis design is desired with lower required cable operation forces in order to provide optimal proprioceptive feedback to the user and guarantee comfortable operation. Solutions might be found by implementing transmission gains or servo mechanisms.

# Recommendations

This research shows that prosthesis design needs to be improved in order to match the capacities and meet the needs of users. One idea is to implement force transmission ratios or servo mechanisms in new prosthesis design. However, follow up research will need to be conducted in order to investigate;

- which transmission ratios should be chosen and whether a constant or variable gain is preferable;
- the relationship between the desired pinch forces and the corresponding cable forces required;
- the optima of cable displacements;
- the effect of sensory weighting between cable force and cable displacement when, for example, grasping a soft object with a prehensor;
- the influence of training and the effect of Extended Physiological Proprioception when operating voluntary closing prostheses.
- whether the same similarities and differences between the groups of subjects with and without arm defects will be found when comparing two groups of the same age with each other.

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